LRC and SRC in the Quenching of Spectroscopic Factors

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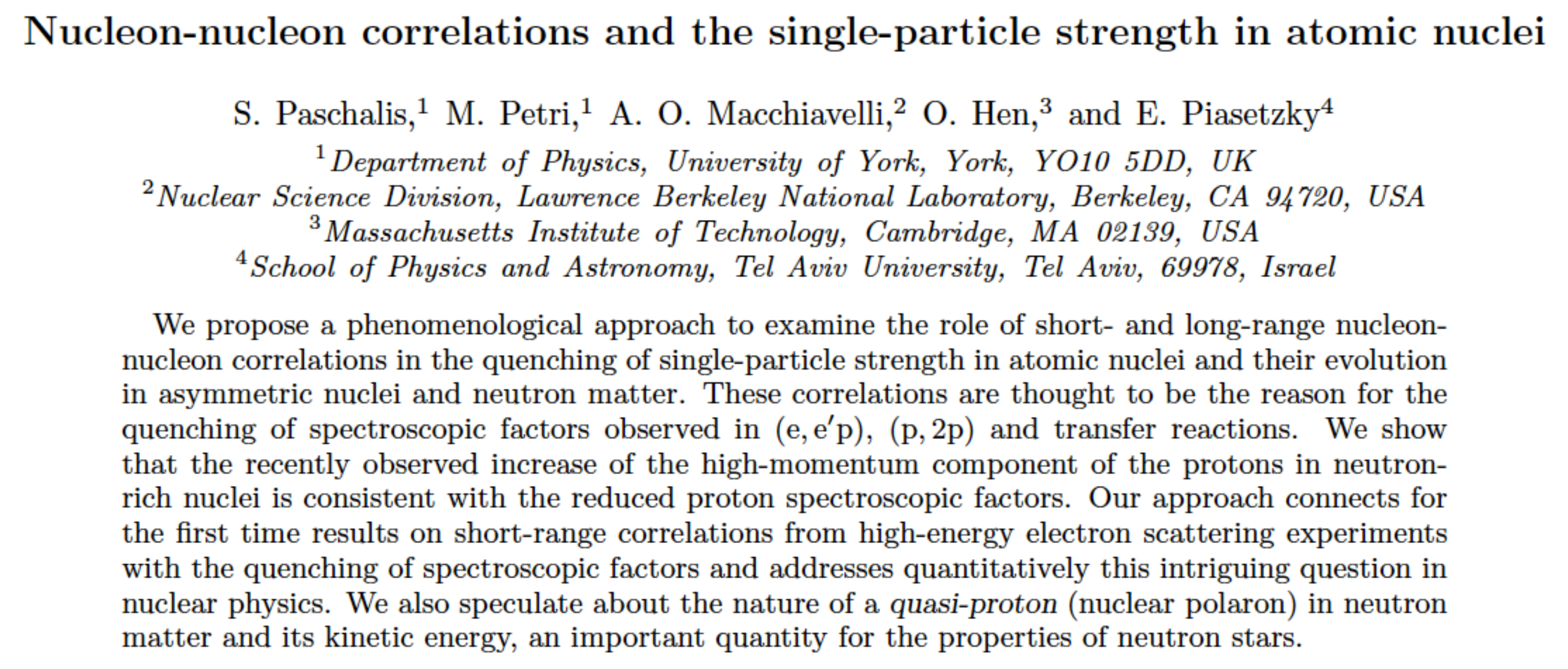

Nucleon-nucleon correlations and the single-particle strength in atomic nuclei

S. Paschalis,[1] M. Petri,[1] A. O. Macchiavelli,[2] O. Hen,[3] and E. Piasetzky[4]
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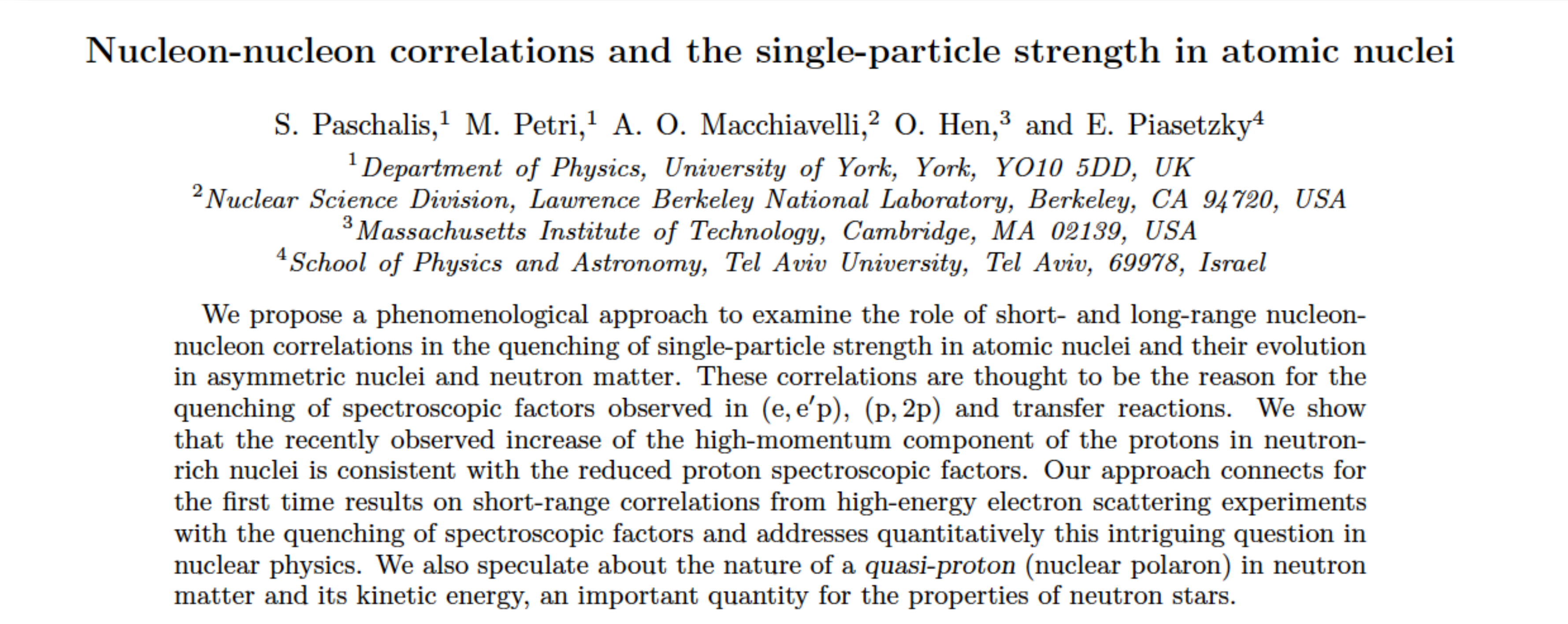
We propose a phenomenological approach to examine the role of short- and long-range nucleon-nucleon correlations in the quenching of single-particle strength in atomic nuclei and their evolution in asymmetric nuclei and neutron matter. These correlations are thought to be the reason for the quenching of spectroscopic factors observed in $(\mathrm{e}, \mathrm{e}'\mathrm{p})$, $(\mathrm{p}, 2\mathrm{p})$ 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 PRL



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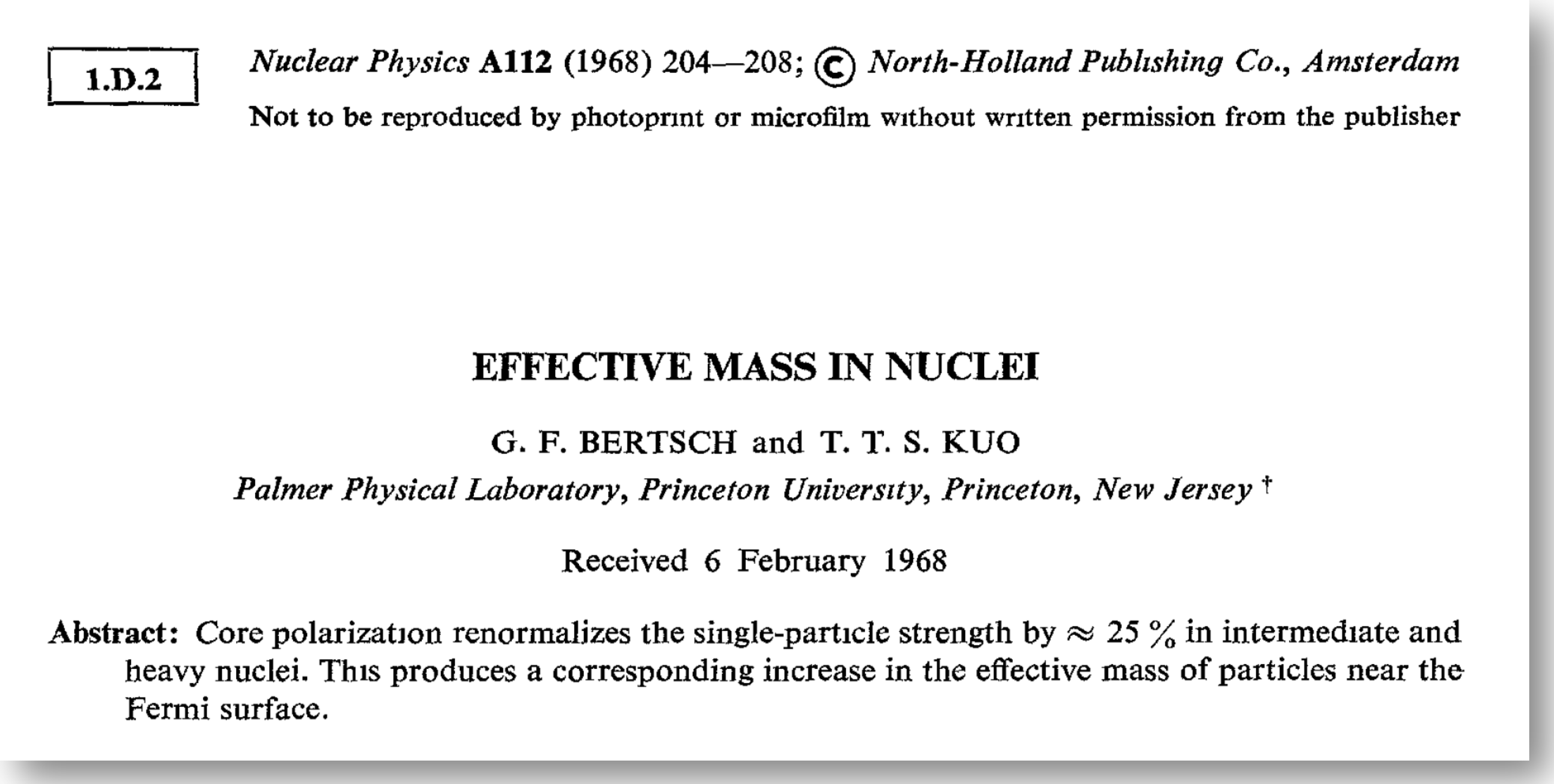

1.D.2

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

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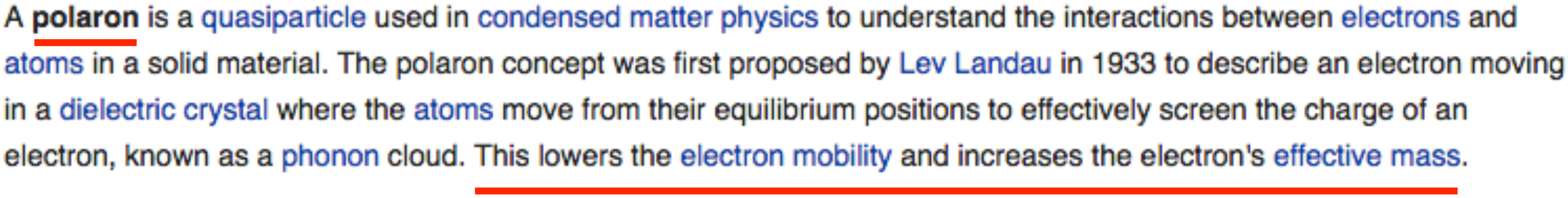
EFFECTIVE MASS IN NUCLEI

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.



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 where the atoms move from their equilibrium positions to effectively screen the charge of an electron, known as a phonon cloud. This lowers the electron mobility and increases the electron's effective mass.

PHYSICAL REVIEW VOLUME 98, NUMBER 5 JUNE 1, 1955

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

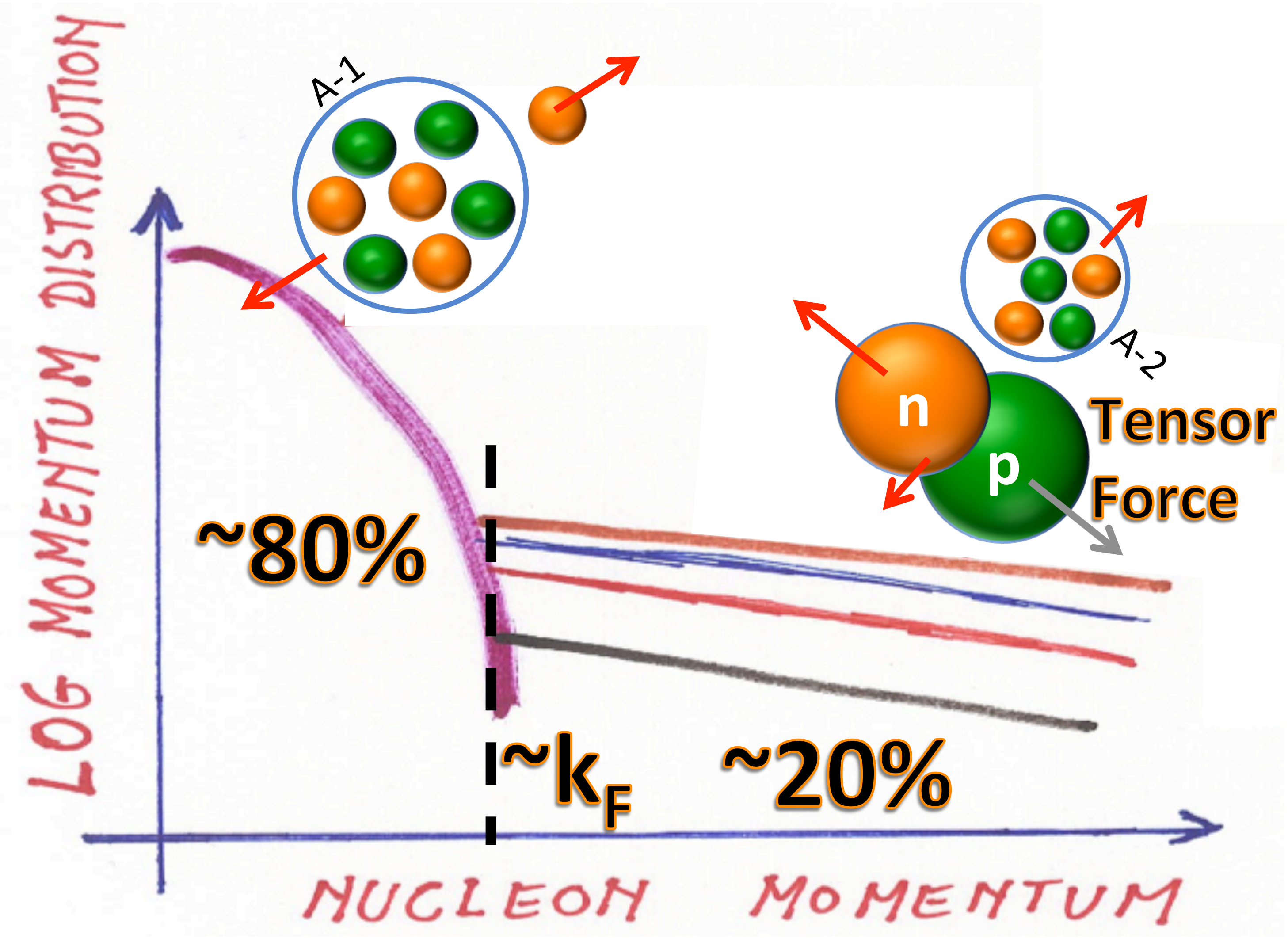
K. A. BRUECKNER, R. J. EDEN,† AND N. C. FRANCIS
Indiana University, Bloomington, Indiana

(Received January 13, 1955)

V. CONCLUSIONS

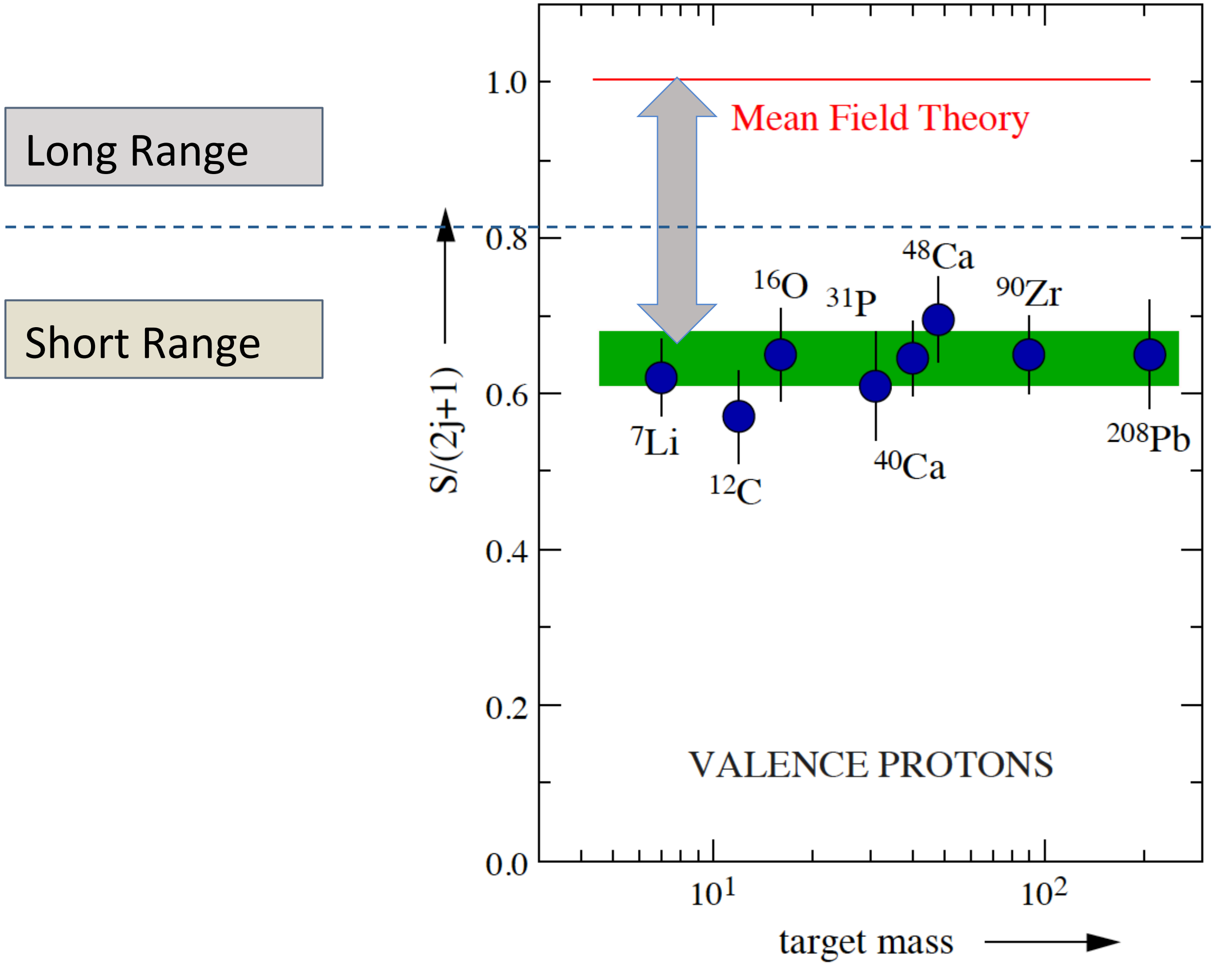
We have analyzed evidence derived from a variety of high-energy experiments which has bearing on the problem of nuclear structure. This evidence is particularly significant since it is for these (or similar) processes that the possible departure of the nuclear ground-state wave function from an independent-particle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



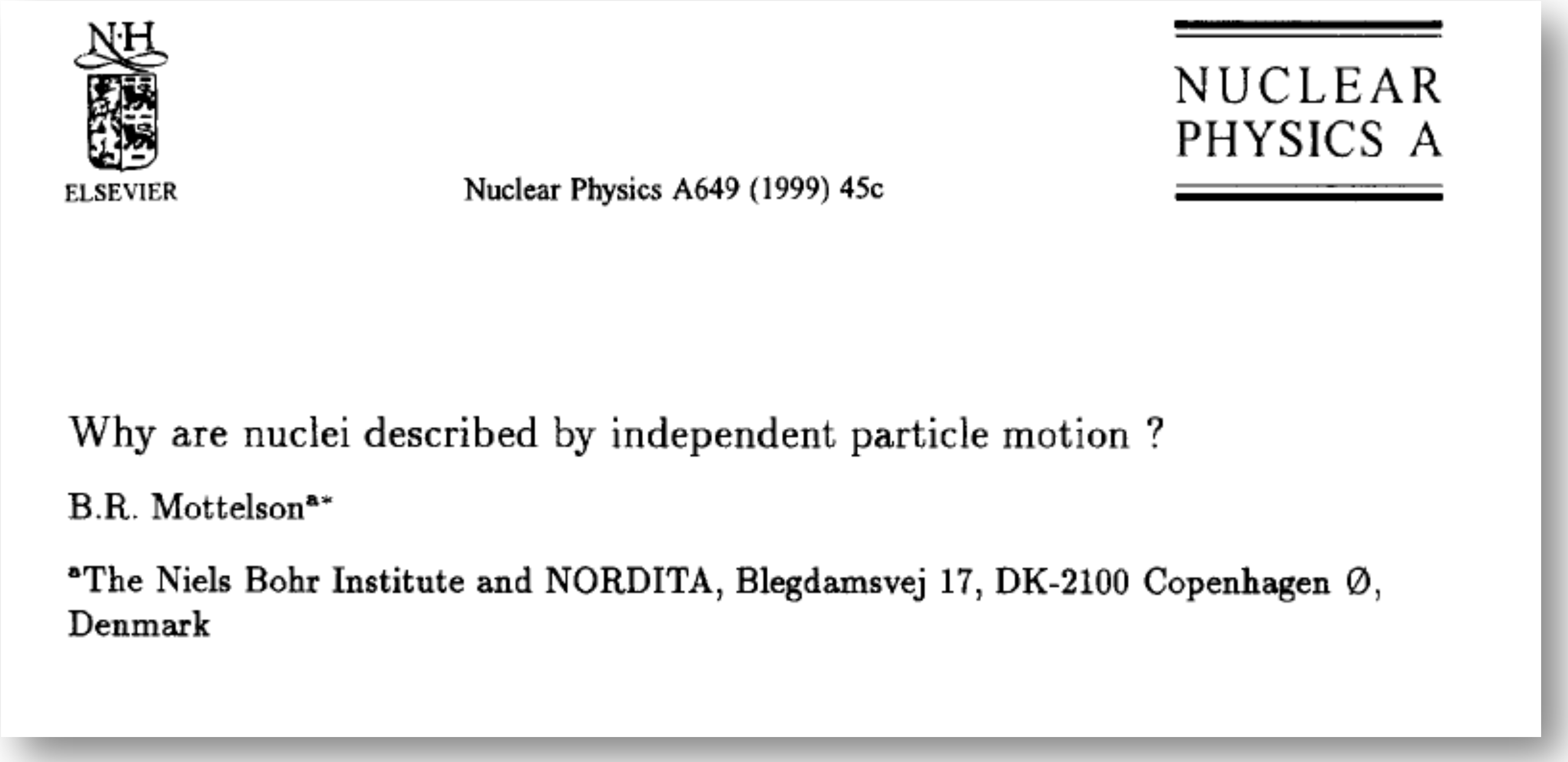
Duer, Nature (2018); Cohen, PRL (2018); Hen, RMP (2017); Hen, Science (2014); Hen, PLB (2013) Korover, PRL (2014); Fomin, PRL (2012); Subedi, Science (2008); Piasetzky, PRL (2007); Egiyan, PRL (2006)

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



- 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).

The applicability of the shell model has actually a profound meaning



ELSEVIER

Nuclear Physics A649 (1999) 45c

NUCLEAR
PHYSICS A

Why are nuclei described by independent particle motion ?

B.R. Mottelson[a]*

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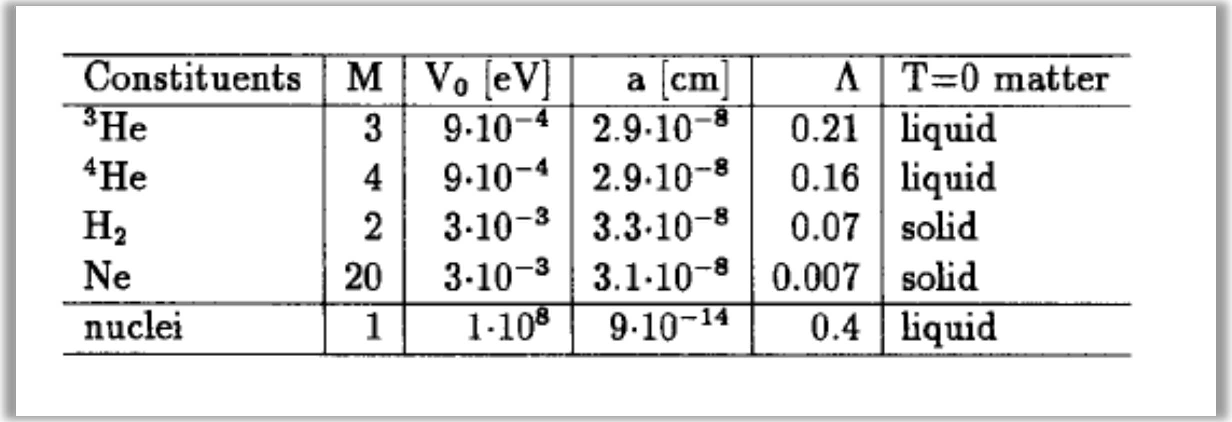
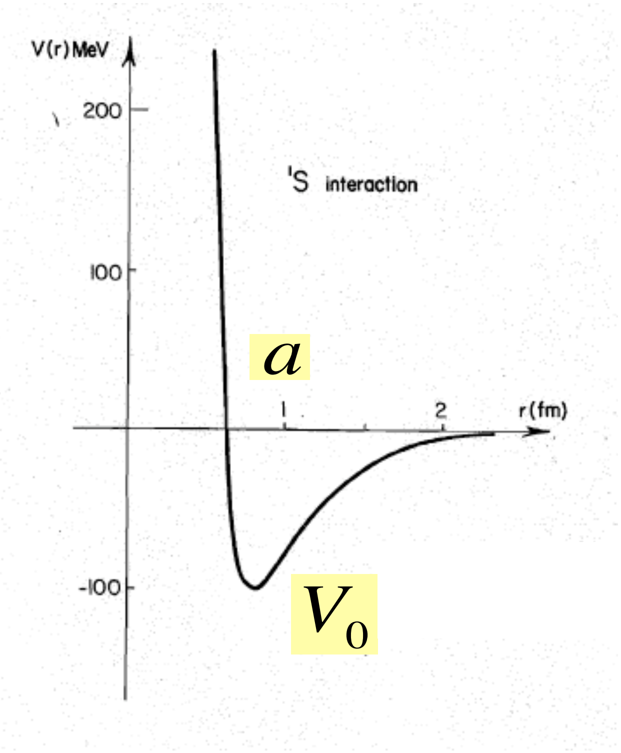
Denmark

“Quantality Parameter”

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

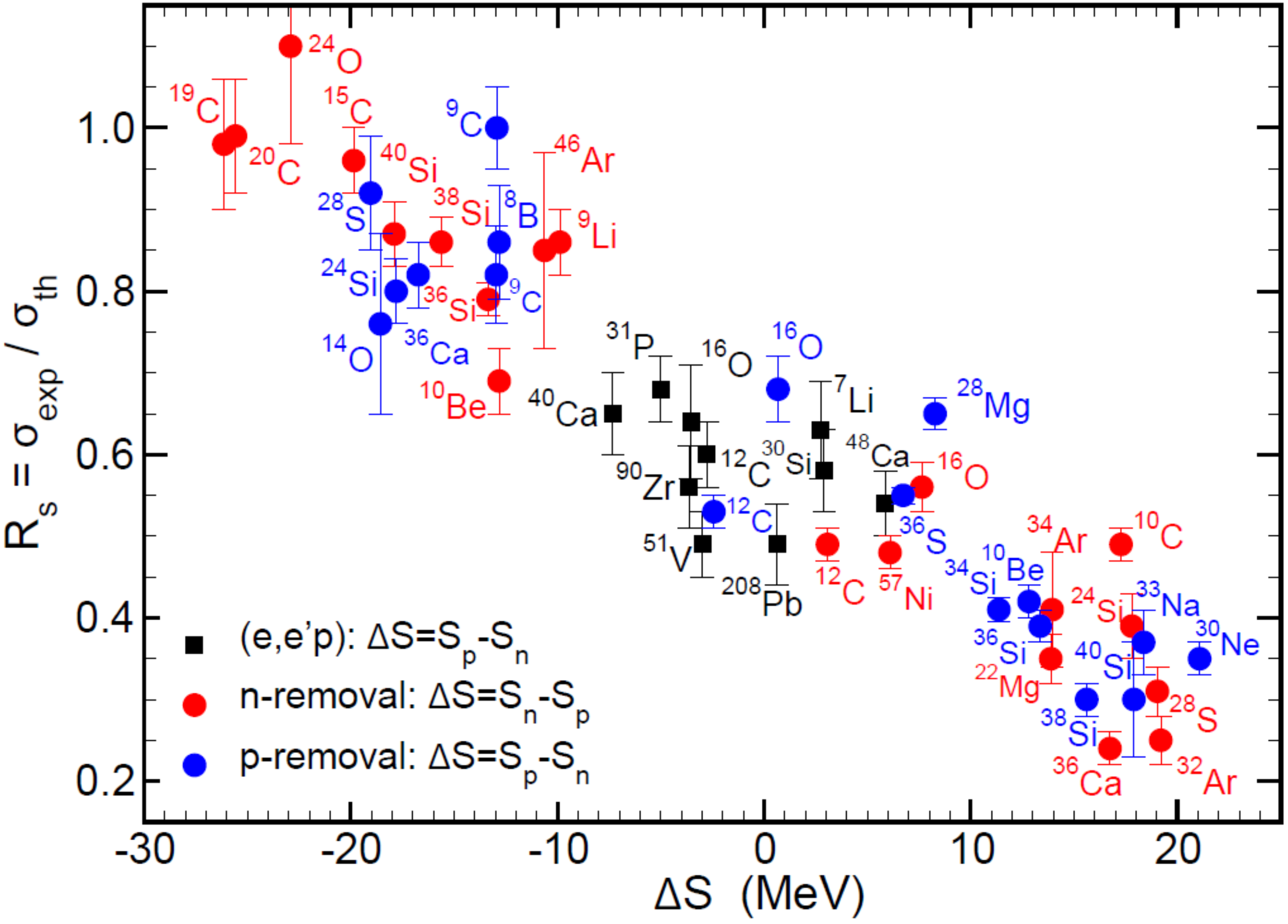


Constituents	M	V_0 [eV]	a [cm]	Λ	T=0 matter
^{3}He	3	$9\cdot10^{-4}$	$2.9\cdot10^{-8}$	0.21	liquid
^{4}He	4	$9\cdot10^{-4}$	$2.9\cdot10^{-8}$	0.16	liquid
H_2	2	$3\cdot10^{-3}$	$3.3\cdot10^{-8}$	0.07	solid
Ne	20	$3\cdot10^{-3}$	$3.1\cdot10^{-8}$	0.007	solid
nuclei	1	$1\cdot10^{8}$	$9\cdot10^{-14}$	0.4	liquid



Fermi Liquid, quasiparticles

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



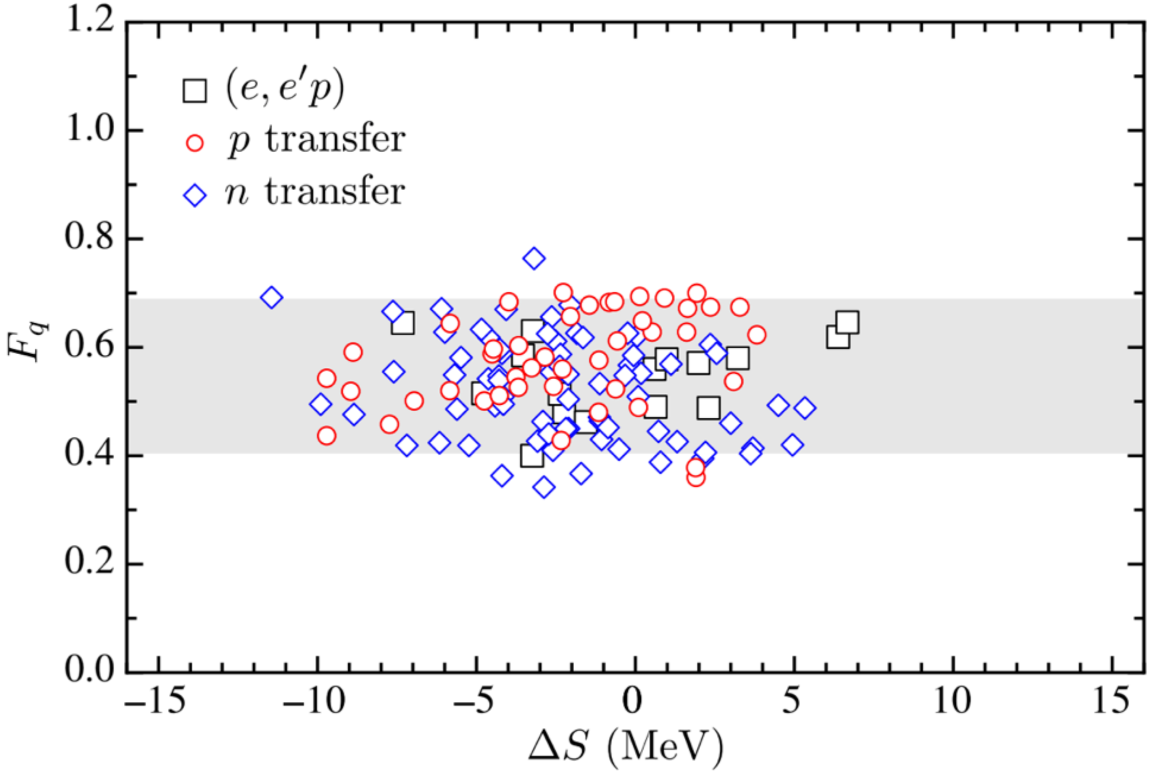
Slide from
A. Gade

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

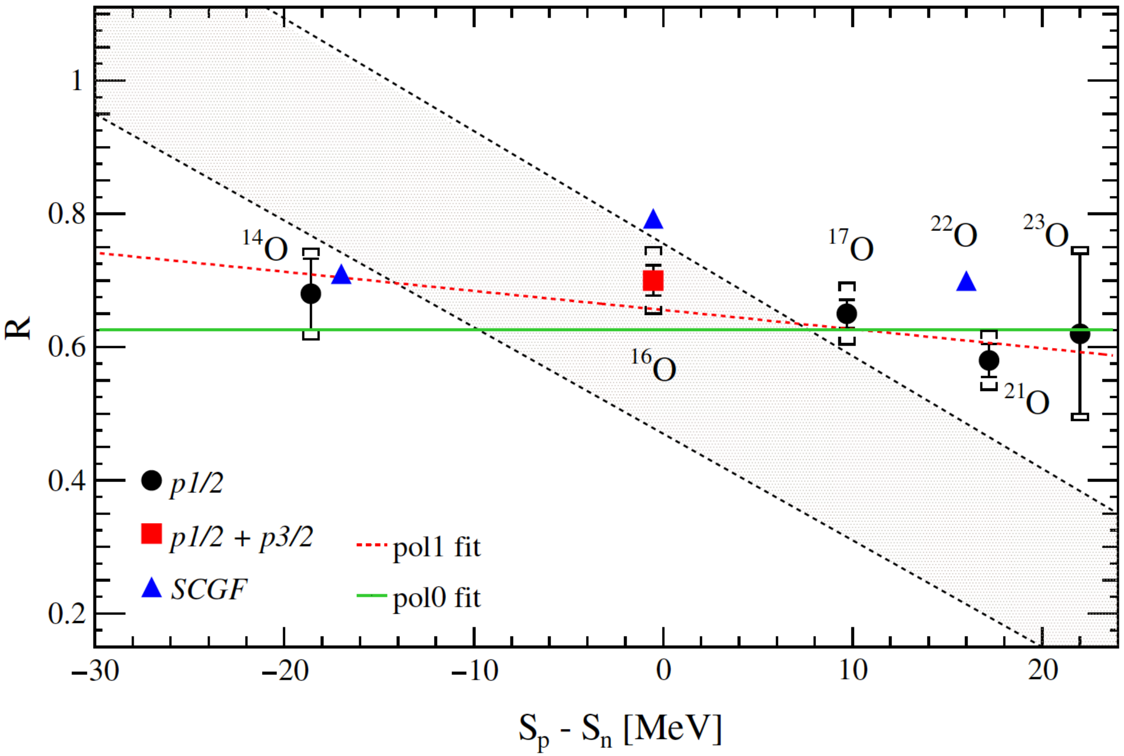
PRL **111,** 042502 (2013) PHYSICAL REVIEW LETTERS week ending 26 JULY 2013

Quenching of Cross Sections in Nucleon Transfer Reactions

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



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



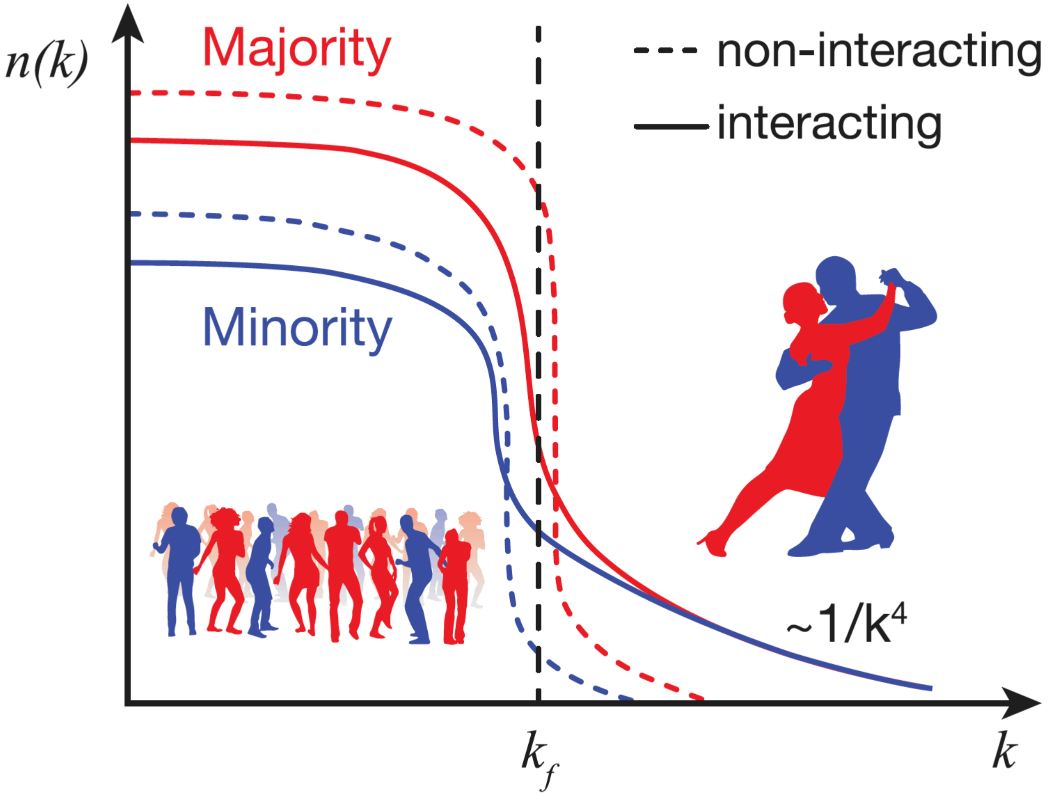
Open questions:

- 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?

The concept

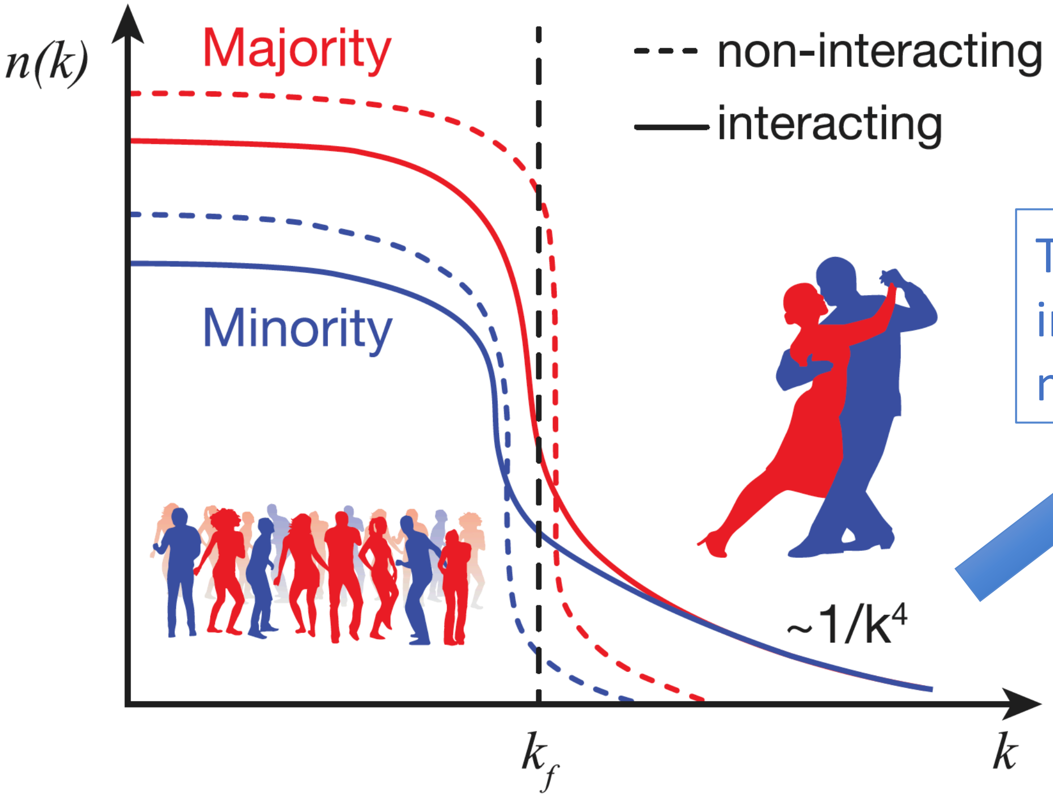
Minority nucleons have on average much higher kinetic energy



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

The concept

Minority nucleons have on average much higher kinetic energy

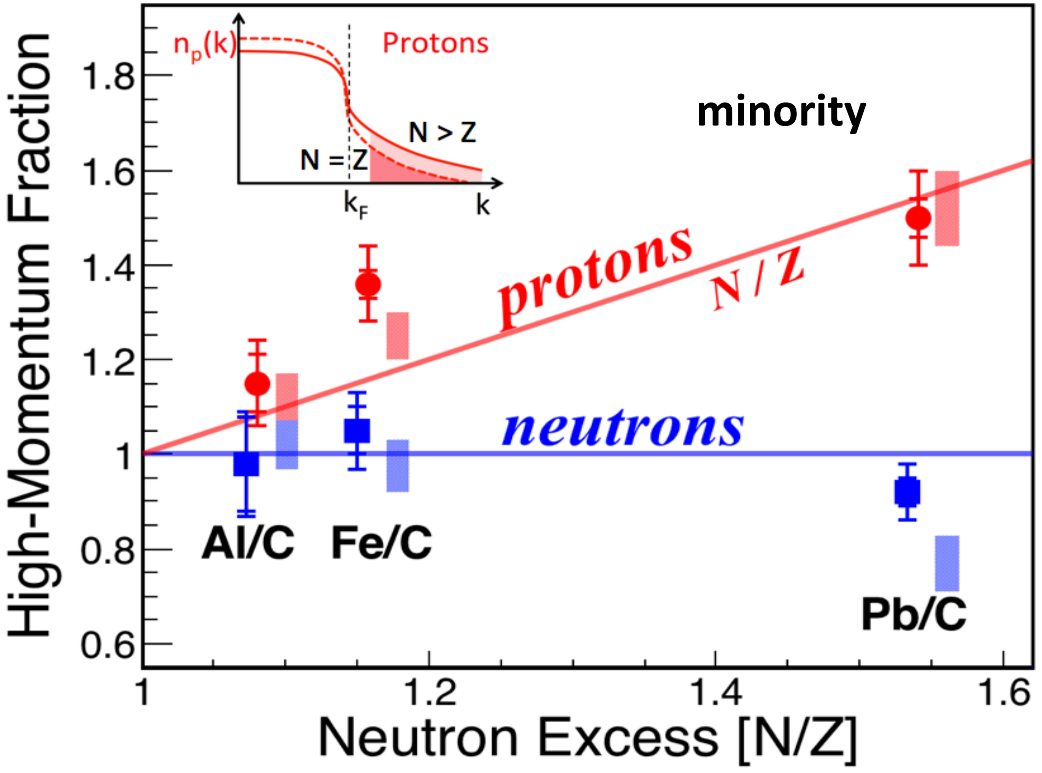


This must be reflected in the SF of the minority nucleons (protons)

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



This morning

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

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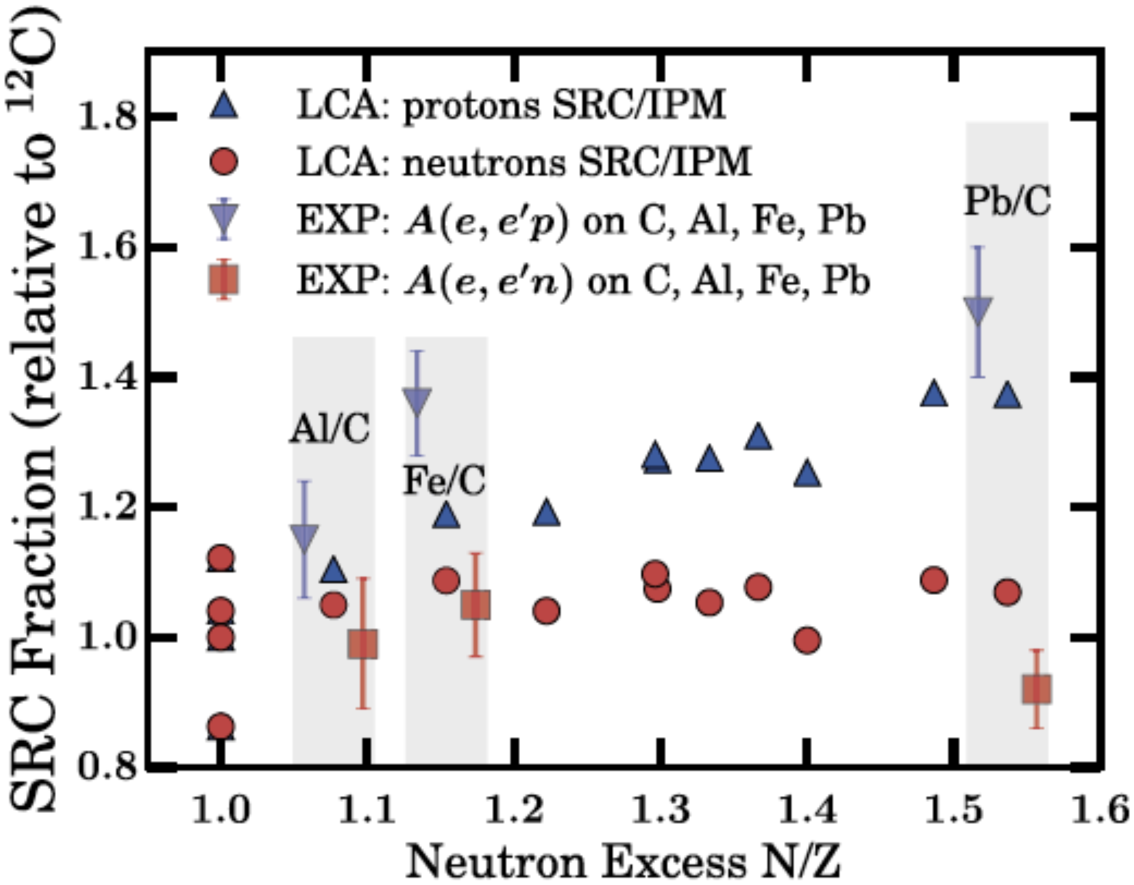


Tomorrow morning

J. Ryckebusch et al. / Phys. Lett. **B 792** (2019) 21

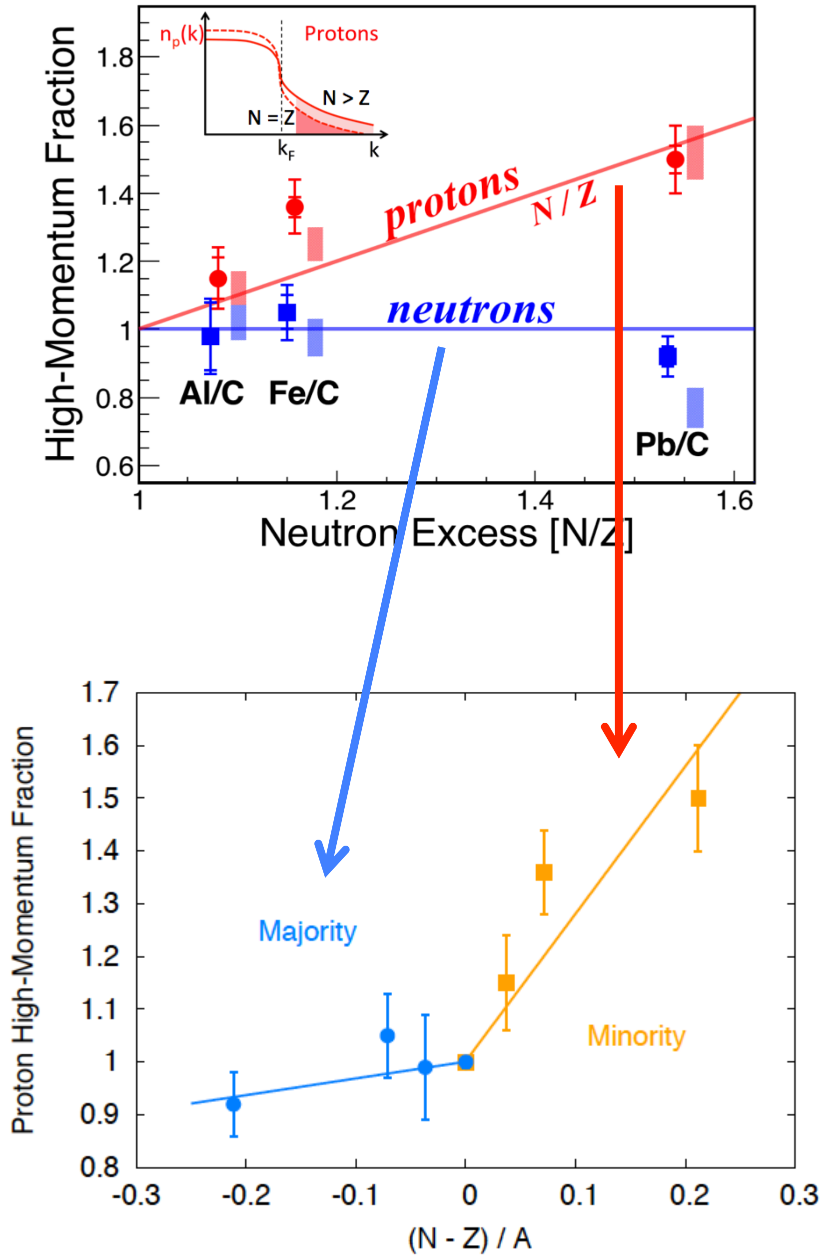
$$|\mathrm{qp}\rangle = \overset{\text{single-particle configuration}}{\mathrm{K_{sp}}|\mathrm{sp}\rangle} + \overset{\text{Particle-vibration coupling}}{\mathrm{K_{PVC}}|\mathrm{PVC}\rangle} + \overset{\text{Pairing correlations}}{\mathrm{K_{PC}}|\mathrm{PC}\rangle} + \overset{\text{Short-range correlations}}{\mathrm{K_{SRC}}|\mathrm{SRC}\rangle}$$

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

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

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

SRC



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

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

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

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

$$\mathrm{R} = 1 - \overbrace{(\underbrace{\mathrm{R}_{\mathrm{PVC}} + \mathrm{R}_{\mathrm{PC}}}_{\text{LRC}} + \mathrm{R}_{\mathrm{SRC}})}^{\text{Missing strength}}$$

Assume first that:

$$\boxed{\mathrm{R}_{\mathrm{PVC}} + \mathrm{R}_{\mathrm{PC}} = \delta \text{ is a constant as a function of isospin}}$$

The data

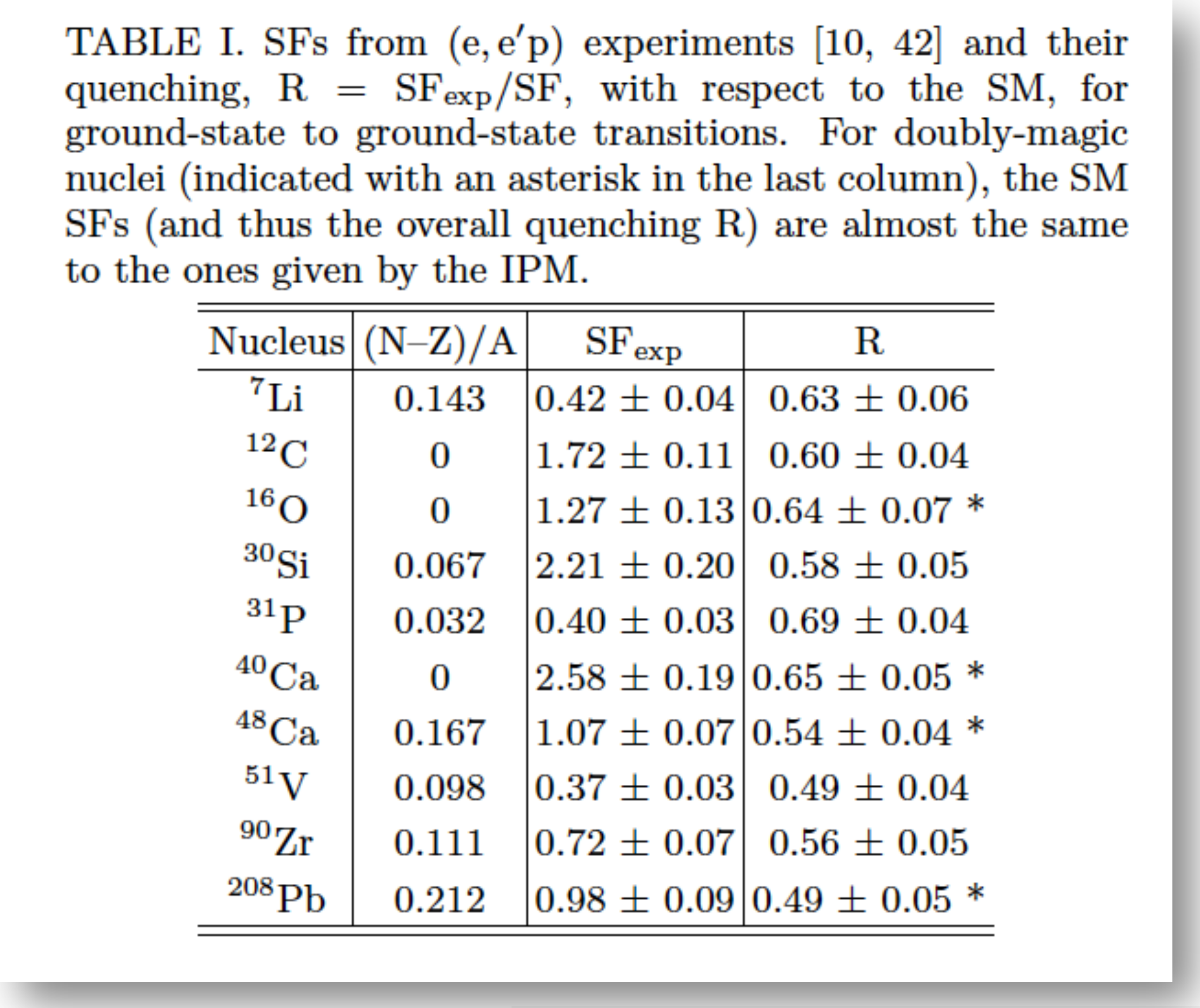
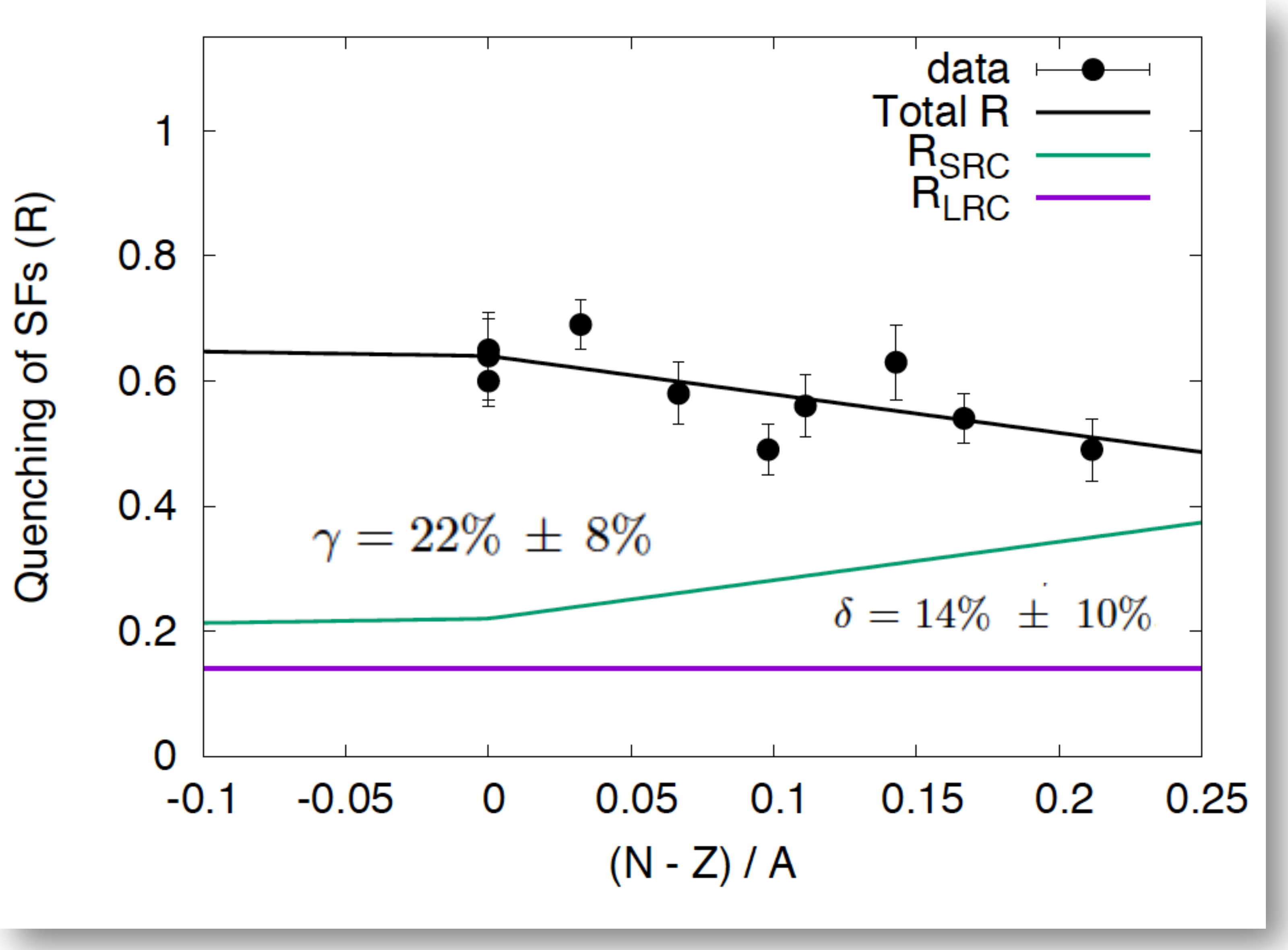


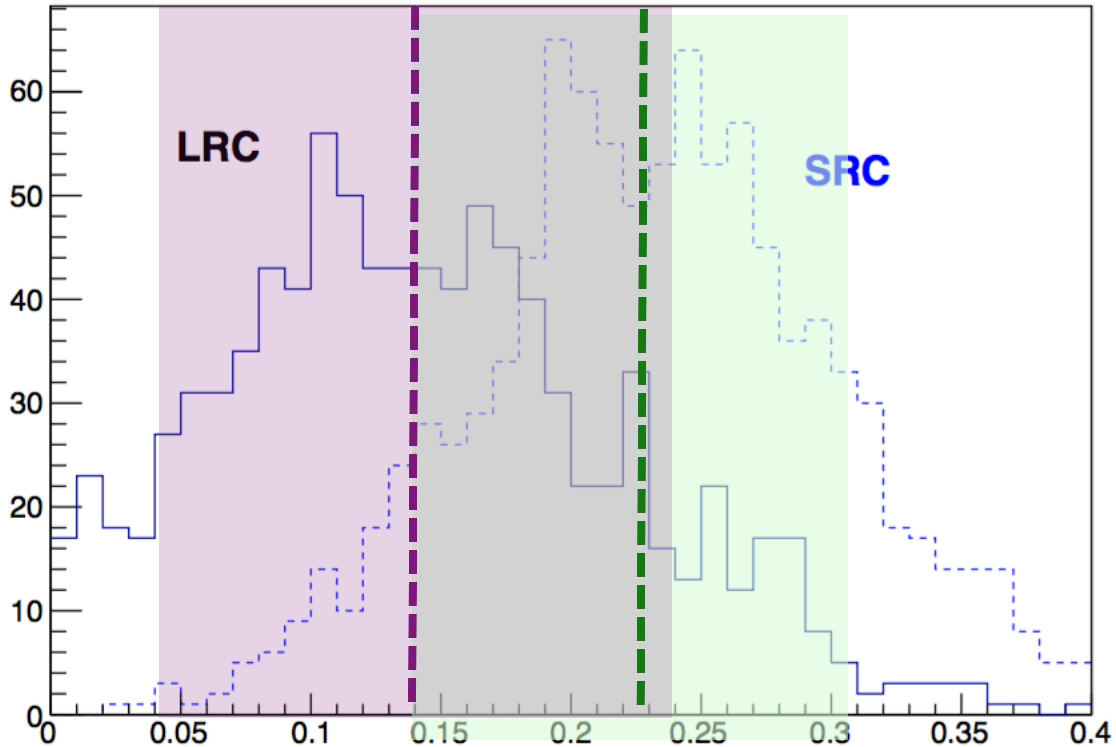
TABLE I. SFs from (e, e′p) experiments [10, 42] and their quenching, $R = SF_{exp}/SF$, with respect to the SM, for ground-state to ground-state transitions. For doubly-magic nuclei (indicated with an asterisk in the last column), the SM SFs (and thus the overall quenching R) are almost the same to the 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}
$\gamma = 22\% \pm 8\%$
$\delta = 14\% \pm 10\%$
Quenching of SFs (R)
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
(N - Z) / A

Statistical significance



$$\mathrm{R} = 1 - \overbrace{(\underbrace{\mathrm{R}_{\mathrm{PVC}} + \mathrm{R}_{\mathrm{PC}}}_{\text{LRC}} + \mathrm{R}_{\mathrm{SRC}})}^{\text{Missing strength}}$$

LRC in more detail

Particle Vibration Coupling

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

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

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

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

$$\mathrm{V} = \mathrm{V}_0\left(1 + \kappa\frac{\mathrm{N}-\mathrm{Z}}{\mathrm{A}}\right)$$

$$\mathrm{R_{PVC}} = \alpha\left(1 + \frac{33}{51}\frac{\mathrm{N}-\mathrm{Z}}{\mathrm{A}}\right)^2$$

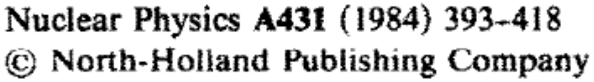
*Bohr & Mottelson

(LRC)Pairing Correlations**

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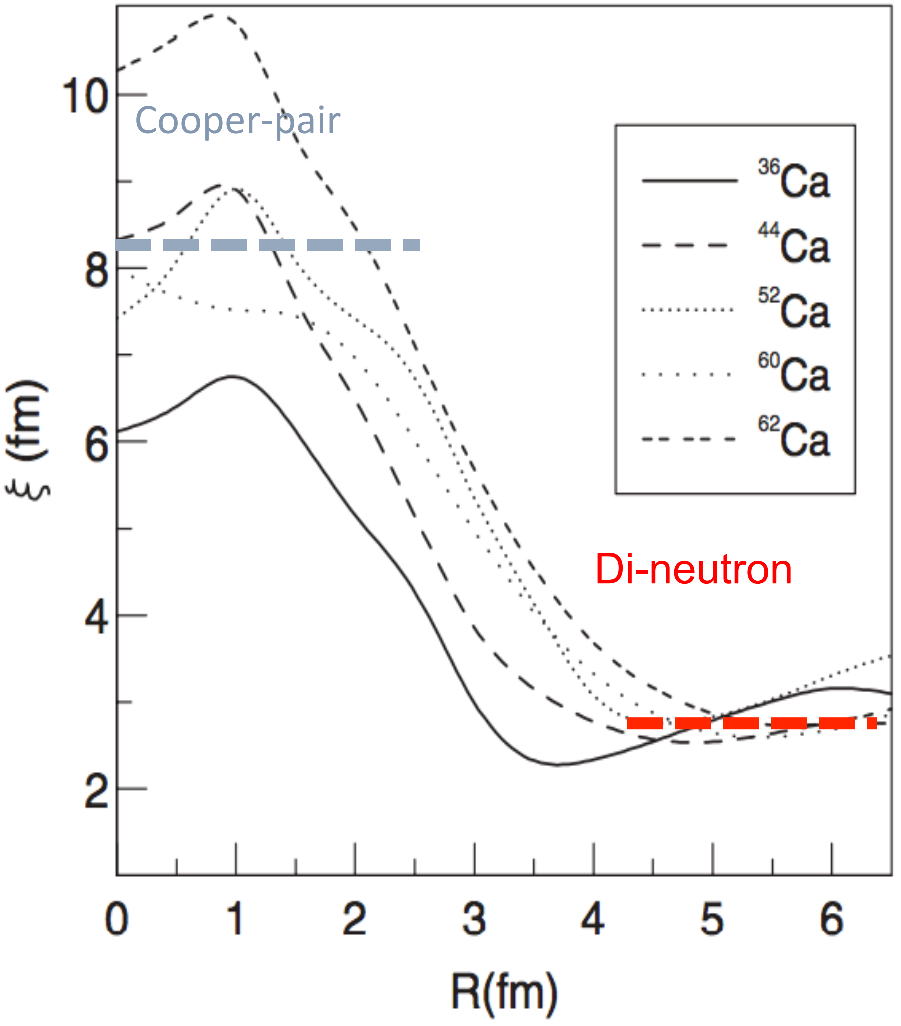
$$R_{PC} = \beta\left(1 - 6.07\left(\frac{N-Z}{A}\right)^2\right)^2$$

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 $((7.55/A^{1/3})/(41/A^{1/3}))^2 \approx 0.03$

**Pair coherence length



$$\boxed{\xi = \frac{1}{\pi}\frac{\hbar^2}{m}\frac{k_F}{\Delta}}$$

N. Pillet et al. PRC **76**, 024310 (2007)

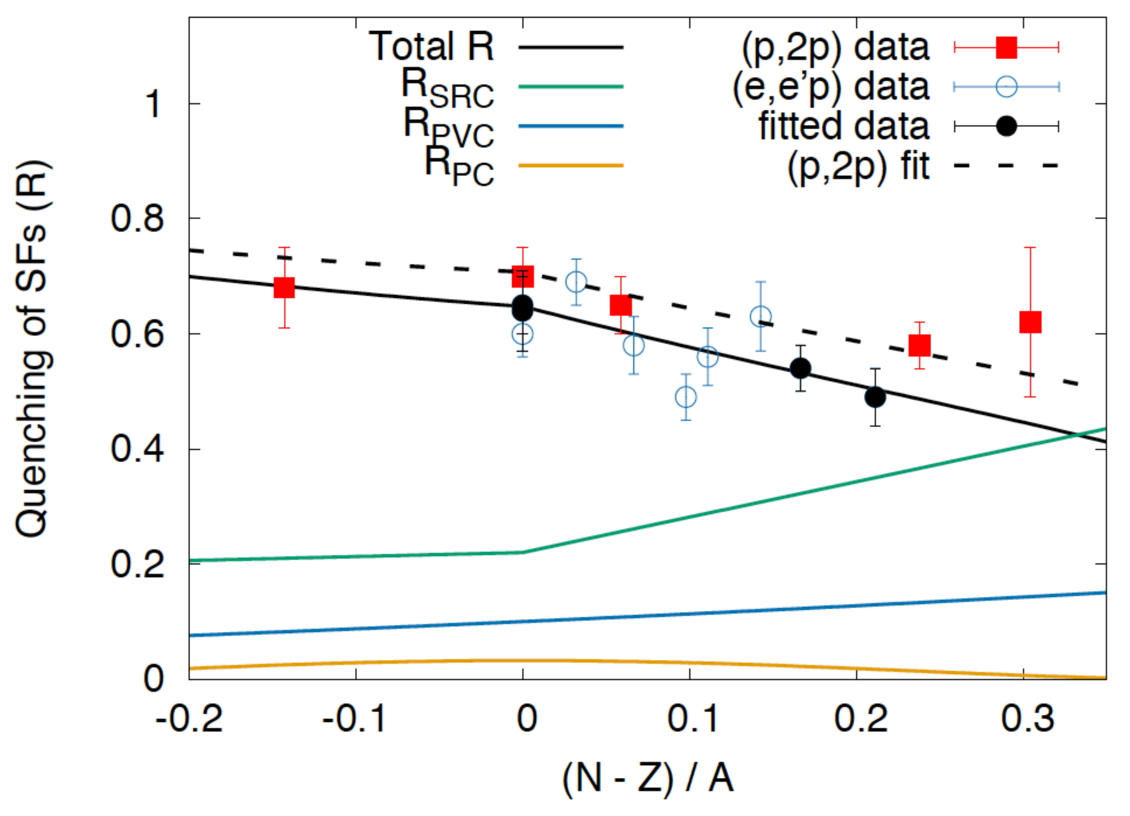
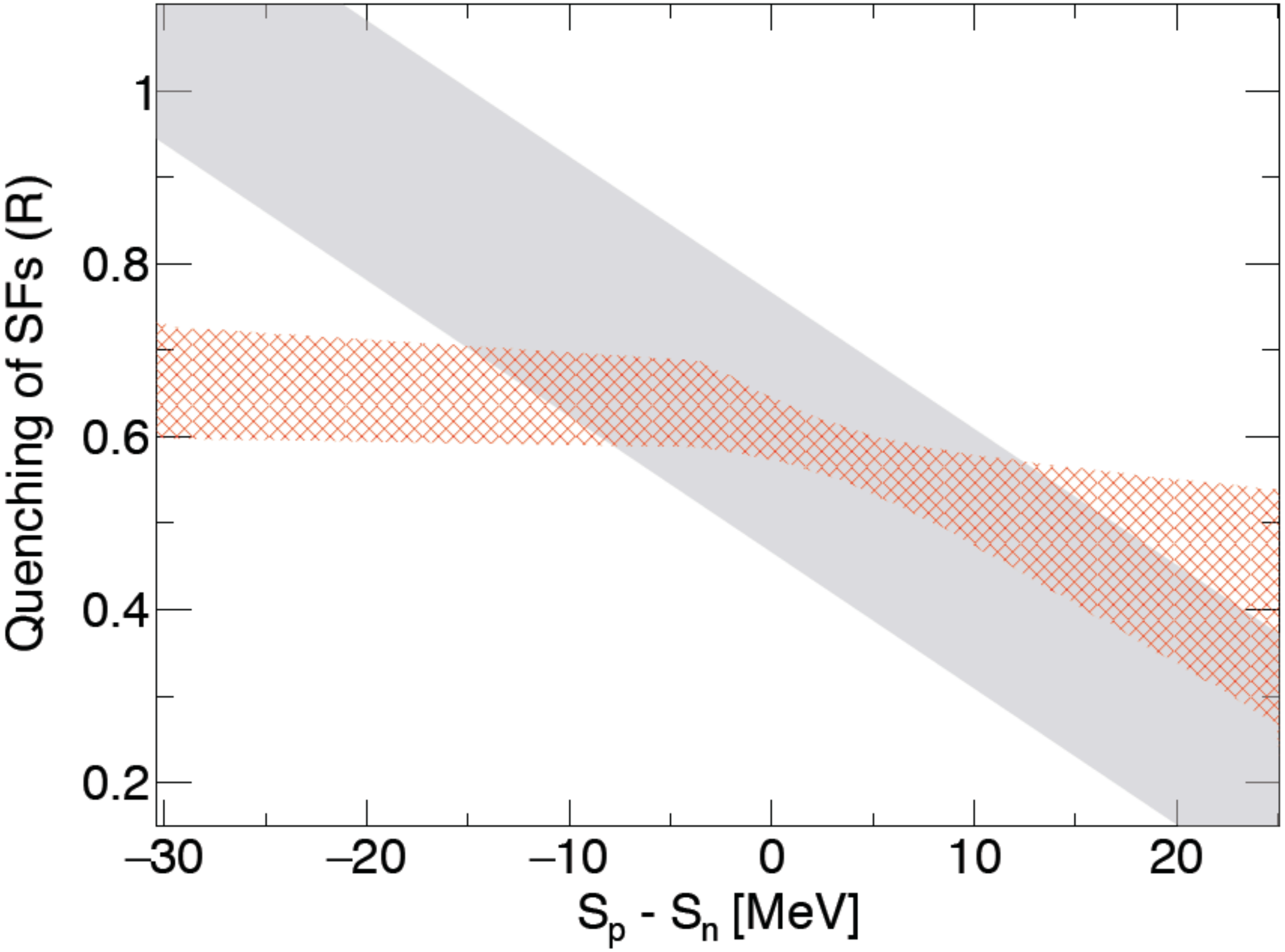


FIG. 3. The full set of (e, e′p) data and (p, 2p) results from [20]. As discussed in the text, the fit corresponds to doubly magic nuclei only. For comparison, the dashed line shows the fit for the (p, 2p) data. The SRC and PC contributions are fixed to $\gamma = 22\%$ and $\beta = 3\%$, respectively. The fit yields a PVC contribution of $\alpha = 10\% \pm 2\%$ for ground- to ground-state transitions and a smaller PVC contribution of $\alpha = 4\% \pm 2\%$ for the (p, 2p) results from [20]; this is expected since the (p,2p) data is an inclusive measurement.

Our results in a Gade/Tostevin plot

(converting A,Z,N → S_n and S_p)

Physics Letters B 790 (2019) 308–313



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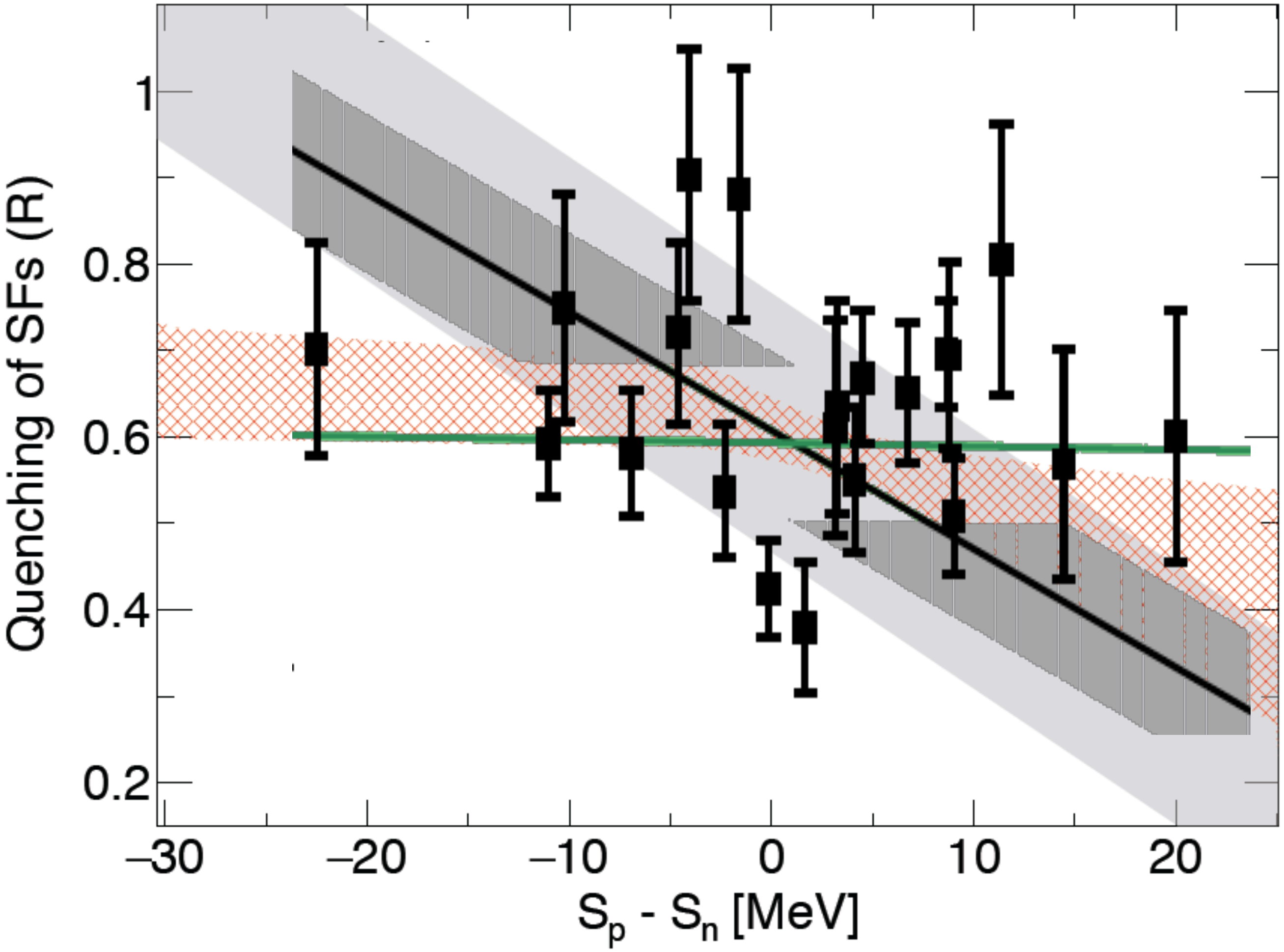
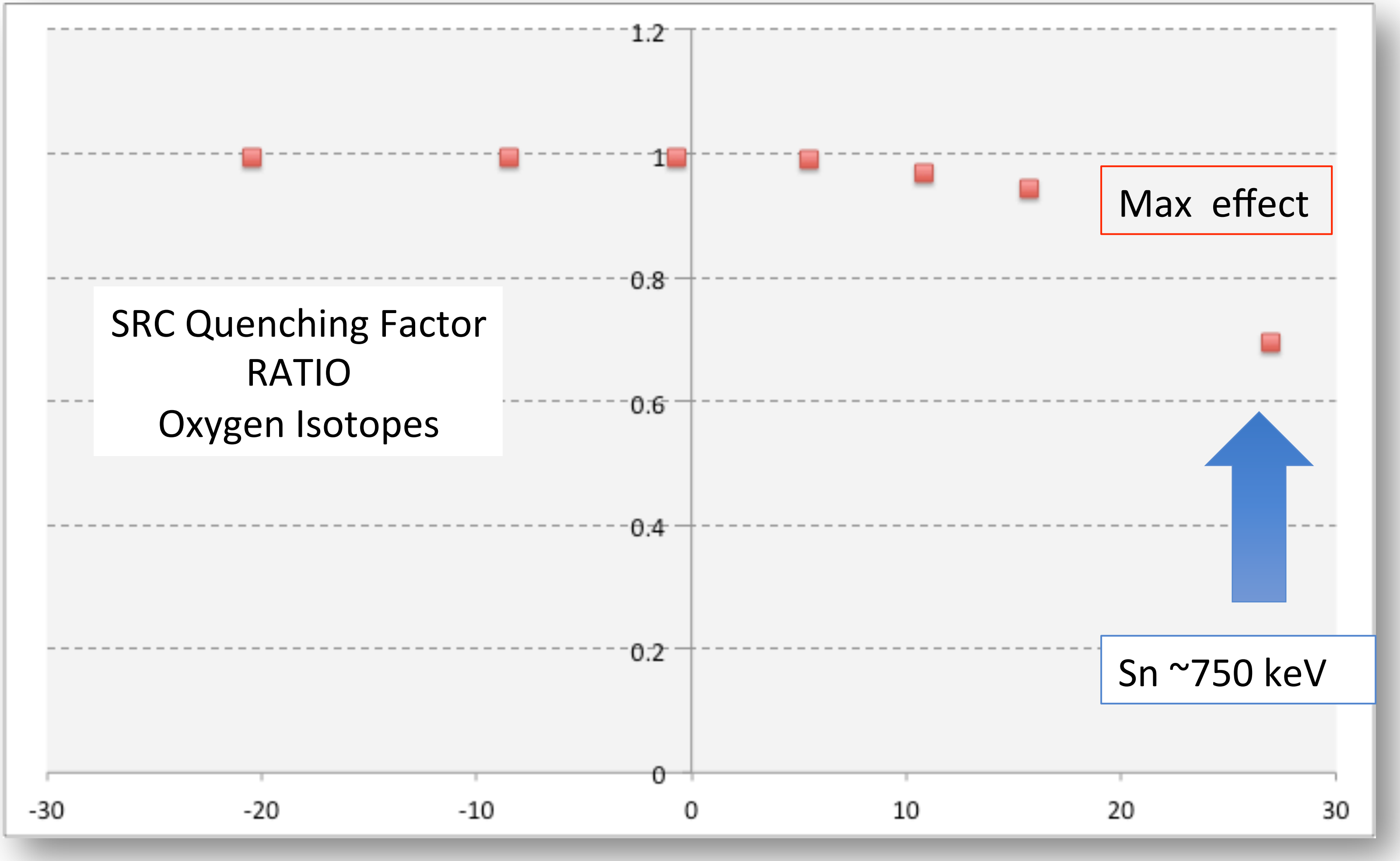


Y. P. Xu, et al. Phys. Lett. **B790** (2019) 308

Effects of weak binding ?

$\boxed{\mathrm{SL}^{\mathrm{P}}_{\mathrm{SRC}} = 2.8 \pm 0.7}$ x $(\mathrm{Vol}_p/\mathrm{Vol}_n)$



Sp-Sn (MeV)

Interesting to consider the limit:

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

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

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

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

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

$$R^{n}_{nM} = 1 - \gamma + \gamma SL^{n}_{SRC} \sim 0.85$$

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

Thank You!