Isospin dependence of NN correlations and quenching of spectroscopic factors

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U.S. DEPARTMENT OF ENERGY | Office of Science

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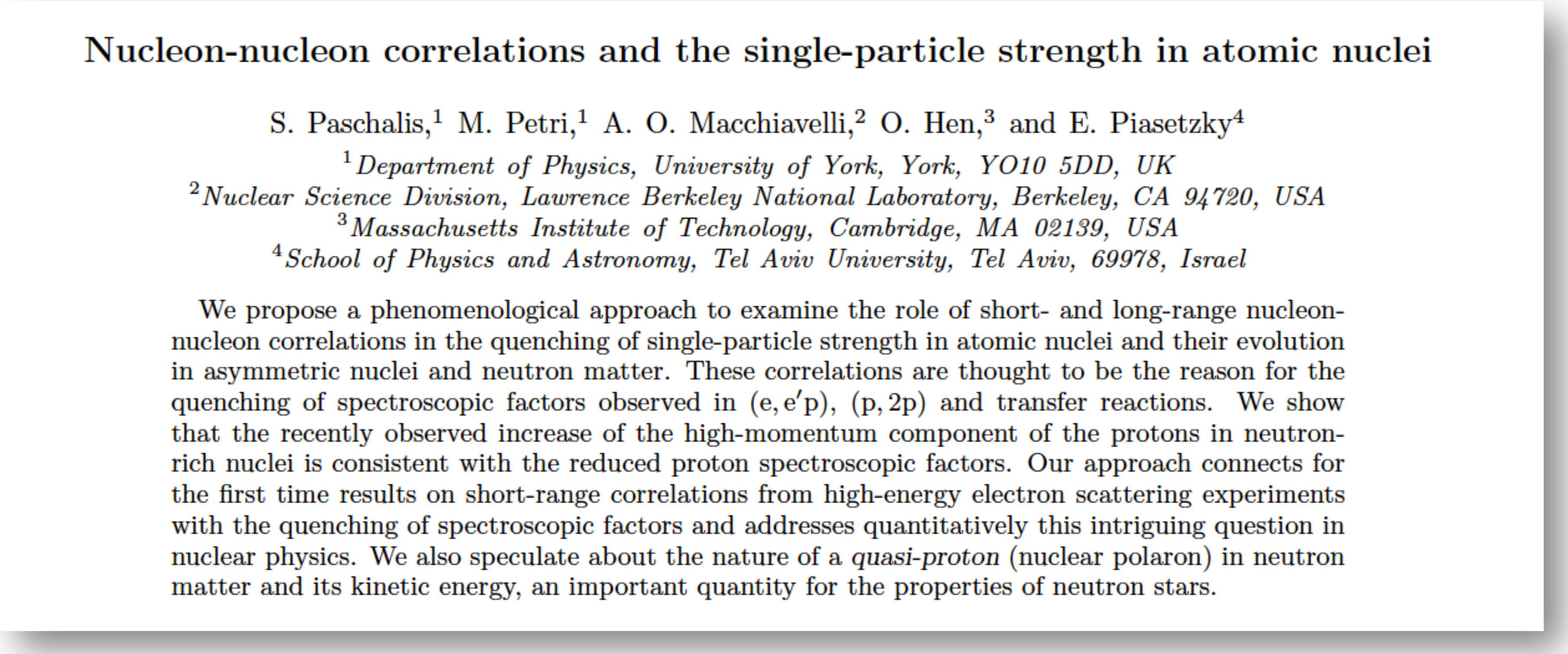

Nucleon-nucleon correlations and the single-particle strength in atomic nuclei

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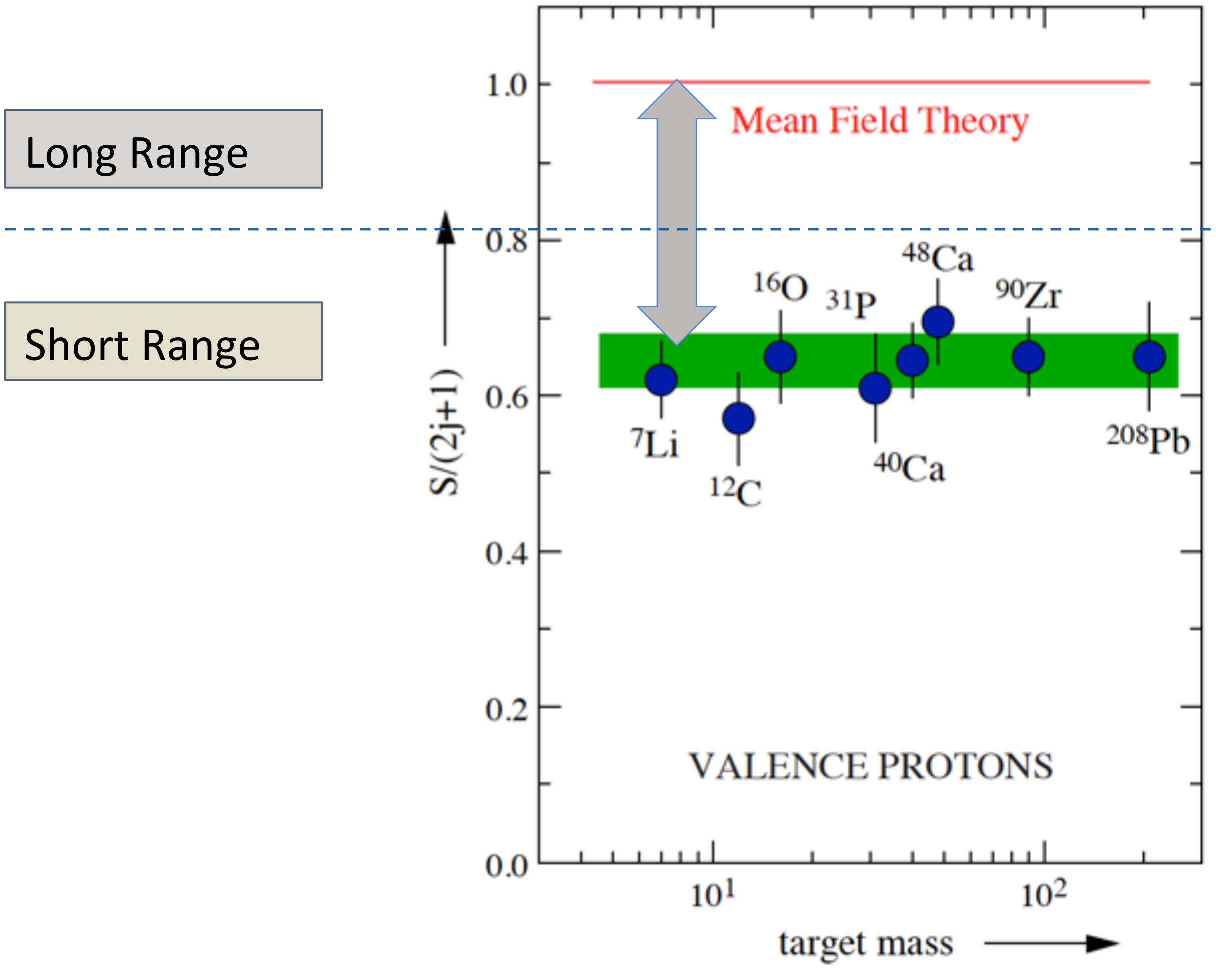
We propose a phenomenological approach to examine the role of short- and long-range nucleon-nucleon correlations in the quenching of single-particle strength in atomic nuclei and their evolution in asymmetric nuclei and neutron matter. These correlations are thought to be the reason for the quenching of spectroscopic factors observed in $(\mathrm{e}, \mathrm{e'p})$, $(\mathrm{p}, 2\mathrm{p})$ and transfer reactions. We show 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 connects for the first time results on short-range correlations from high-energy electron scattering experiments with the quenching of spectroscopic factors and addresses quantitatively this intriguing question in nuclear physics. We also speculate about the nature of a *quasi-proton* (nuclear polaron) in neutron matter and its kinetic energy, an important quantity for the properties of neutron stars.

arXiv:1812.08051v2 [nucl-ex] 21 Jan 2019

Submitted to PLB

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



Long Range

Short Range

- Correlations between nucleons modify the mean-field approximation and are thought to be the reason for the quenching of SF observed in (e,e’p), (p,2p) and transfer reactions.
- About 30% – 40% of the nucleons participate in NN correlations, which are distinguished into long-range (LRC) and short-range (SRC).

PHYSICAL REVIEW VOLUME 98, NUMBER 5 JUNE 1, 1955

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

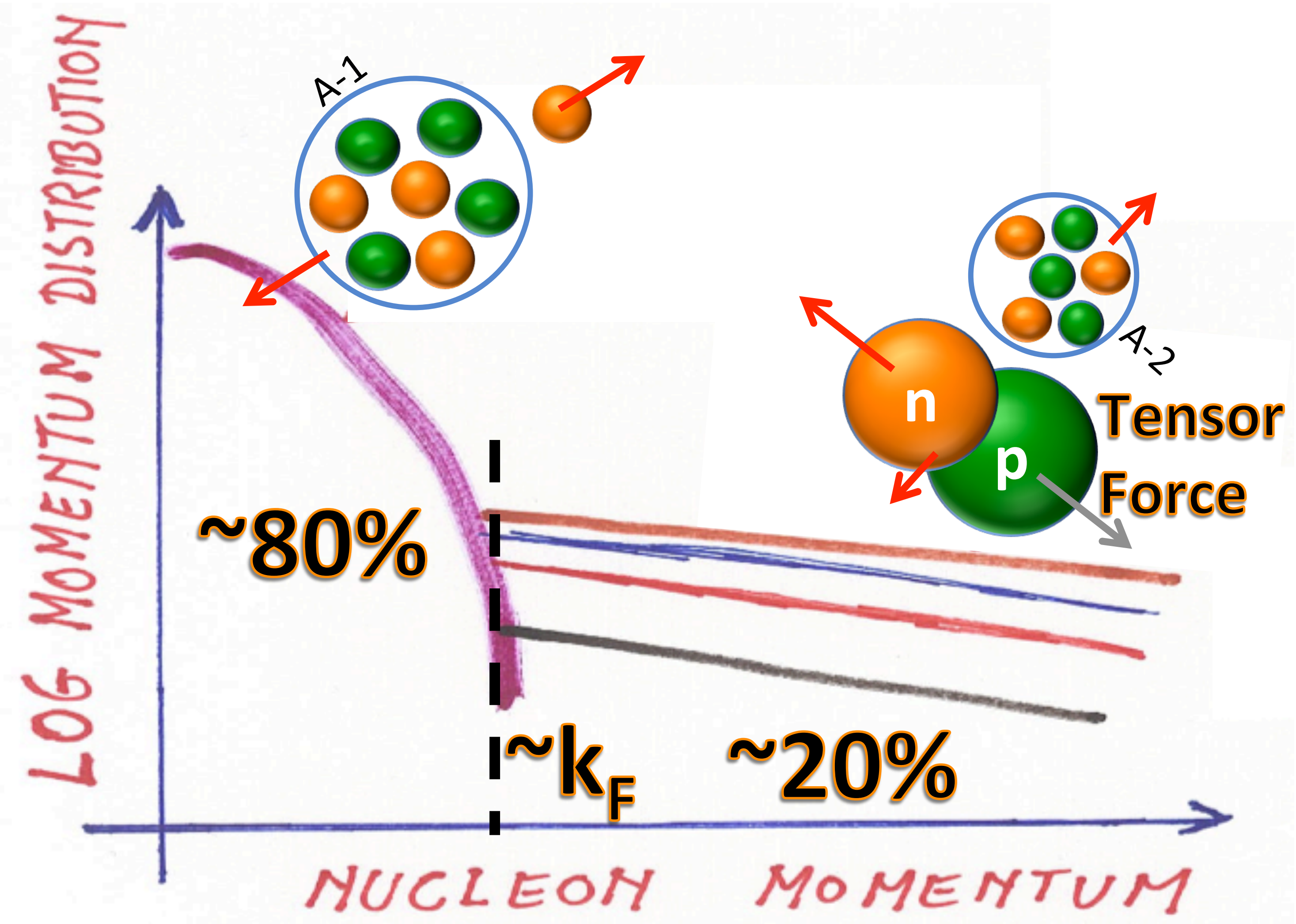
K. A. BRUECKNER, R. J. EDEN,† AND N. C. FRANCIS
Indiana University, Bloomington, Indiana

(Received January 13, 1955)

V. CONCLUSIONS

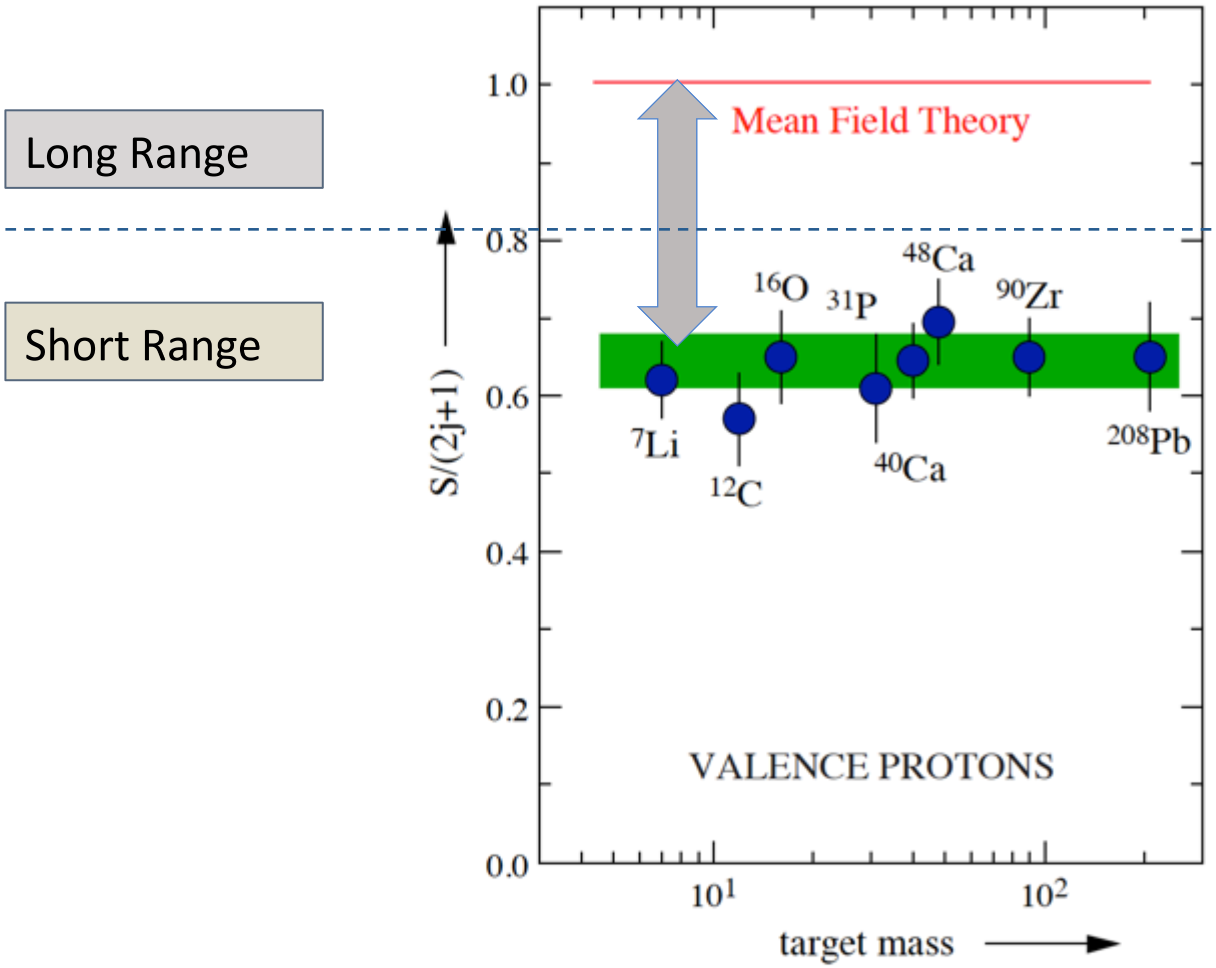
We have analyzed evidence derived from a variety of high-energy experiments which has bearing on the problem of nuclear structure. This evidence is particularly significant since it is for these (or similar) processes that the possible departure of the nuclear ground-state wave function from an independent-particle 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.

A high-momentum tail is attributed to SRCs between a pair of strongly interacting nucleons; a value of about 20% SRC contribution was indirectly inferred.



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)

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



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1.D.2

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

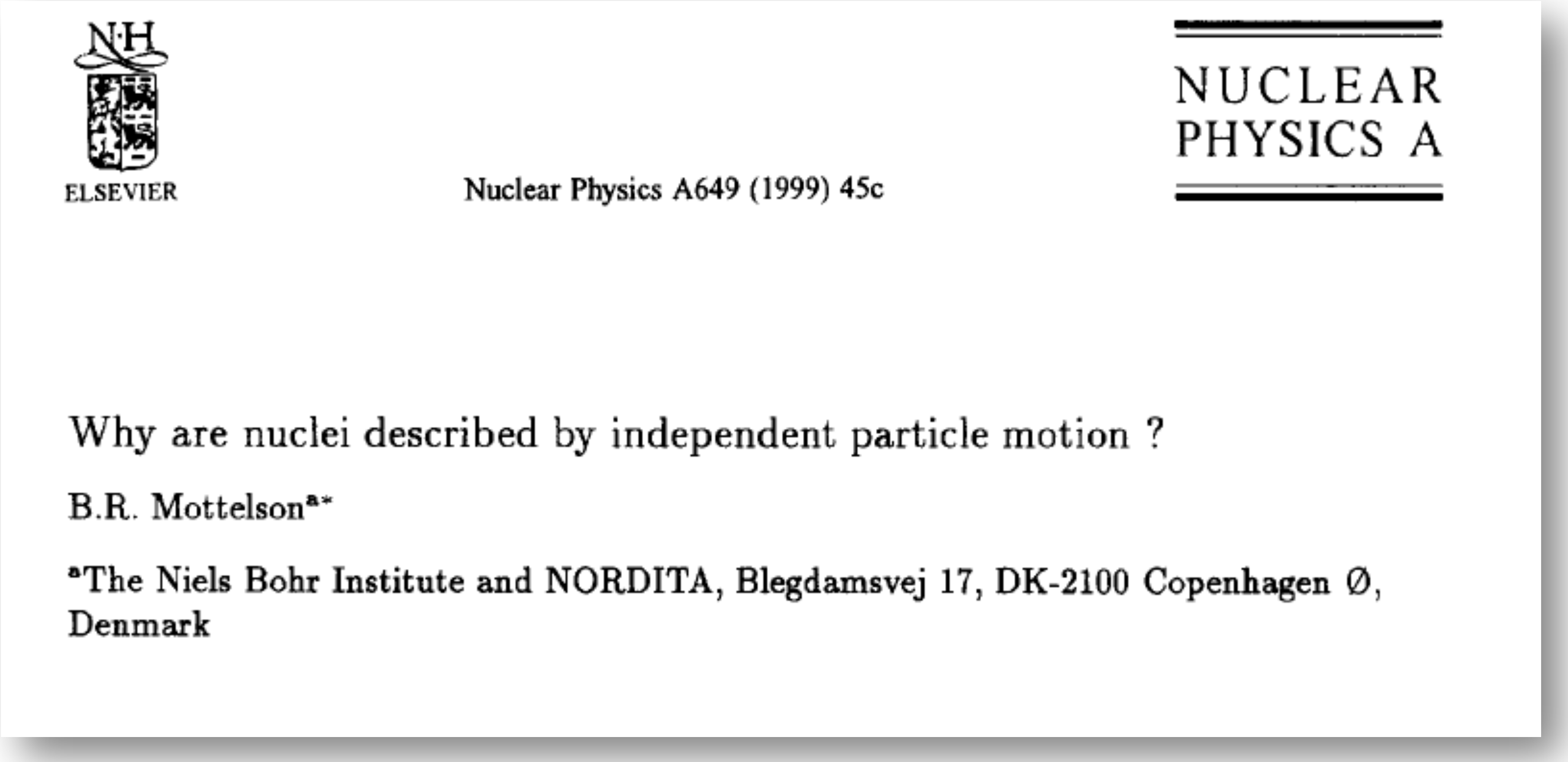
EFFECTIVE MASS IN NUCLEI

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 $\approx 25\,\%$ in intermediate and heavy nuclei. This produces a corresponding increase in the effective mass of particles near the Fermi surface.



ELSEVIER

Nuclear Physics A649 (1999) 45c

NUCLEAR
PHYSICS A

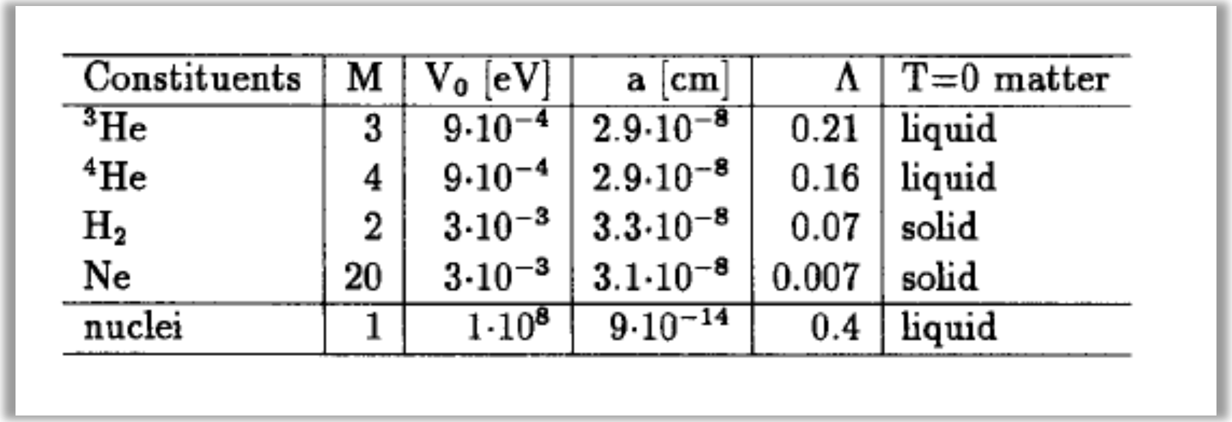
Why are nuclei described by independent particle motion ?

B.R. Mottelson[a*]

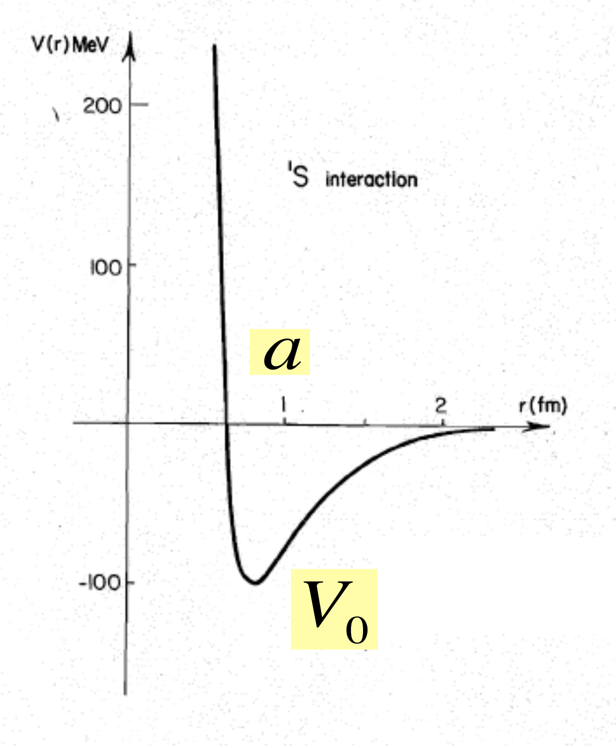
[a]The Niels Bohr Institute and NORDITA, Blegdamsvej 17, DK-2100 Copenhagen Ø,
Denmark

"Quantality Parameter"

$$\Lambda = \frac{\hbar^2 / Ma^2}{V_0}$$



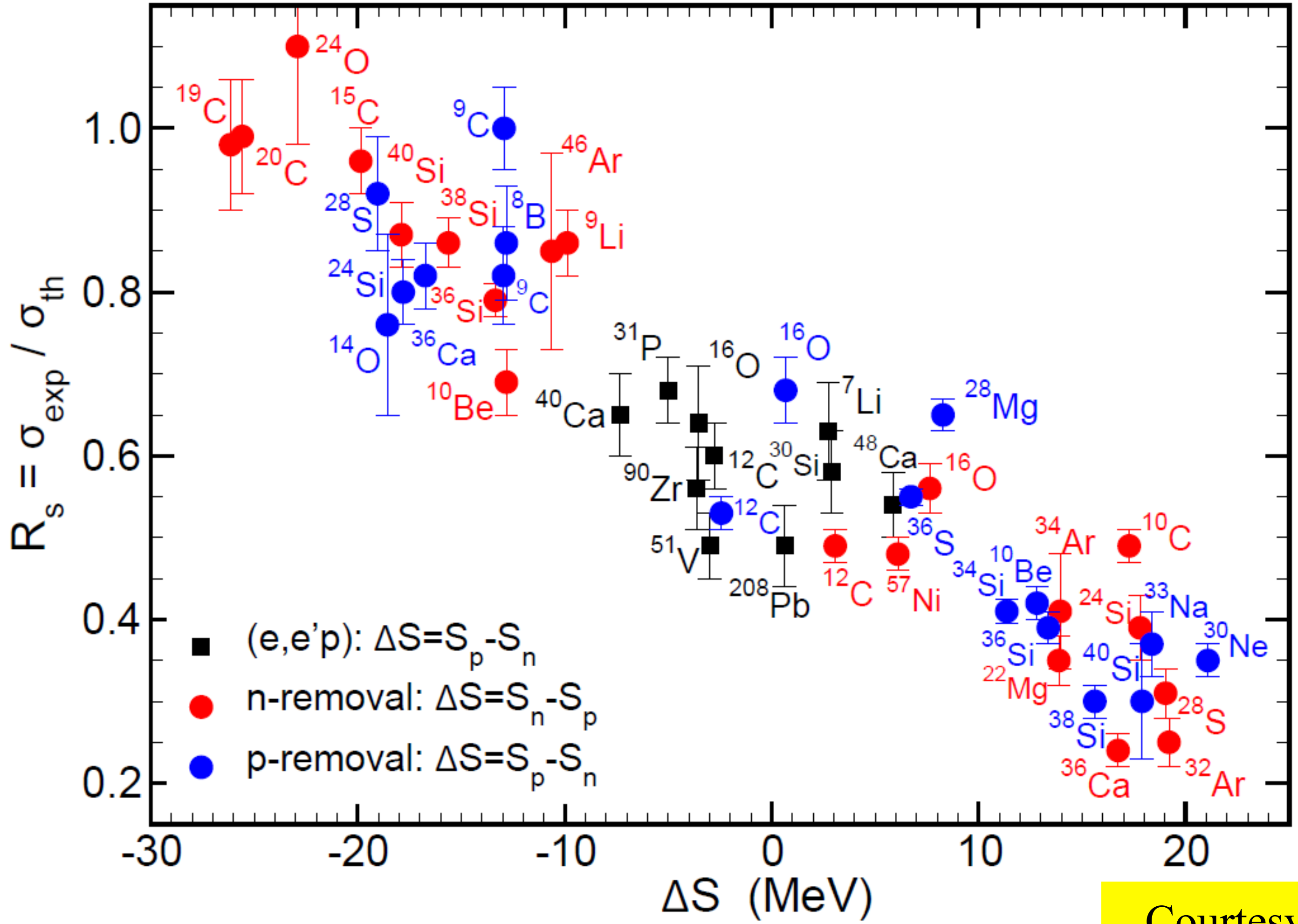
Constituents	M	V_0 [eV]	a [cm]	Λ	T=0 matter
^{3}He	3	$9 \cdot 10^{-4}$	$2.9 \cdot 10^{-8}$	0.21	liquid
^{4}He	4	$9 \cdot 10^{-4}$	$2.9 \cdot 10^{-8}$	0.16	liquid
H_2	2	$3 \cdot 10^{-3}$	$3.3 \cdot 10^{-8}$	0.07	solid
Ne	20	$3 \cdot 10^{-3}$	$3.1 \cdot 10^{-8}$	0.007	solid
nuclei	1	$1 \cdot 10^{8}$	$9 \cdot 10^{-14}$	0.4	liquid



Fermi Liquid → quasiparticles

Motivation

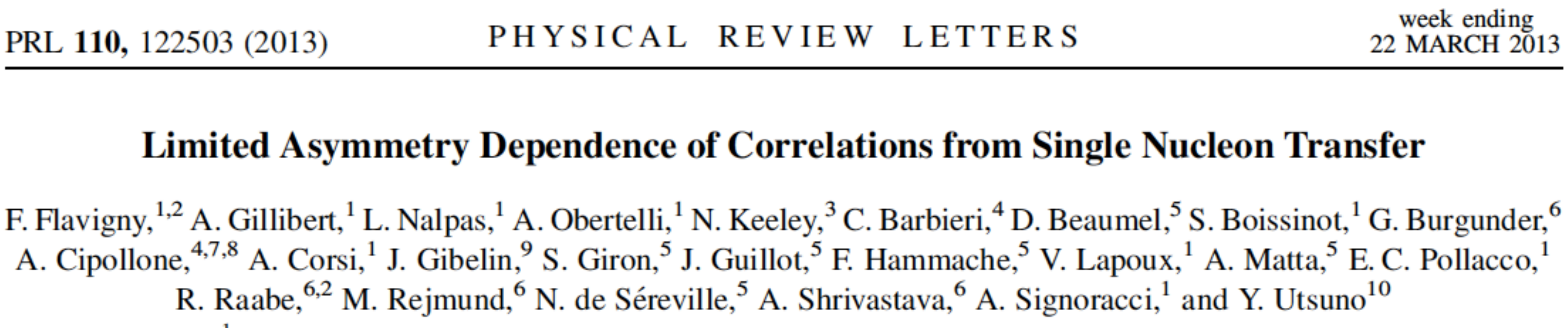
Data today – contains data from NSCL, RIKEN, Lanzhou, Bevalac



Courtesy of A. Gade

National Science Foundation
Michigan State University

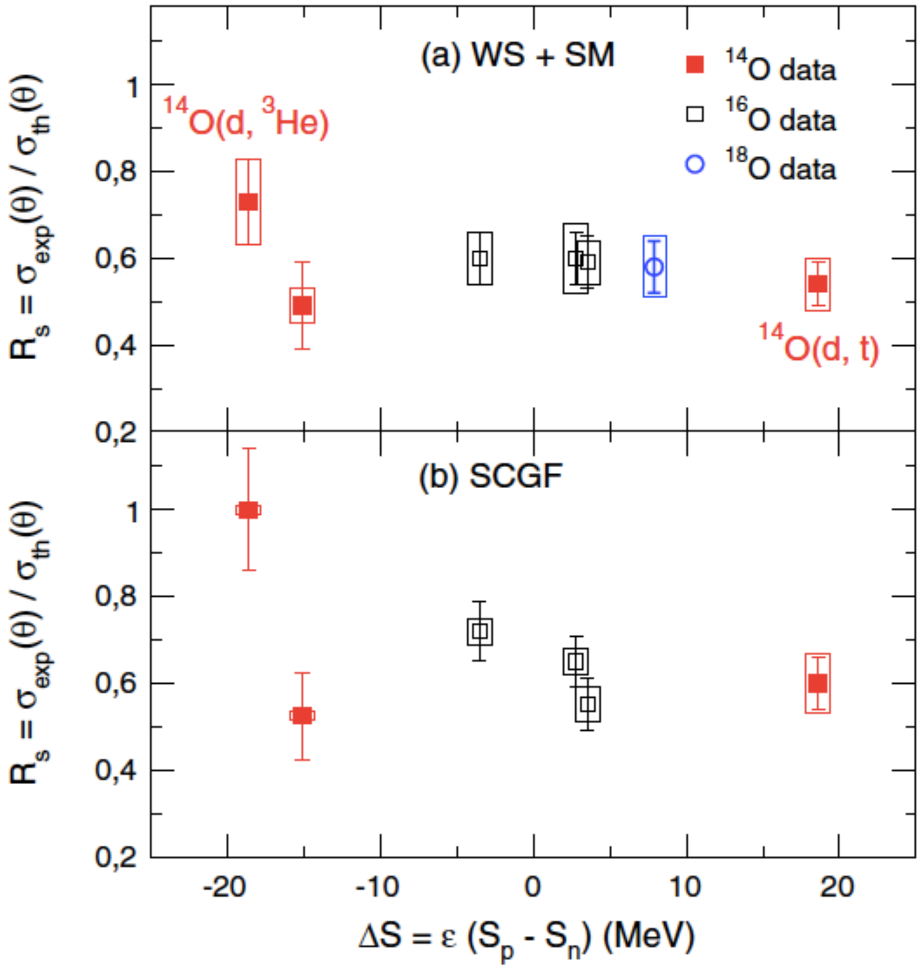
Figure: Jeff Tostevin's 2017 update from
J. A. Tostevin and A. Gade, PRC 90, 057602 (2014)



PRL 110, 122503 (2013) PHYSICAL REVIEW LETTERS week ending 22 MARCH 2013

Limited Asymmetry Dependence of Correlations from Single Nucleon Transfer

F. Flavigny,[1,2] A. Gillibert,[1] L. Nalpas,[1] A. Obertelli,[1] N. Keeley,[3] C. Barbieri,[4] D. Beaumel,[5] S. Boissinot,[1] G. Burgunder,[6] A. Cipollone,[4,7,8] A. Corsi,[1] J. Gibelin,[9] S. Giron,[5] J. Guillot,[5] F. Hammache,[5] V. Lapoux,[1] A. Matta,[5] E. C. Pollacco,[1] R. Raabe,[6,2] M. Rejmund,[6] N. de Séreville,[5] A. Shrivastava,[6] A. Signoracci,[1] and Y. Utsuno[10]



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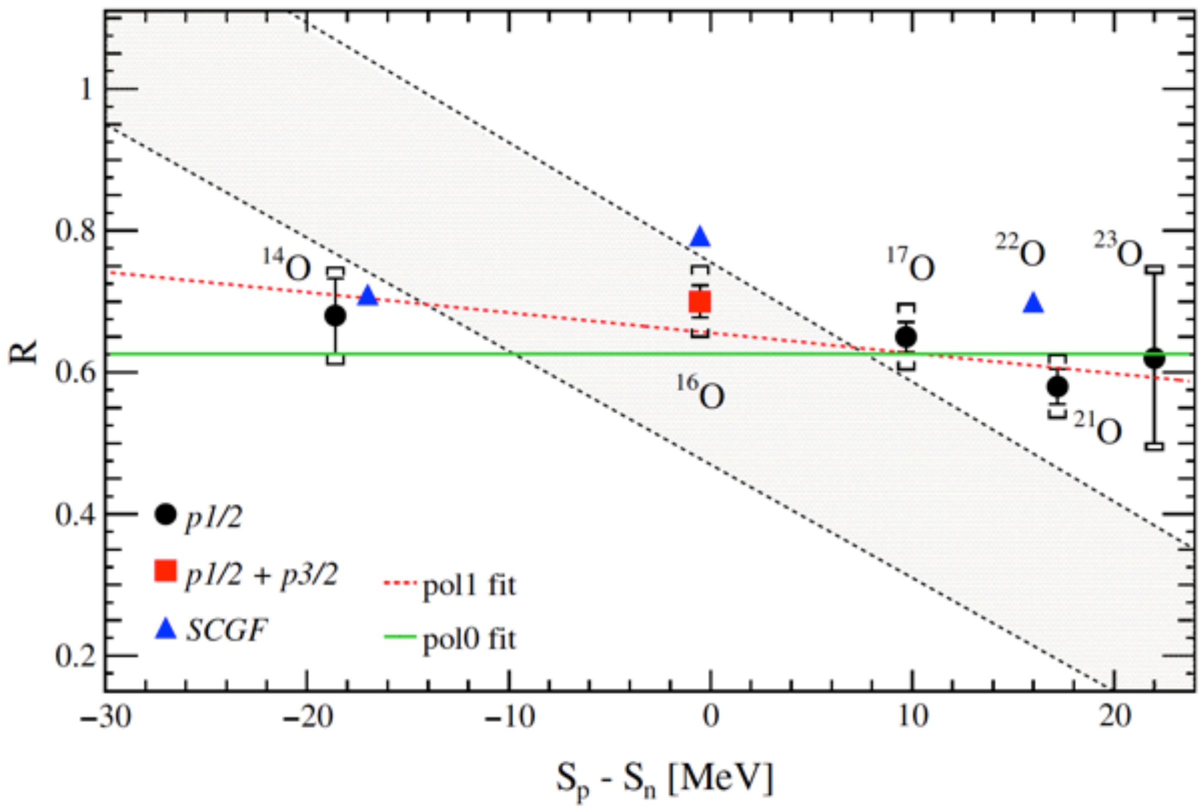
PHYSICAL REVIEW LETTERS **120,** 052501 (2018)

Quasifree (p, 2p) 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] …..

(R^{3}B Collaboration)



GSI

The open questions we address:

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

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

Our approach:

In the spirit of Mottelson's Fermi liquid single-particle configuration

Long-range correlations

Short-range correlations

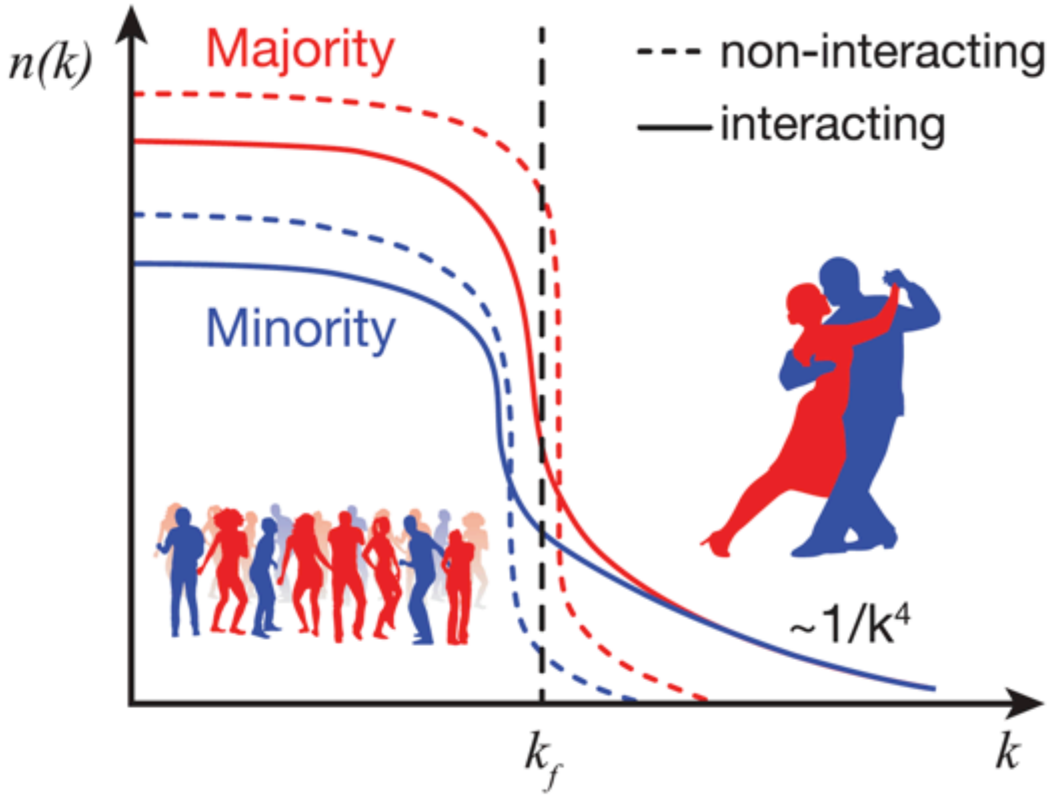
$$|\mathrm{qp}\rangle \approx \mathrm{a}|\mathrm{sp}\rangle + \underbrace{\mathrm{b}|\mathrm{LRC}\rangle}_{\text{Pairing correlations} \quad \text{Particle-vibration coupling}} + \mathrm{c}|\mathrm{SRC}\rangle$$

$$\mathrm{R} \approx \mathrm{a}^2 = 1 - \overbrace{\mathrm{R}_{\mathrm{LRC}} - \mathrm{R}_{\mathrm{SRC}}}^{\text{Missing strength}}$$

R = total single-particle Quenching Factor
represents the probability to find a nucleon in the pure single-particle configuration

SRC quenching

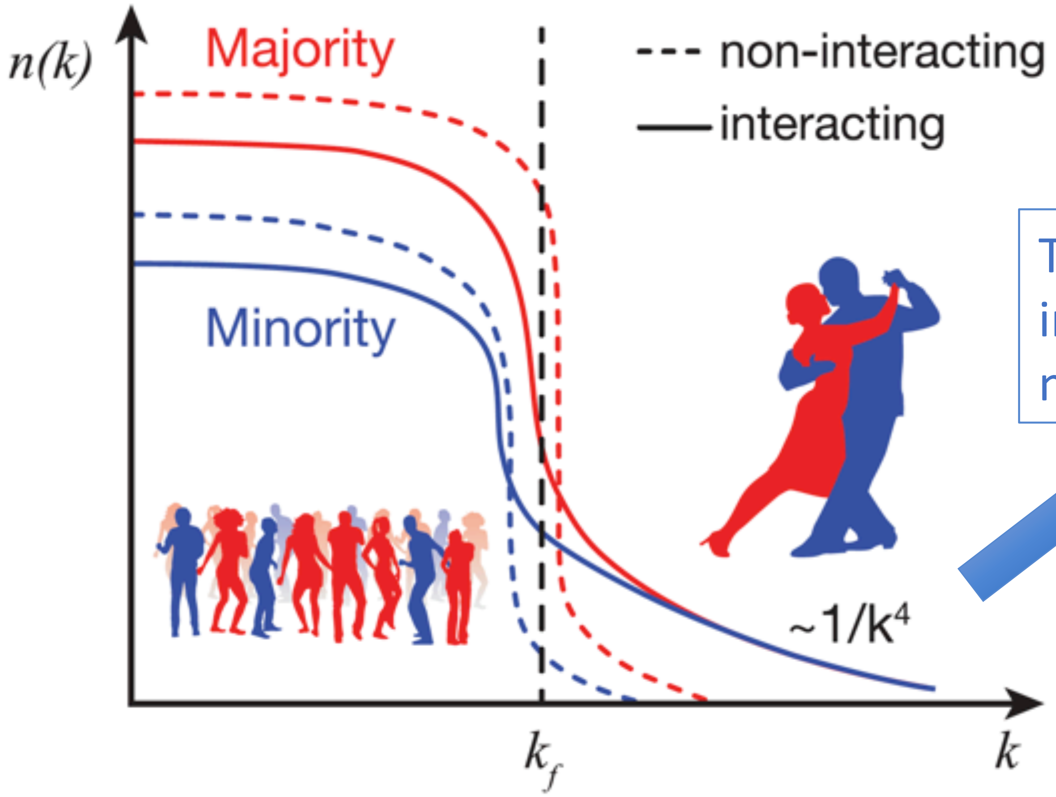
Minority nucleons have on average much higher kinetic energy



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

SRC quenching

Minority nucleons have on average much higher kinetic energy

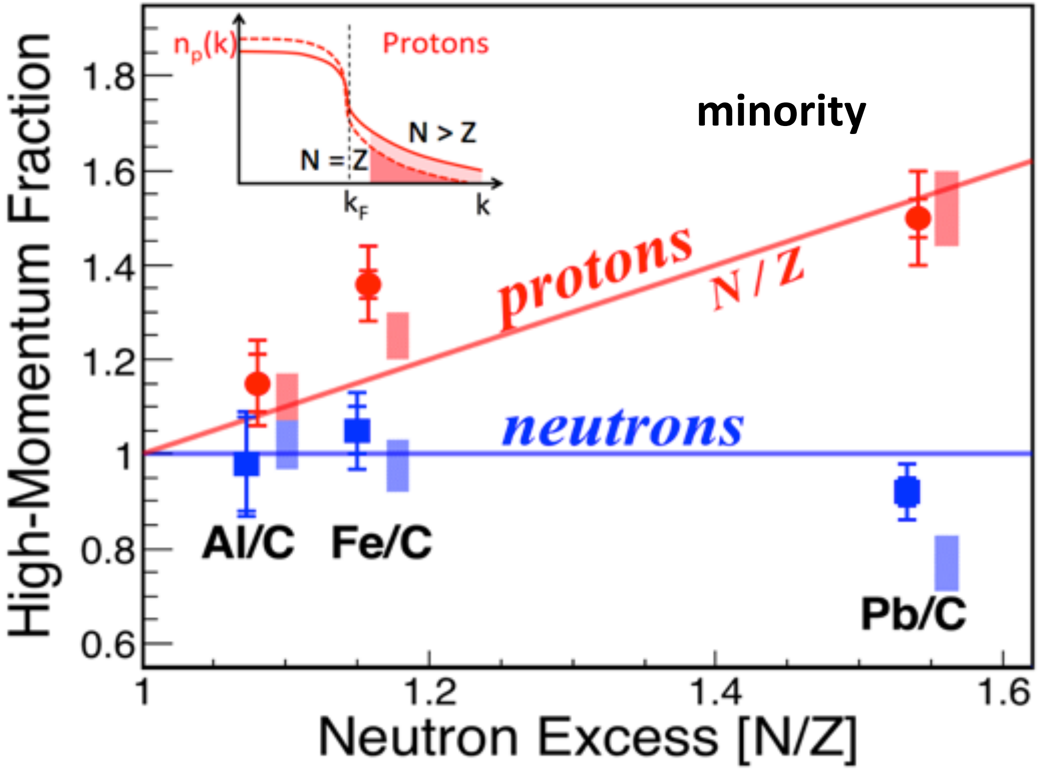


This must be reflected in the SF of the minority nucleons (protons)

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

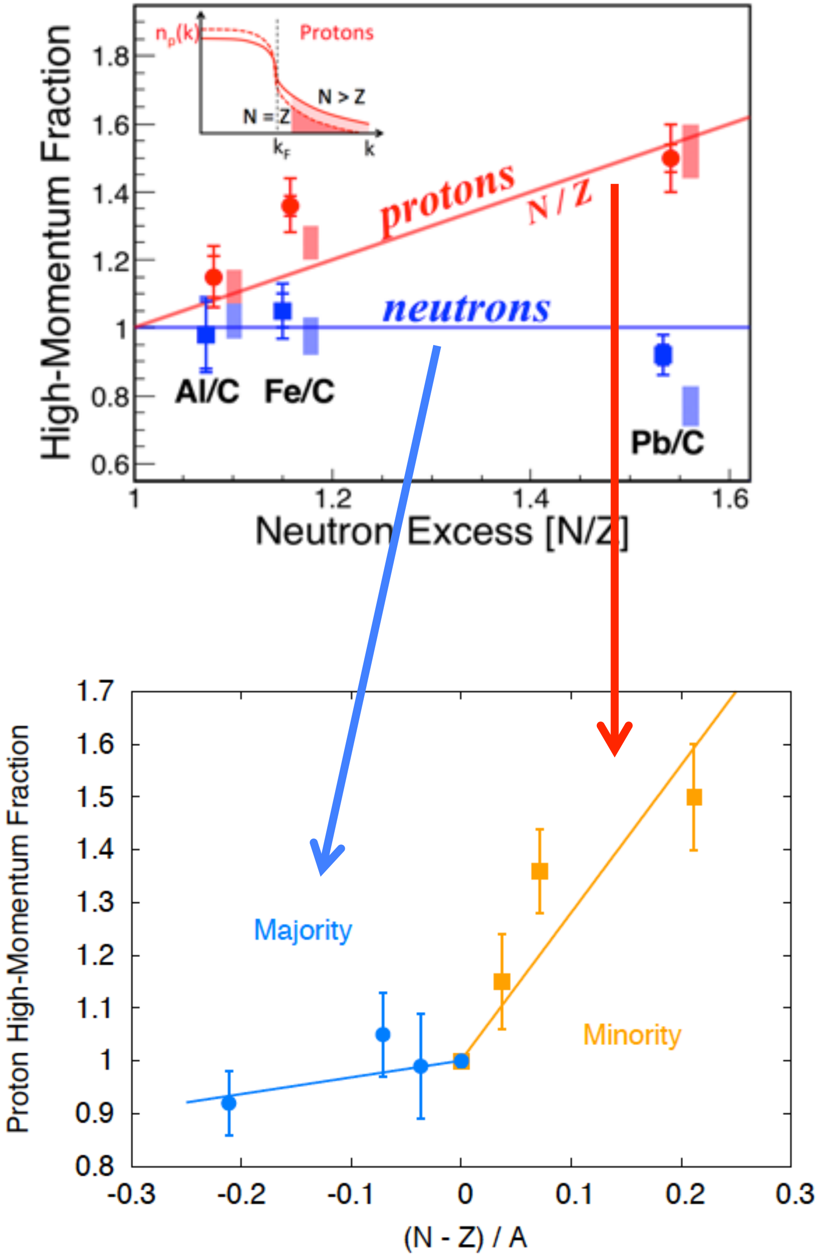
SRC: Quantitative information from JLAB

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

SRC



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

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

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

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

$$\mathrm{R} \approx \mathrm{a}^2 = 1 - \overbrace{\mathrm{R}_{\mathrm{LRC}} - \mathrm{R}_{\mathrm{SRC}}}^{\text{Missing strength}} \quad ✓$$

Assume that the LRC quenching is constant with isospin

In this approach, the weighting of each component are the only free parameters that are extracted by fits to the overall quenching reported in (e,e’p) measurements

The data

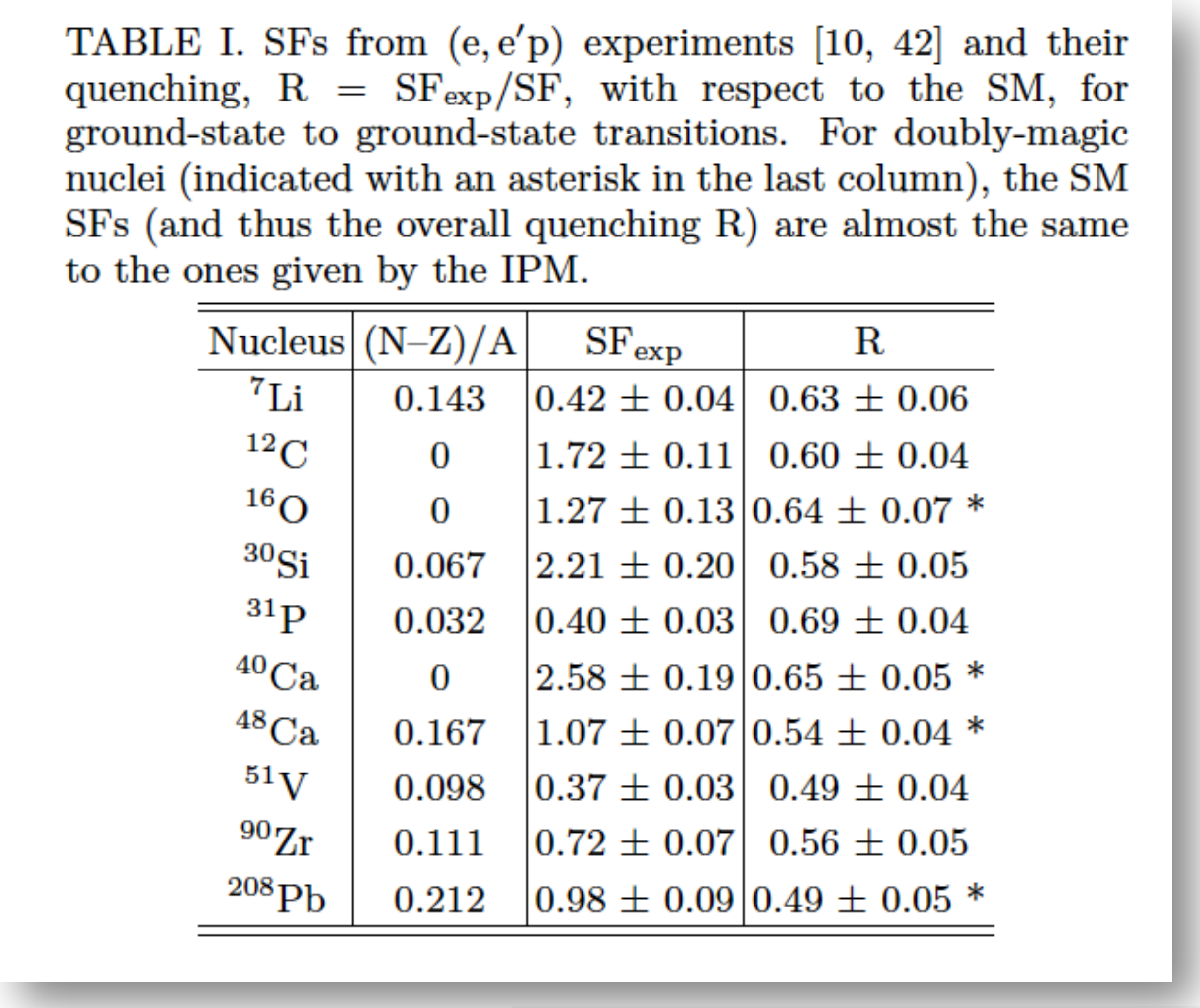
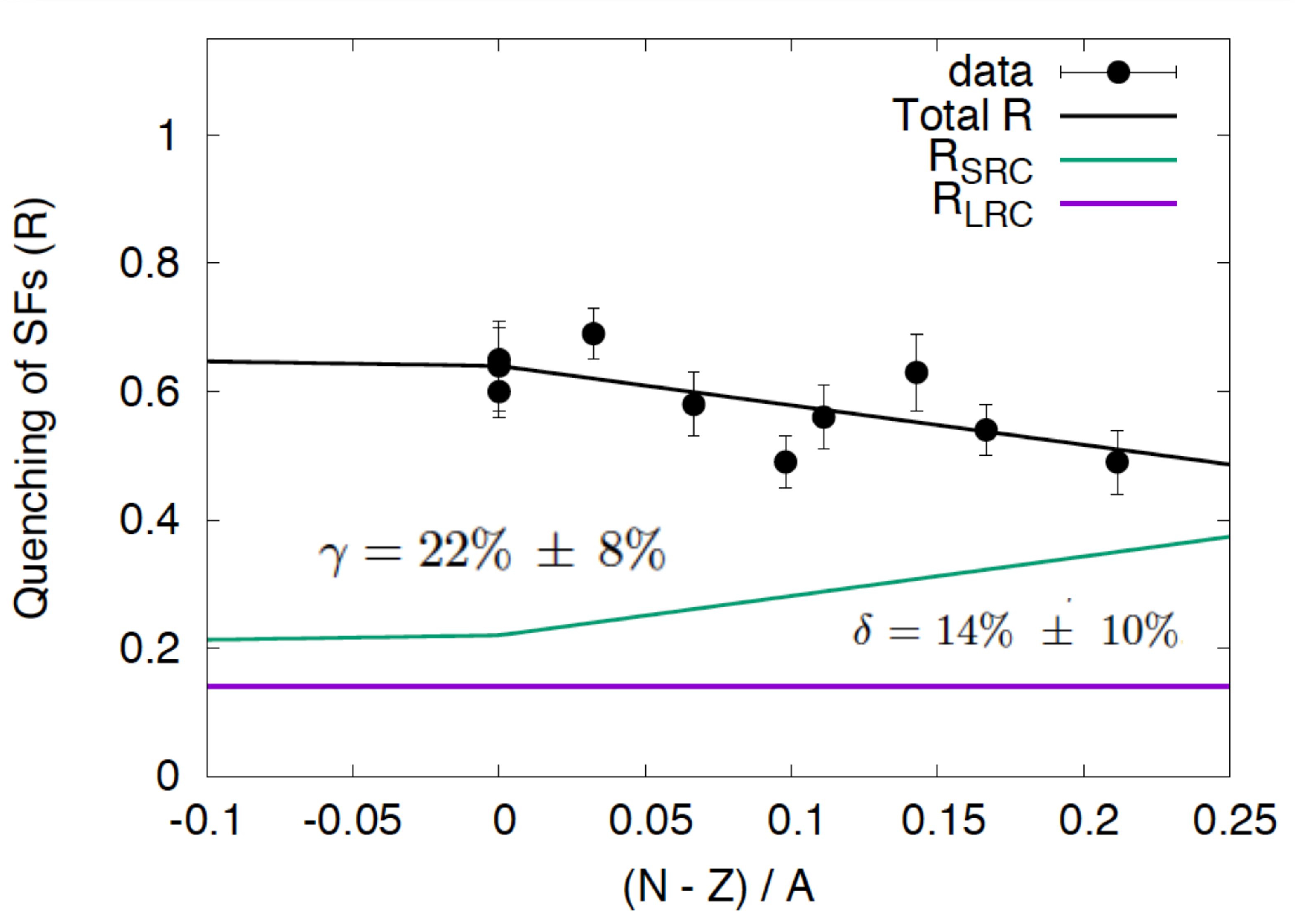


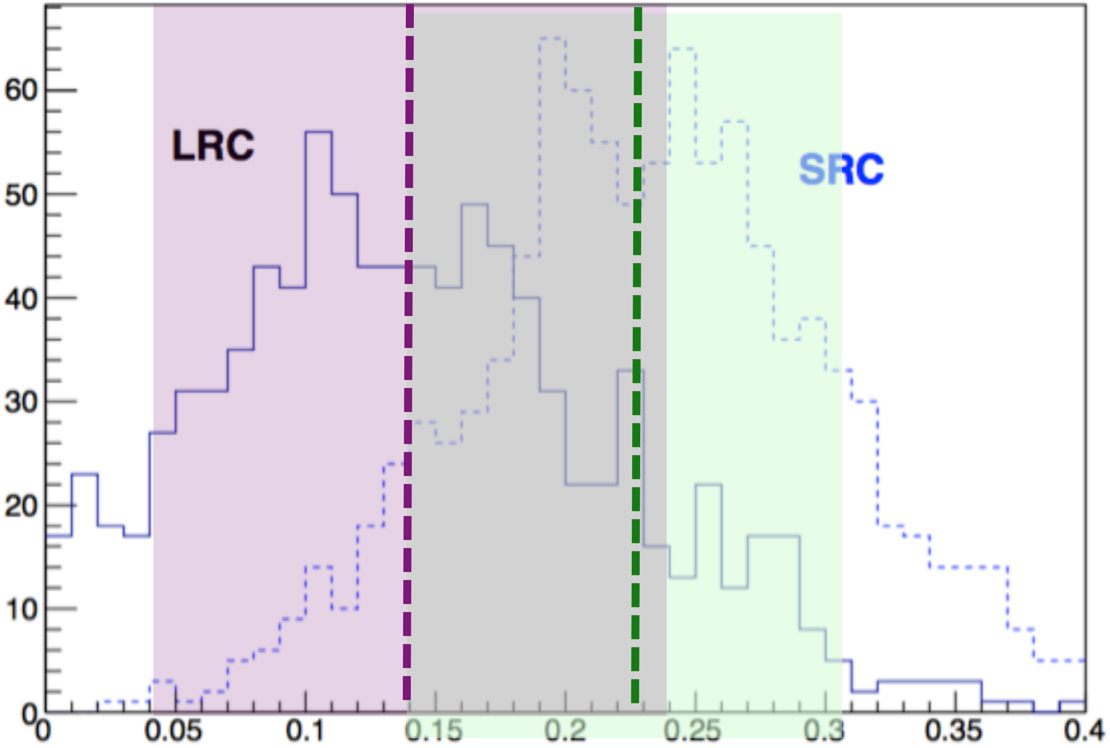
TABLE I. SFs from (e, e′p) experiments [10, 42] and their quenching, R = SF_{exp}/SF, with respect to the SM, for ground-state to ground-state transitions. For doubly-magic nuclei (indicated with an asterisk in the last column), the SM SFs (and thus the overall quenching R) are almost the same to the ones given by the IPM.

Nucleus	(N–Z)/A	SF_{exp}	R
^{7}Li	0.143	0.42 ± 0.04	0.63 ± 0.06
^{12}C	0	1.72 ± 0.11	0.60 ± 0.04
^{16}O	0	1.27 ± 0.13	0.64 ± 0.07 *
^{30}Si	0.067	2.21 ± 0.20	0.58 ± 0.05
^{31}P	0.032	0.40 ± 0.03	0.69 ± 0.04
^{40}Ca	0	2.58 ± 0.19	0.65 ± 0.05 *
^{48}Ca	0.167	1.07 ± 0.07	0.54 ± 0.04 *
^{51}V	0.098	0.37 ± 0.03	0.49 ± 0.04
^{90}Zr	0.111	0.72 ± 0.07	0.56 ± 0.05
^{208}Pb	0.212	0.98 ± 0.09	0.49 ± 0.05 *

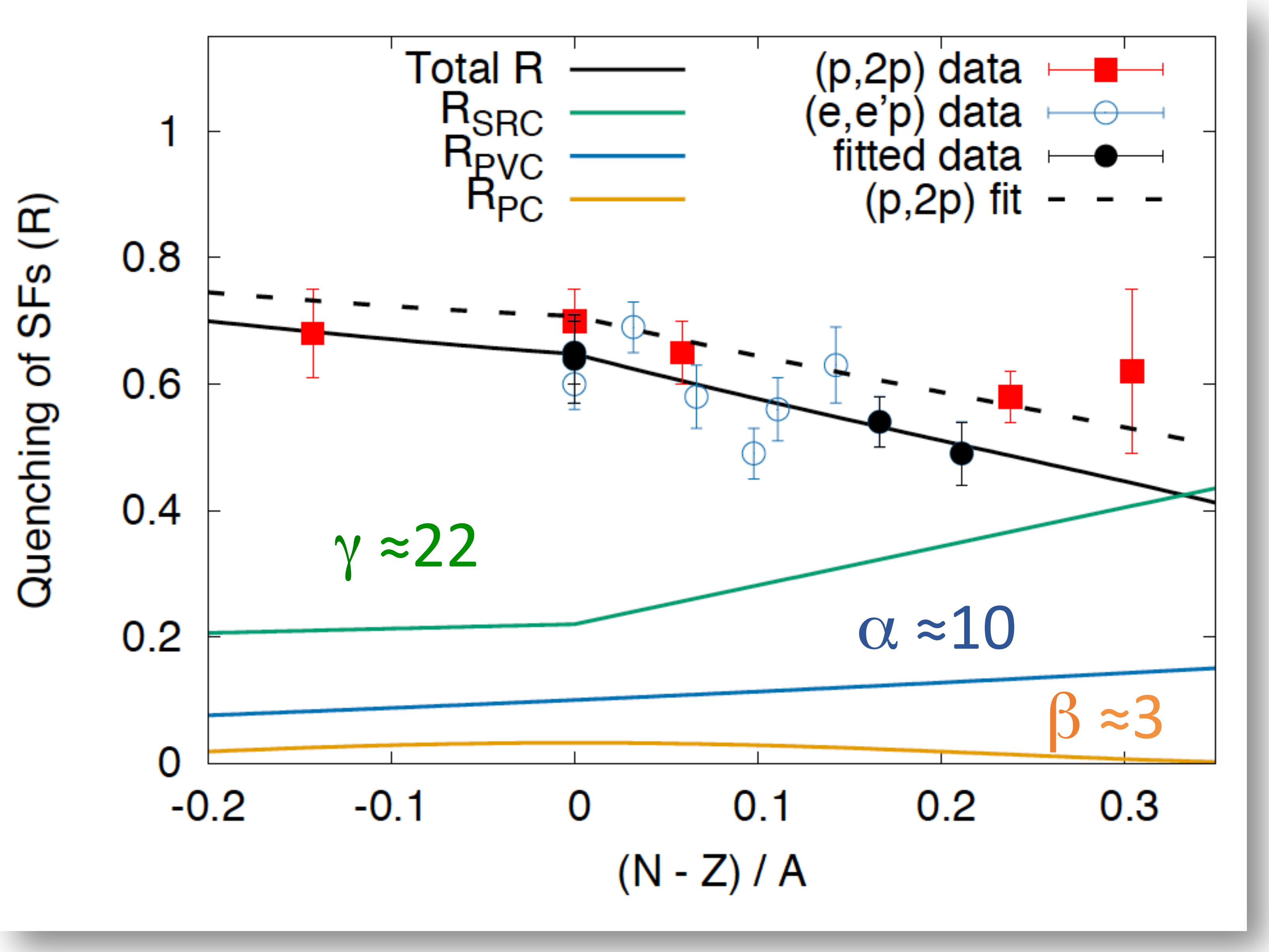
[10] G. Kramer, et al., Nucl. Phys. A **679** (2001) 267
[42] J. Lee, et al., Phys. Rev. C**73** (2006) 044608


data
Total R
R_{SRC}
R_{LRC}
Quenching of SFs (R)
(N - Z) / A
$\gamma = 22\% \pm 8\%$
$\delta = 14\% \pm 10\%$
0
0.2
0.4
0.6
0.8
1
-0.1
-0.05
0
0.05
0.1
0.15
0.2
0.25

Statistical significance

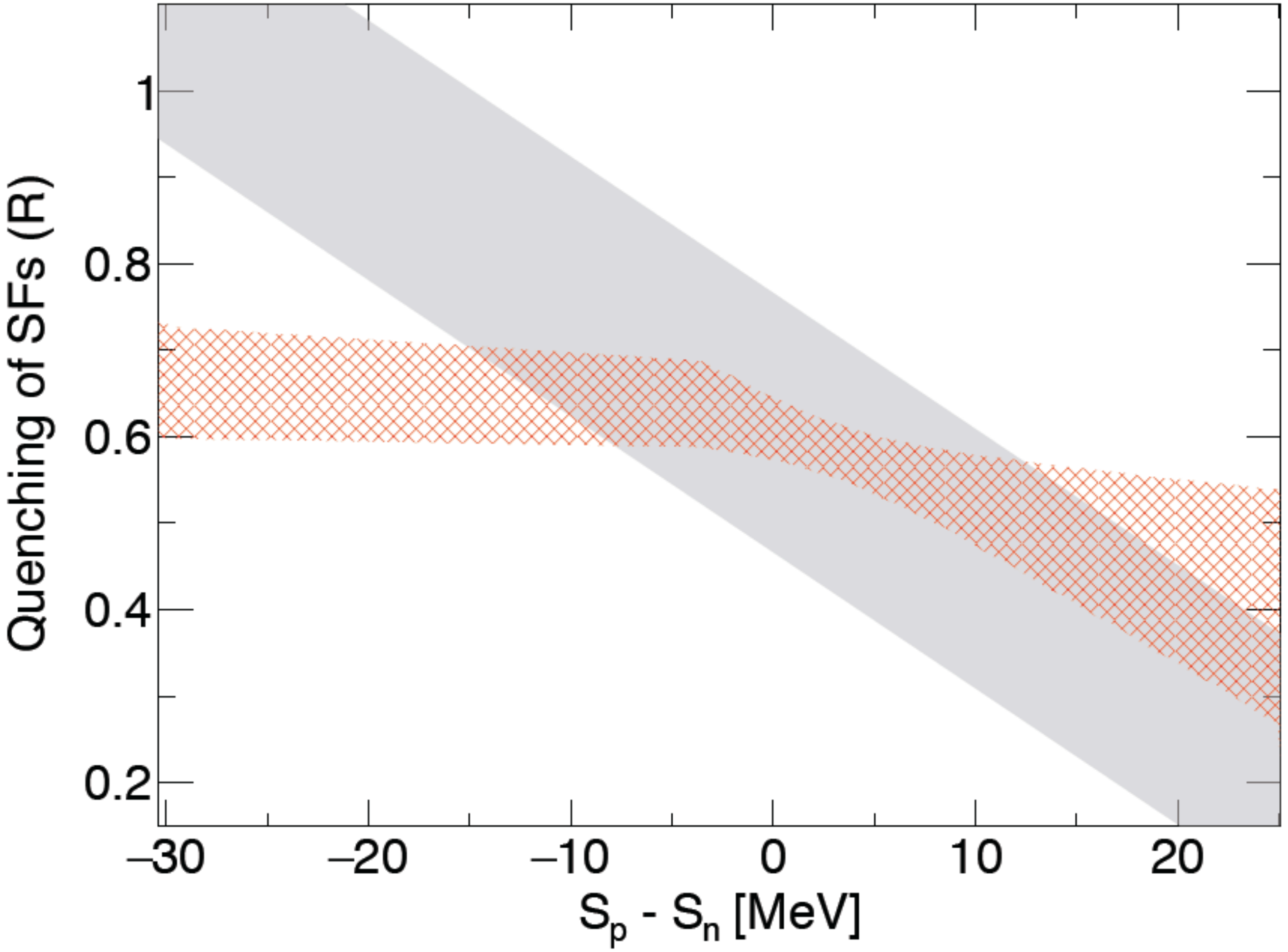


With isospin dependence of the LRC quenching



Our results in a Gade/Tostevin plot

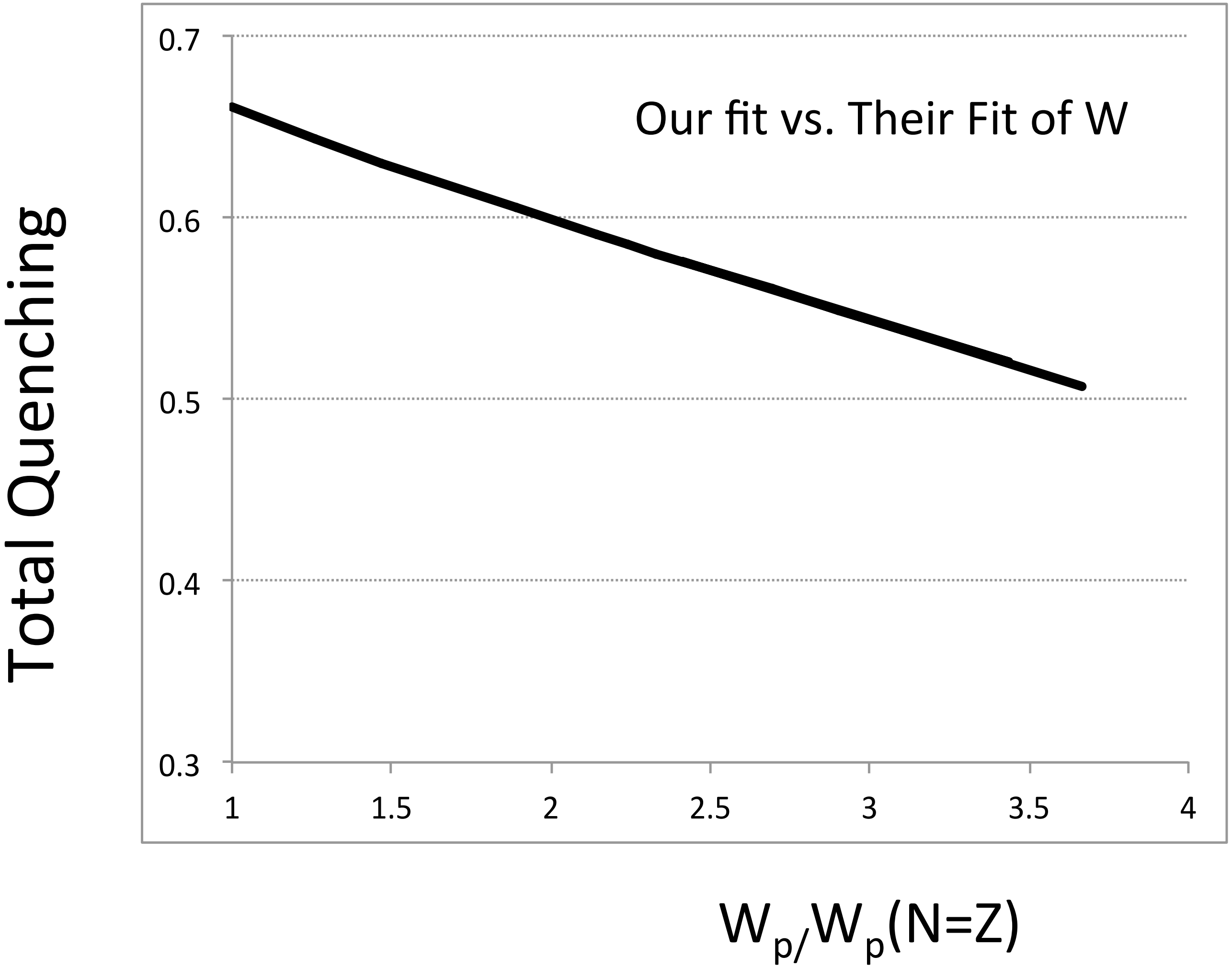
(converting A,Z,N → S_n and S_p)



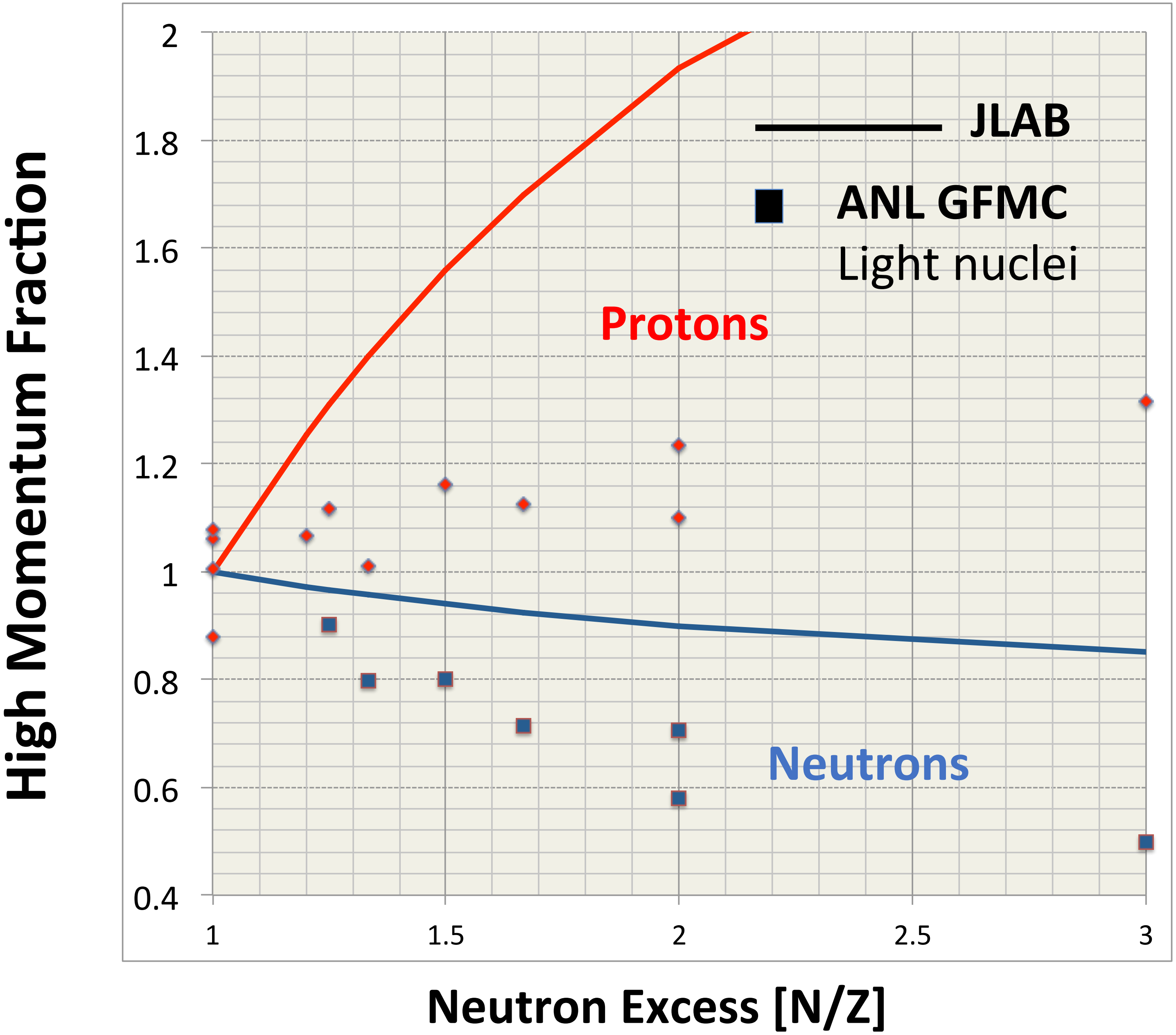
PHYSICAL REVIEW C **83**, 064605 (2011)

Asymmetry dependence of nucleon correlations in spherical nuclei extracted from a dispersive-optical-model analysis

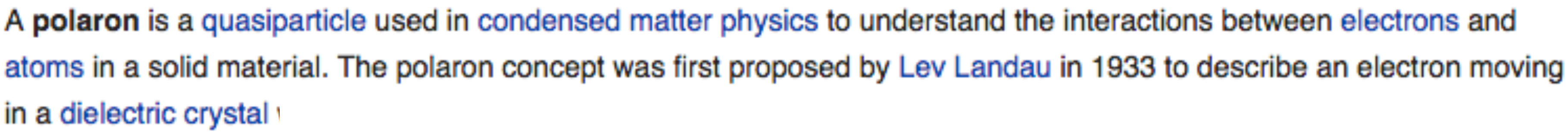
J. M. Mueller, R. J. Charity, R. Shane, L. G. Sobotka, S. J. Waldecker, W. H. Dickhoff, et al.



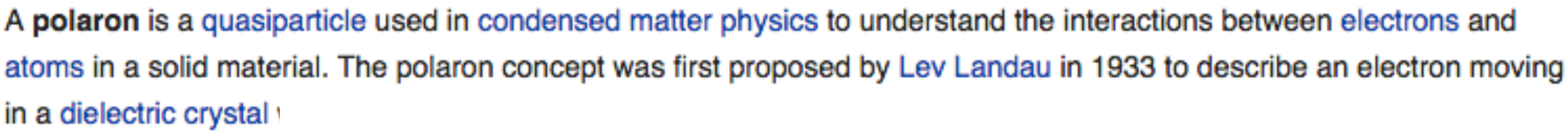
http://www.phy.anl.gov/theory/research/momenta/



Some speculations



A **polaron** is a quasiparticle used in condensed matter physics to understand the interactions between electrons and atoms in a solid material. The polaron concept was first proposed by Lev Landau in 1933 to describe an electron moving in a dielectric crystal


A **polaron** is a quasiparticle used in condensed matter physics to understand the interactions between electrons and atoms in a solid material. The polaron concept was first proposed by Lev Landau in 1933 to describe an electron moving in a dielectric crystal

Interesting to consider the limit:

Quasi-proton (**nuclear polaron**) in neutron matter

$$\mathrm{A} \to \infty \text{ and } (\mathrm{N}-\mathrm{Z})/\mathrm{A} \to 1$$

LRC (Surface) → 0

$$\mathrm{R_{nM}} = 1-\gamma-\gamma \mathrm{SL^{p}_{SRC}} \sim 0.2$$

$$\left\langle \mathrm{T_p} \right\rangle_{\mathrm{nM}} = \left(\mathrm{R_{nM}} + \left(1-\mathrm{R_{nM}}\right)\frac{5}{3}\frac{\mathrm{p_{Max}}}{\mathrm{p_F}}\right)\left\langle \mathrm{E_F} \right\rangle$$

$\langle \mathrm{T_p} \rangle_{\mathrm{nM}}$ approximately 2.5 times that of a proton in a Fermi Gas

M*/M ~ 0.4

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

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

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

SRC and charge radius

Due to short range correlations single particle excitations of $\Delta E \sim 70$ MeV will occur with the probability discussed above.

$$\Delta p \sim \frac{\hbar}{\Delta \mathrm{x}}$$

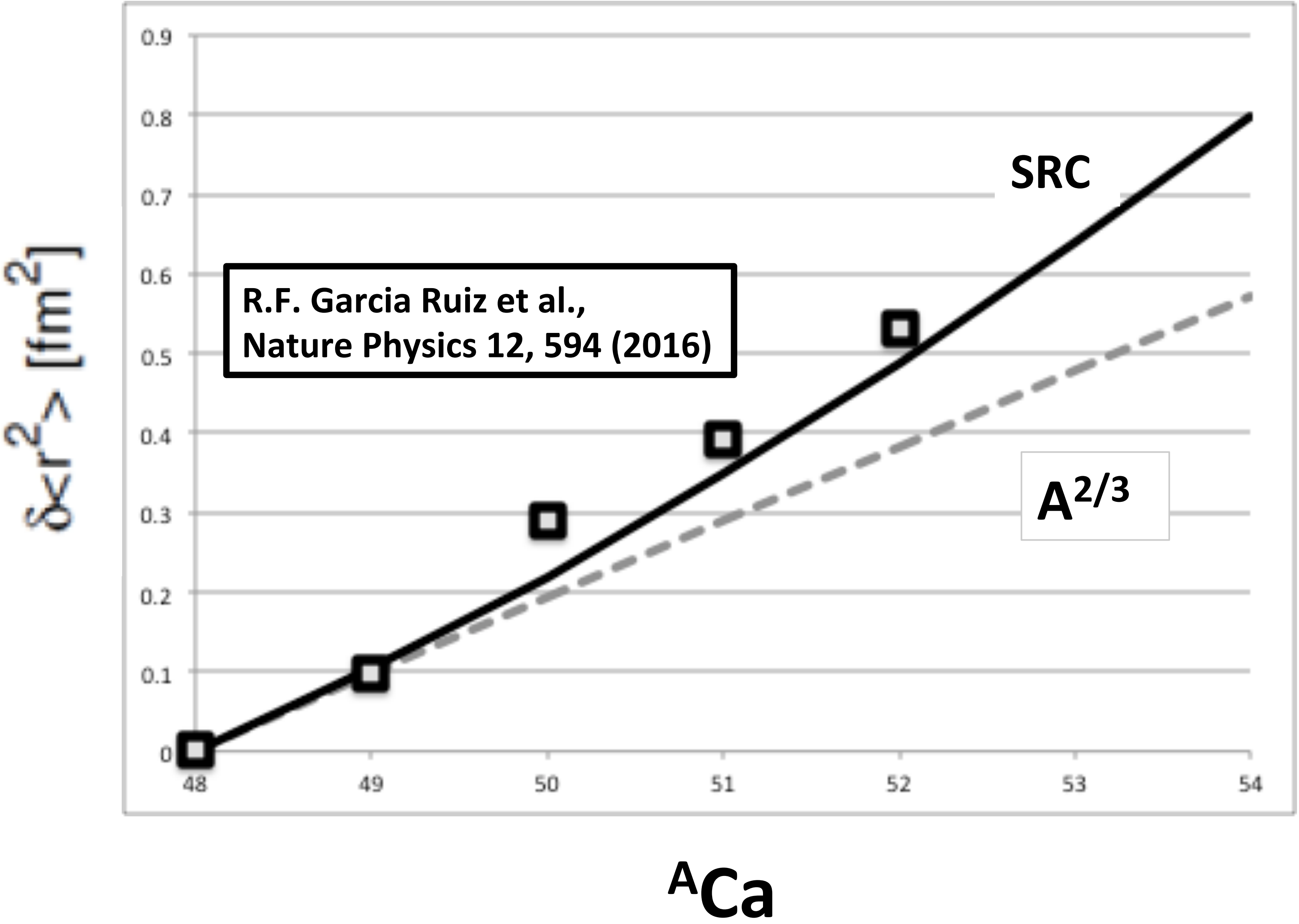
This corresponds to changes in the principal oscillator quantum number

$$\Delta N \sim \Delta E / \hbar\omega_0$$

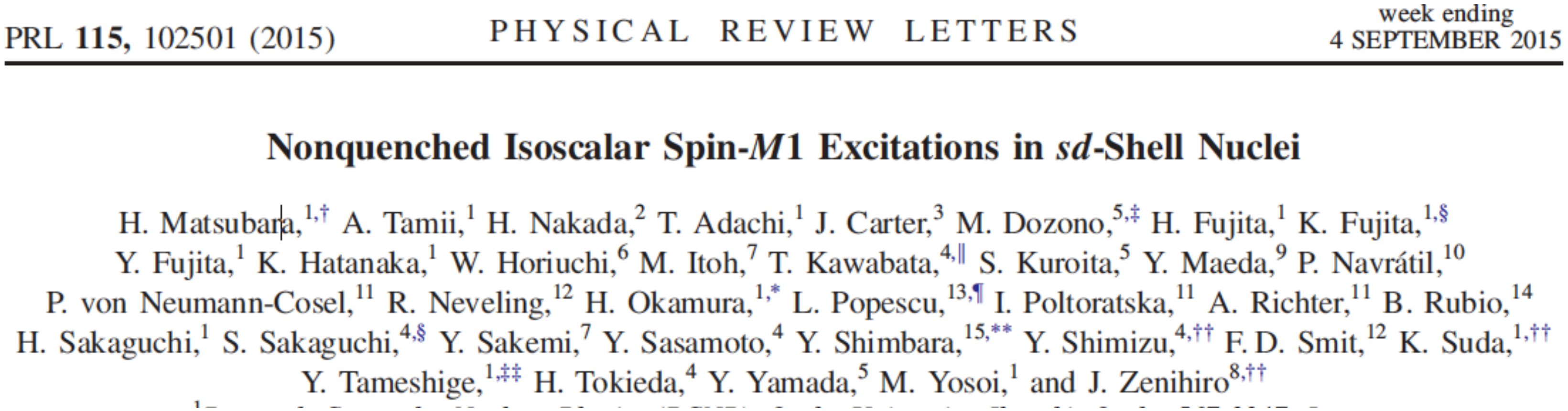
And consequently a change in the radius:

$$\Delta < r^2 > \sim r_0^2 \Delta \mathrm{N} \ \gamma \left(1 + \mathrm{SL}_{\mathrm{SRC}}^{\mathrm{p}} \frac{\mathrm{N}-\mathrm{Z}}{\mathrm{A}}\right)$$

Calcium isotopes



R.F. Garcia Ruiz et al.,
Nature Physics 12, 594 (2016)

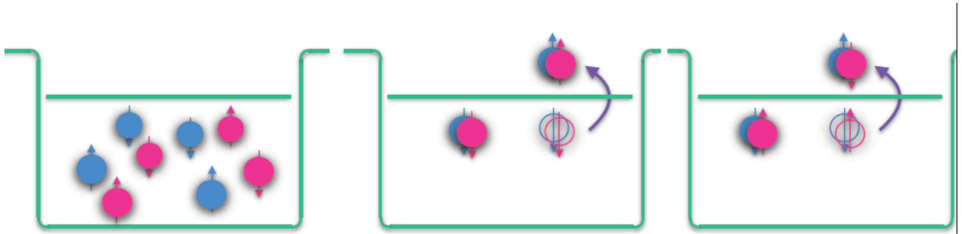


PRL **115,** 102501 (2015) PHYSICAL REVIEW LETTERS week ending 4 SEPTEMBER 2015

Nonquenched Isoscalar Spin-*M*1 Excitations in *sd*-Shell Nuclei

H. Matsubara,[1,†] A. Tamii,[1] H. Nakada,[2] T. Adachi,[1] J. Carter,[3] M. Dozono,[5,‡] H. Fujita,[1] K. Fujita,[1,§]
Y. Fujita,[1] K. Hatanaka,[1] W. Horiuchi,[6] M. Itoh,[7] T. Kawabata,[4,∥] S. Kuroita,[5] Y. Maeda,[9] P. Navrátil,[10]
P. von Neumann-Cosel,[11] R. Neveling,[12] H. Okamura,[1,*] L. Popescu,[13,¶] I. Poltoratska,[11] A. Richter,[11] B. Rubio,[14]
H. Sakaguchi,[1] S. Sakaguchi,[4,§] Y. Sakemi,[7] Y. Sasamoto,[4] Y. Shimbara,[15,**] Y. Shimizu,[4,††] F. D. Smit,[12] K. Suda,[1,††]
Y. Tameshige,[1,‡‡] H. Tokieda,[4] Y. Yamada,[5] M. Yosoi,[1] and J. Zenihiro[8,††]

$$\left\langle \vec{s}_n \cdot \vec{s}_p \right\rangle = \begin{cases} +\dfrac{1}{4} & \text{for IS } np \text{ pair (deuteron)} \\ -\dfrac{3}{4} & \text{for IV } np \text{ pair} \end{cases}$$



unperturbed ground state

$\left\langle \vec{S}_n \cdot \vec{S}_p \right\rangle = 0$

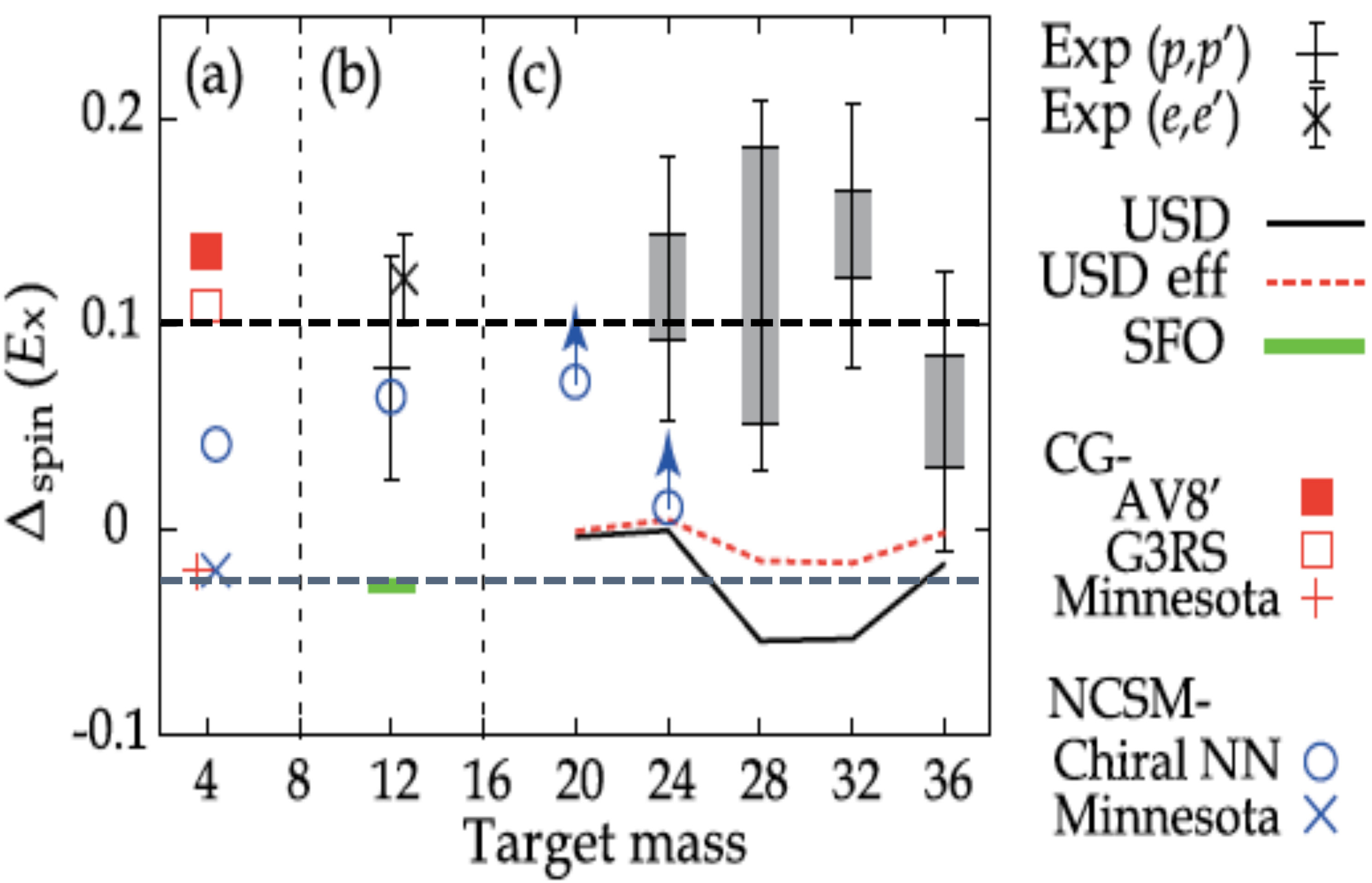
IS *np* pairing

$\left\langle \vec{S}_n \cdot \vec{S}_p \right\rangle > 0$

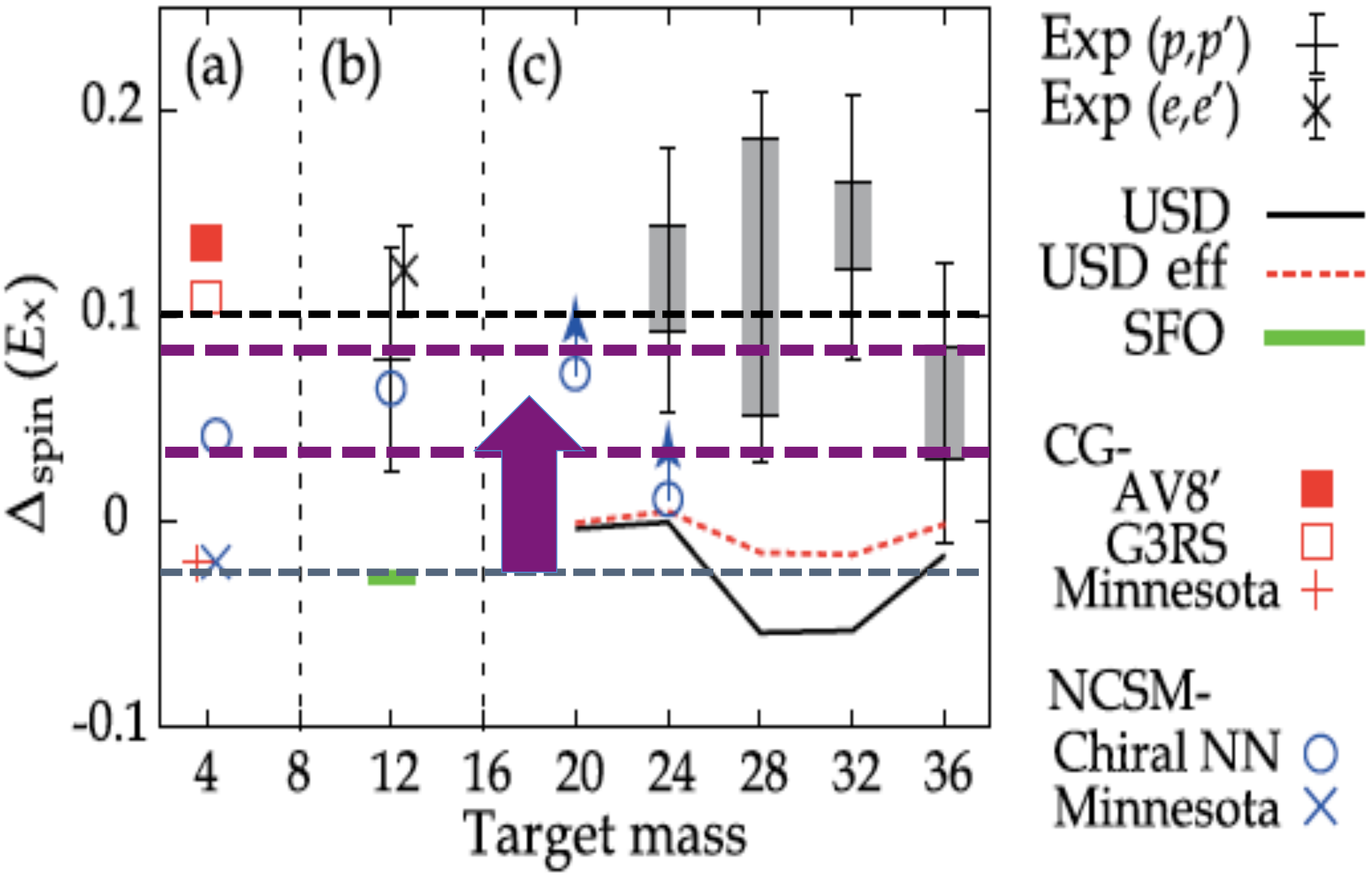
IV *np* pairing

$\left\langle \vec{S}_n \cdot \vec{S}_p \right\rangle < 0$

correlated ground state


(a)
(b)
(c)
0.2
0.1
0
-0.1
$\Delta_{\rm spin}$ (E_X)
4
8
12
16
20
24
28
32
36
Target mass
Exp (p,p′)
Exp (e,e′)
USD
USD eff
SFO
CG-
AV8′
G3RS
Minnesota
NCSM-
Chiral NN
Minnesota

SRC ??



(a)
(b)
(c)
$\Delta_{\rm spin}(E_x)$
0.2
0.1
0
-0.1
4
8
12
16
20
24
28
32
36
Target mass
Exp (p,p′)
Exp (e,e′)
USD
USD eff
SFO
CG-
AV8′
G3RS
Minnesota
NCSM-
Chiral NN
Minnesota

Conclusions

- We derived simple phenomenological parametrizations for the combined effects of SRC, PVC, and PC that were used in an analysis of published data from electron scattering experiments

- Our analysis consistently shows that ~ 20% of the missing strength observed in the region of N ≈ Z can be attributed to SRC, in agreement with reported expectations

- We show how the missing strength evolves with (N – Z)/A

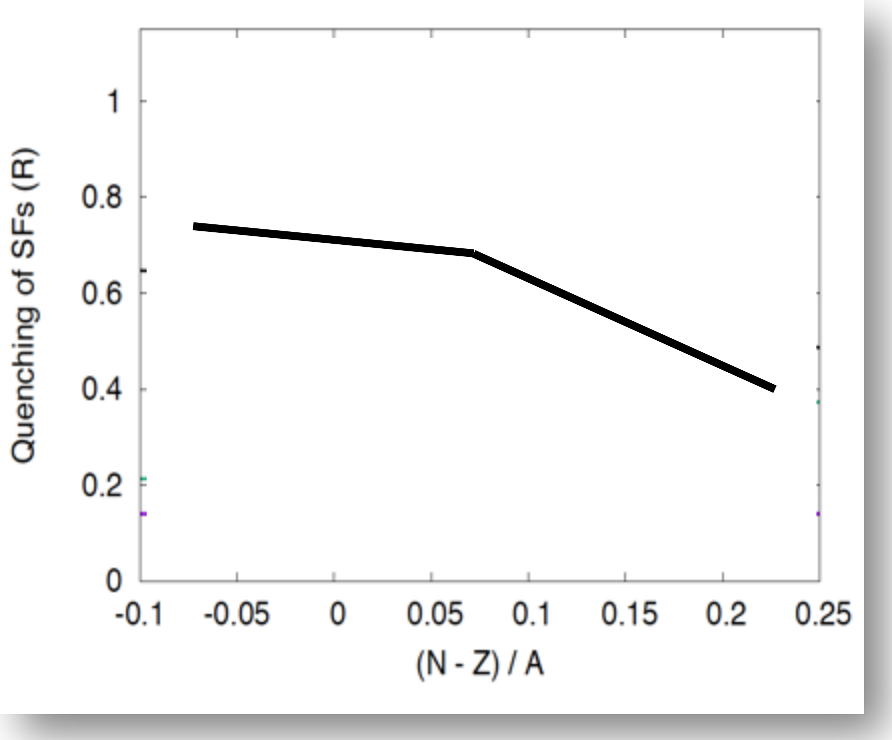
- Speculation on a quasi-proton (**nuclear polaron**) in the limit of neutron matter, A → ∞ and (N-Z)/A → 1, proton R ~ 0.2

- Possible effects on the charge radius of neutron-rich Ca's

  and spin content of N=Z ground states.

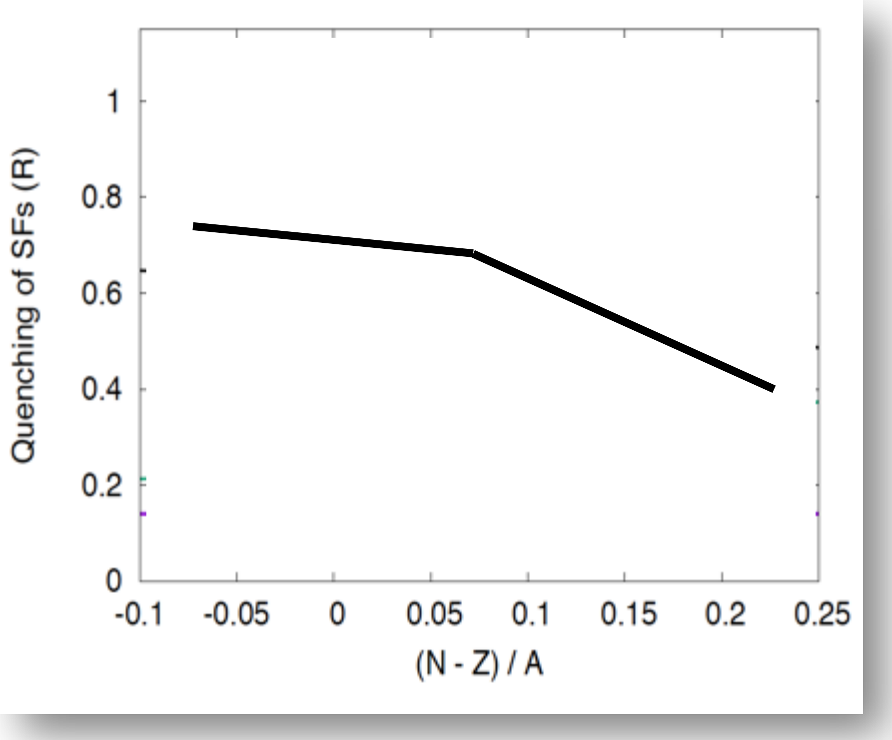
A puzzle:

One-nucleon direct reaction



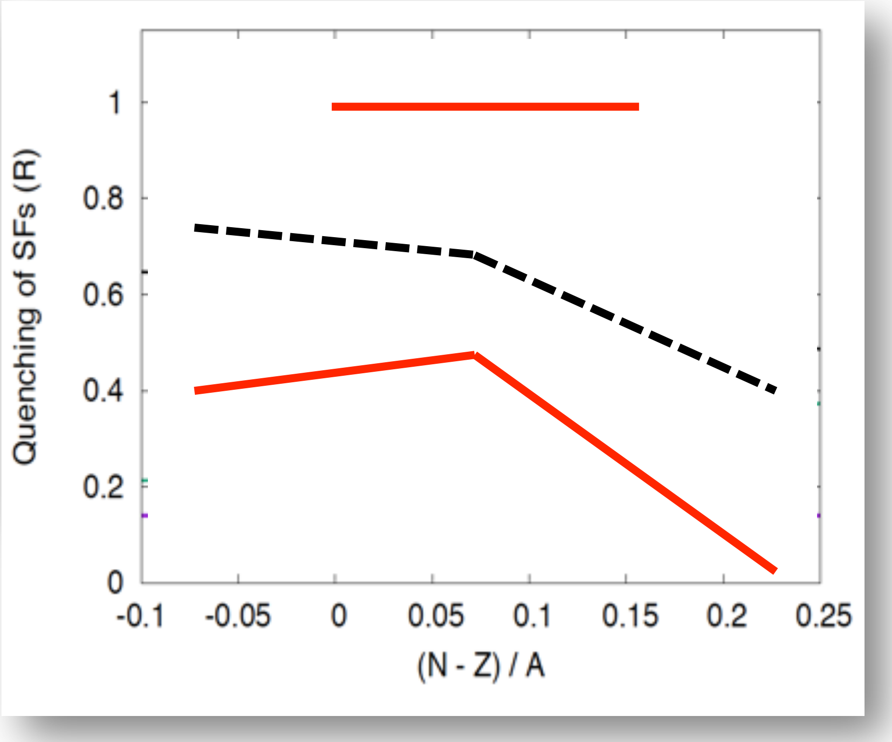
A puzzle:

One-nucleon direct reaction



Two-nucleon direct reaction

?????



Merci !