Neutron halo to Tensor Interactions

My trek in physics continue

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October 13, 2025

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Projectile Fragmentation of the Extremely Neutron-Rich Nucleus ^{11}Li at 0.79 GeV/nucleon

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and

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(Received 25 September 1987)

Projectile fragmentations of ^{11}Li, ^{8}He, and ^{6}He have been measured at 0.7
tion cross sections and momentum distributions of the produced isotopes (
clusively. Transverse-momentum distributions of ^{9}Li from the fragmentation c
components of different widths. The width of the wide component is consisten
in the fragmentation of stable nuclei, whereas the other component shows ar
reflecting the weak binding of the two outer neutrons in the ^{11}Li nucleus.

PACS numbers: 25.70.Np, 21.10.Gv, 27.20.+n

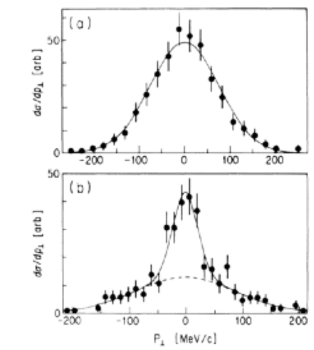

FIG. 1. Transverse-momentum distributions of (a) ^{4}He fragments from reaction $^{6}He+C$ and (b) ^{9}Li fragments from reaction $^{11}Li+C$. The solid lines are fitted Gaussian distributions. The dotted line is a contribution of the wide component in the ^{9}Li distribution.

Projectile fragmentation is one of the most common ... same one as describe

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ELECTROMAGNETIC DISSOCIATION AND SOFT GIANT DIPOLE RESONANCE OF THE NEUTRON-DRIPLINE NUCLEUS ^{11}Li

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Received 2 June 1989

The electromagnetic dissociation (EMD) cross sections of light neutron-dripline projectile ^{11}Li have been inferred from the target dependence of the interaction cross section, σ_I, and the two-neutron-removal cross section, σ_{-2n}, at an incident energy of 0.8 GeV/nucleon. The EMD cross sections of ^{11}Li projectiles on a lead target were found to be quite large; $\sigma_I^{EMD}(^{11}Li+Pb)=1.72\pm0.65$ b and $\sigma_{-2n}^{EMD}(^{11}Li+Pb)=0.89\pm0.10$ b, which are approximately 80 times larger than those of ^{12}C projectiles after scaling the cross section by Z^2_{proj}. The large EMD cross section is related to the possible existence of a soft mode of the giant dipole resonance at low excitation energy in the extremely neutron-rich nuclei.

Neutron halo was not discovered without him!

Hans Geissel

a long fruitful collaboration

ELSEVIER

Nuclear Physics A 691 (2001) 599–617

www.elsevier.com/locate/npe

2001

Measurements of interaction cross sections for light neutron-rich nuclei at relativistic energies and determination of effective matter radii

A. Ozawa [a,*], O. Bochkarev [c], L. Chulkov [c], D. Cortina [b], H. Geissel [b], M. Hellström [b], M. Ivanov [d], R. Janik [d], K. Kimura [e], T. Kobayashi [f], A.A. Korsheninnikov [a], G. Münzenberg [b], F. Nickel [b], Y. Ogawa [g], A.A. Ogloblin [c], M. Pfützner [h], V. Pribora [c], H. Simon [b], B. Sitár [d], P. Strmen [d], K. Sümmerer [b], T. Suzuki [i], I. Tanihata [a], M. Winkler [b], K. Yoshida [a]

a

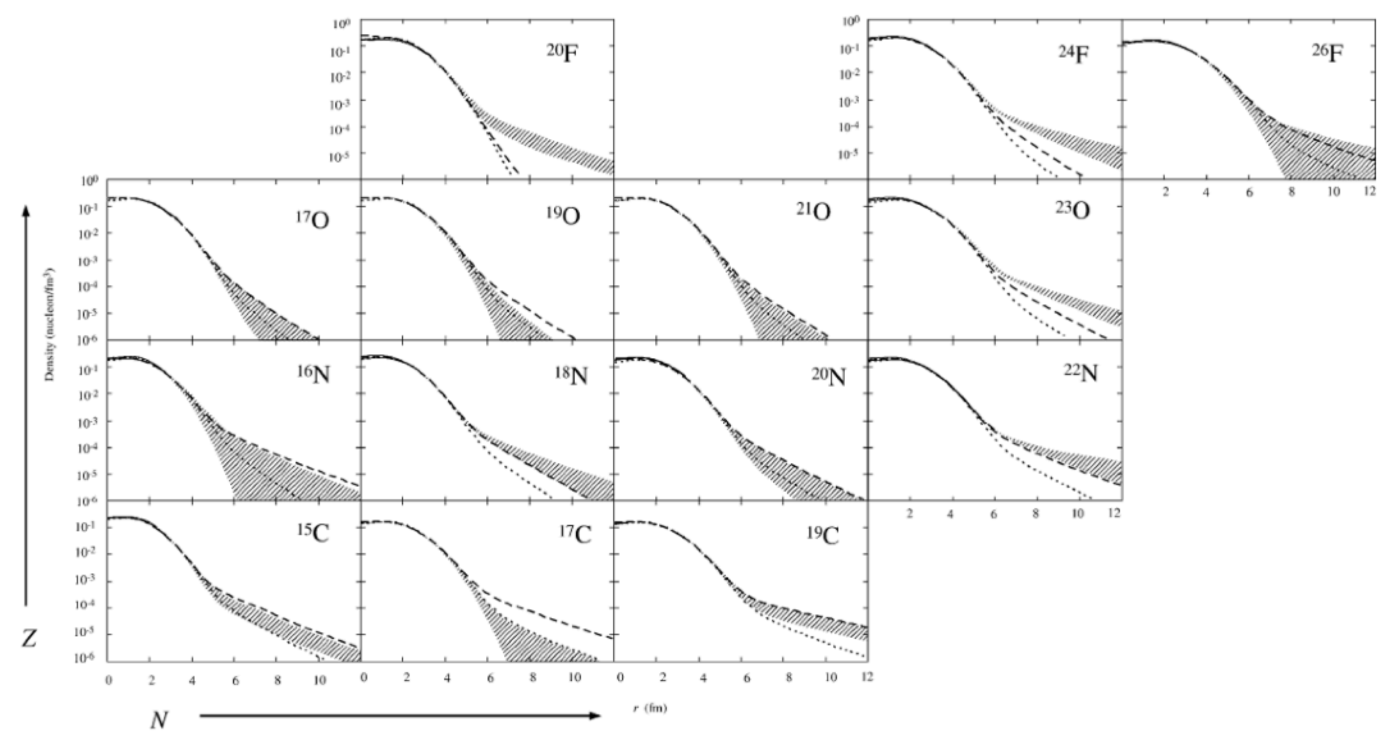

Fig. 6. Nucleon-density distributions for nuclei with odd-N nuclei in the light neutron-rich region. The dashed line (dotted line) shows the density distributions deduced from a core plus $2s_{1/2}$ (a core plus $1d_{5/2}$) configuration using the experimentally observed S_n. The hatched area shows the density distribution required to reproduce the observed σ_I for both the core and the respective nucleus.

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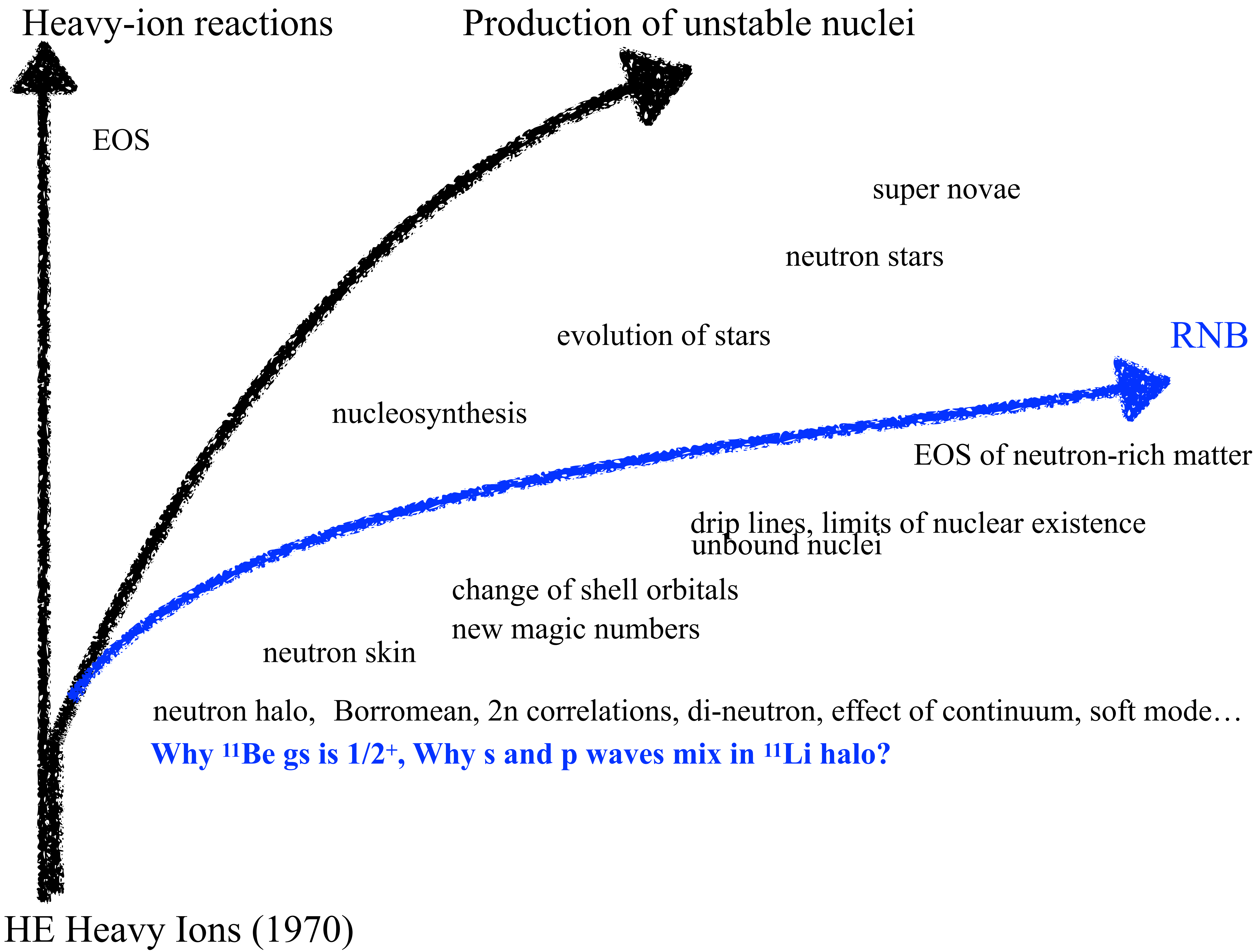
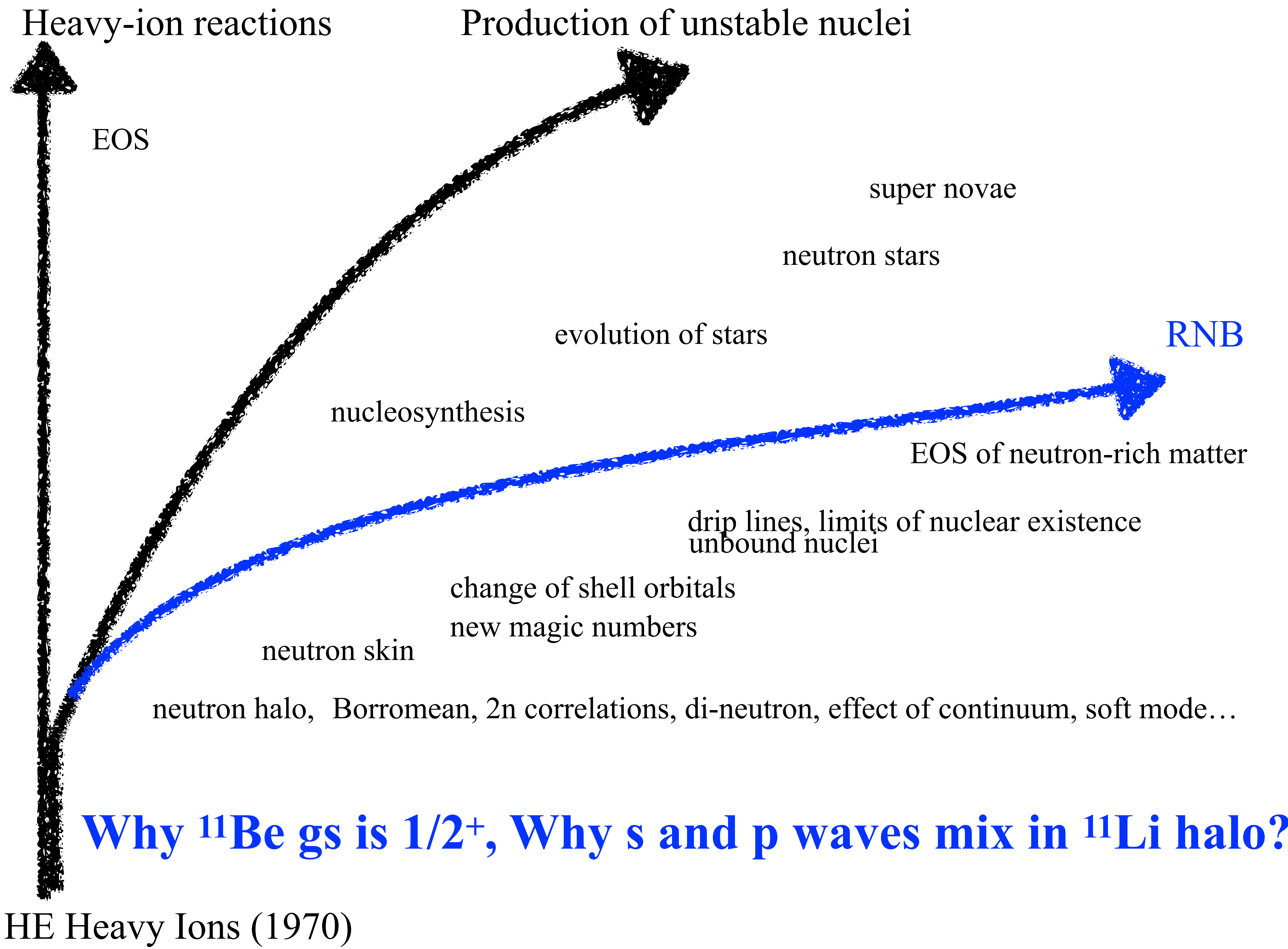
Keywords: NUCLEAR REACTIONS

($^{18-26}$F, $^{18-26}$F), $E \sim 950$ MeV/nucleon; Measured interaction σ; ^{10,11}B, $^{12-20}$C, $^{14-23}$N, $^{16-24}$O, $^{18-26}$F deduced effective radii



Heavy-ion reactions
Production of unstable nuclei
EOS
super novae
neutron stars
evolution of stars
RNB
nucleosynthesis
EOS of neutron-rich matter
drip lines, limits of nuclear existence
unbound nuclei
change of shell orbitals
new magic numbers
neutron skin
neutron halo, Borromean, 2n correlations, di-neutron, effect of continuum, soft mode…
Why 11Be gs is 1/2+, Why s and p waves mix in 11Li halo?
HE Heavy Ions (1970)


Heavy-ion reactions
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Why ¹¹Be gs is 1/2⁺, Why s and p waves mix in ¹¹Li halo?
HE Heavy Ions (1970)

Mystery of s-wave behavior in ^{11}Be

- **^{11}Be ground state is $1/2^+$ instead of $1/2^-$.**
  - *I. Talmi and I. Unna, PRL 4 (1960) 469.*

    They found that this change can be understood as shell model behavior due to single and two particle residual interactions. However no realistic calculations has been done.
  - *"No-core shell model" by C. Foreseen, P. Navratilova, and W. E. Ormand, UCRL-JRNL-208555 (2004) .*

    did not succeed to make $1/2^+$ ground state.
  - *"First principle calculations using chiral 2-,3-nucleon interactions with continuum effects" by A. Calci, P. Navrátil, PRL 117 (2016) 242501.*
    - A tiny bit inversion of $1/2^+$.

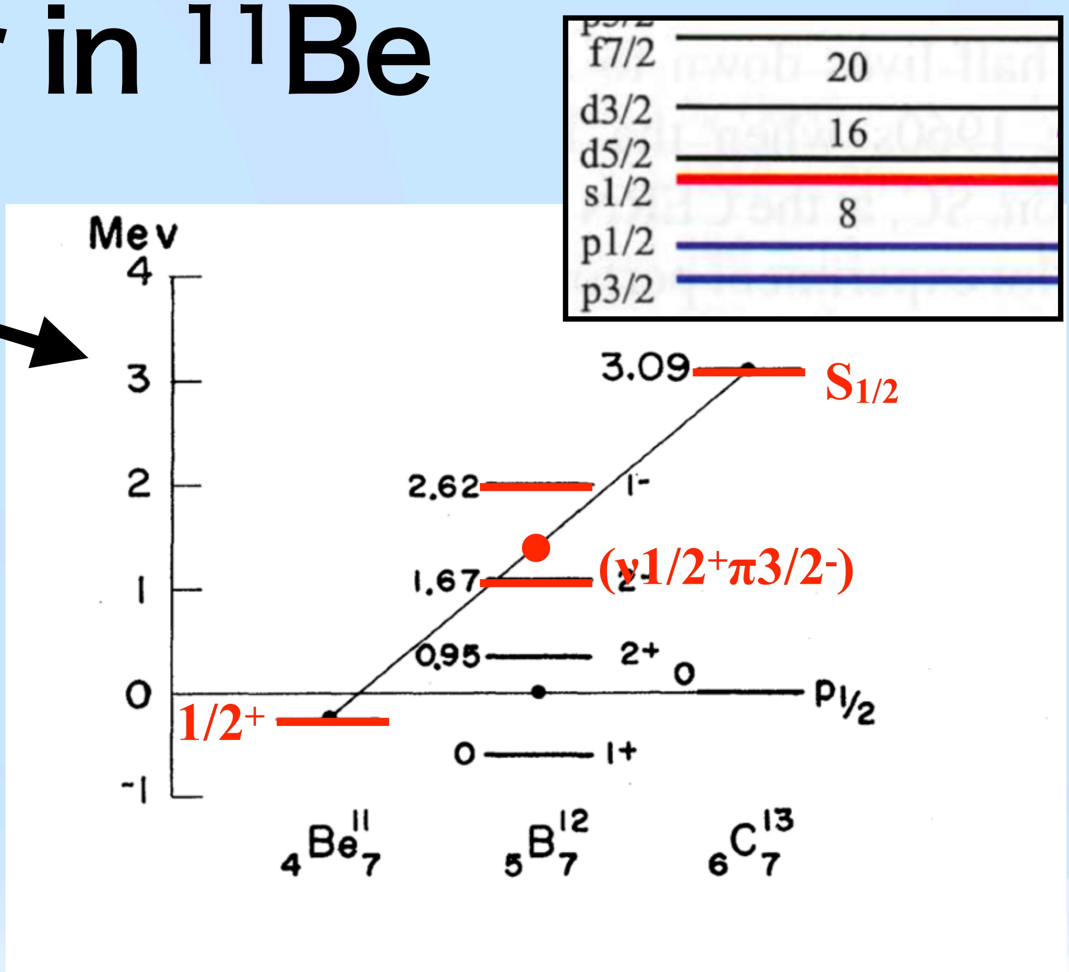
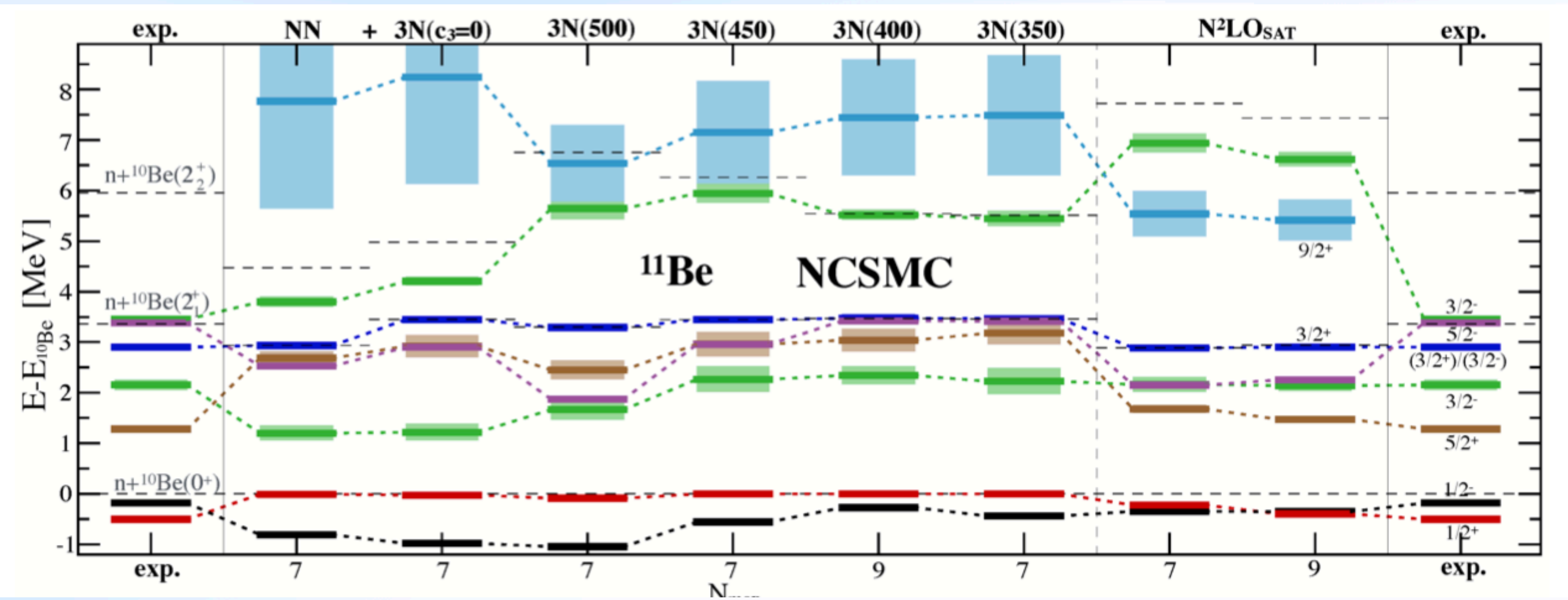


FIG. 1. Competition between $s_{1/2}$ and $p_{1/2}$ levels.



Another mystery is the equal mixing of $s_{1/2}$ and $p_{1/2}$ mixing in the neutron halo of ^{11}Li.

Be ground state is 1/2 instead of 1/2 .

- *I. Talmi and I. Unna, PRL 4 (1960) 469.*

  They found that this change can be understood as shell model behavior due to single and two particle residual interactions. However no realistic calculations has been done.

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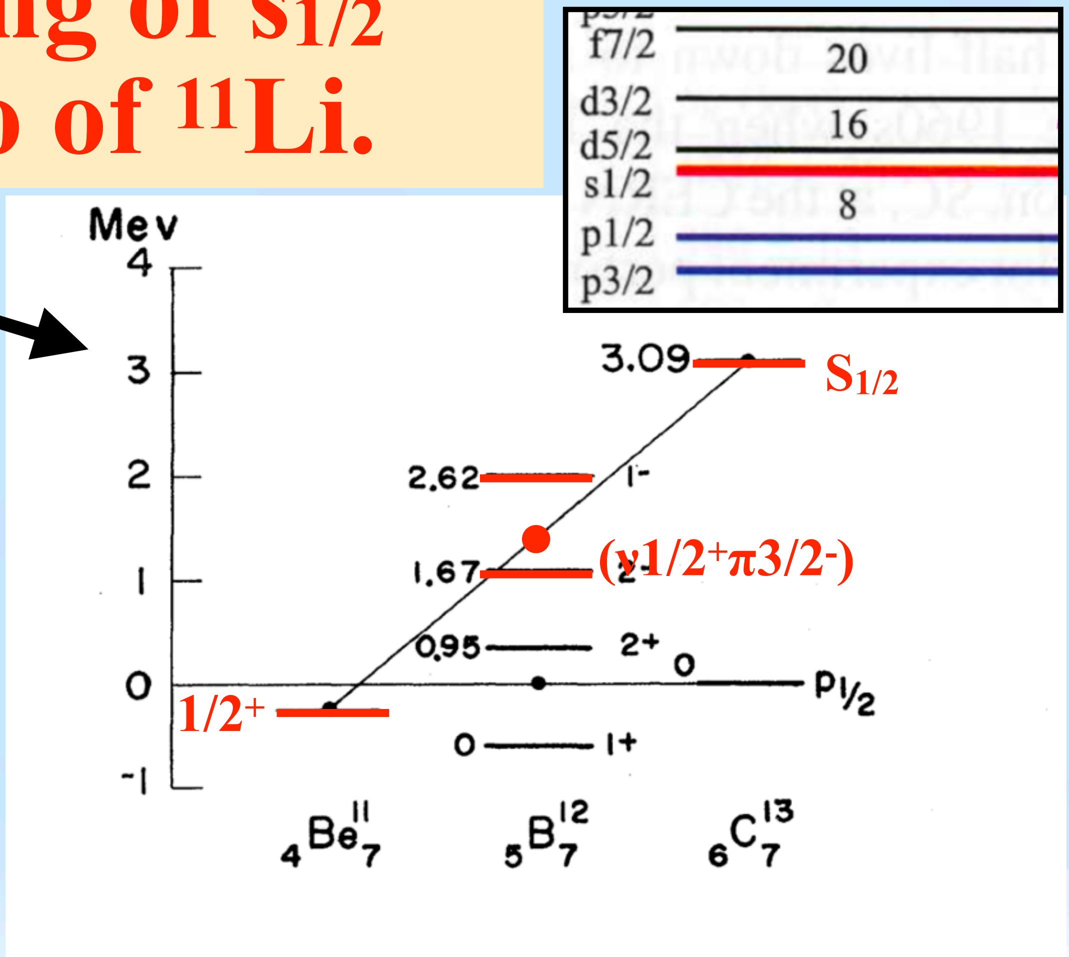

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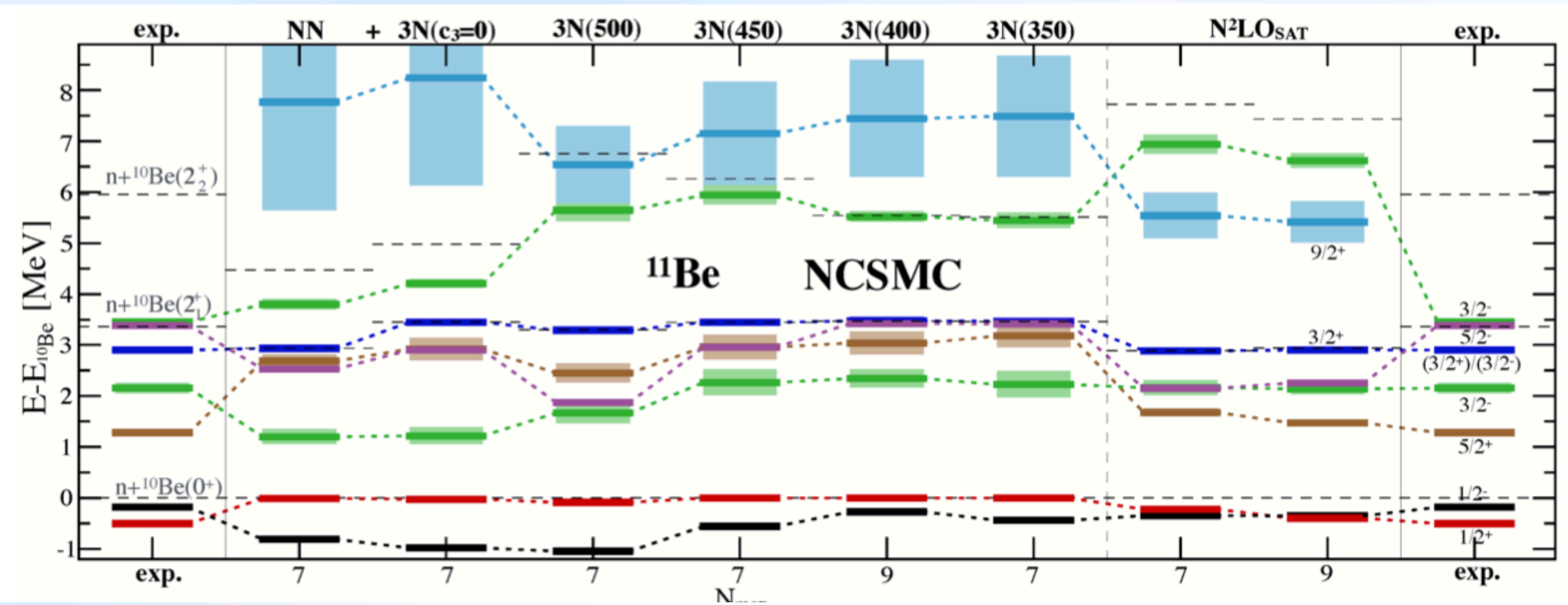
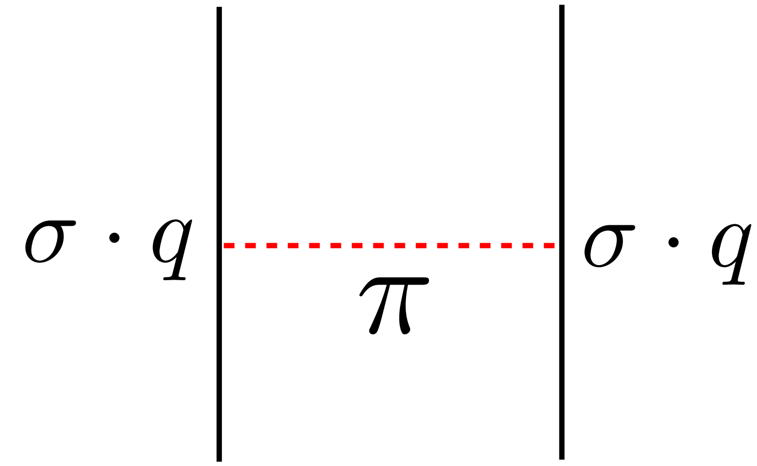


Slide from H. Toki

Why tensor interaction is strong?

Pion is a pseudoscalar meson $J^\pi = 0^-$

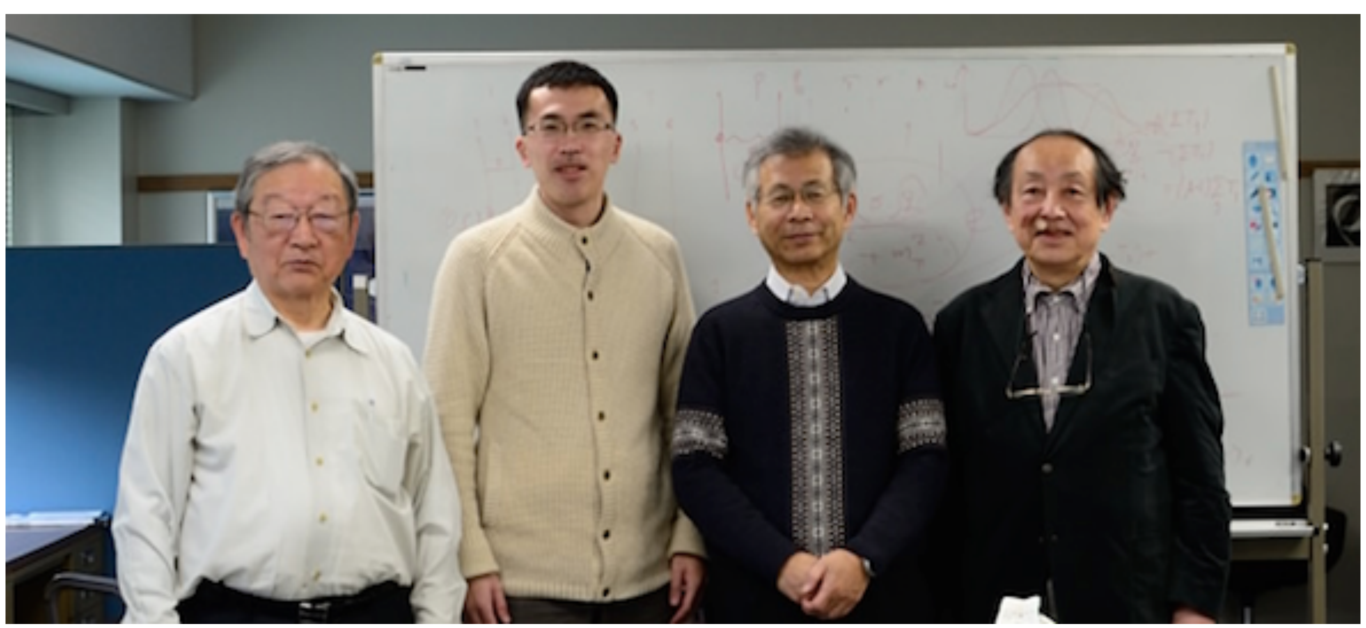
$$V_\pi = \frac{f_\pi^2}{m_\pi^2} \frac{(\sigma_1 \cdot q)(\sigma_2 \cdot q)}{m_\pi^2 + q^2} \tau_1 \tau_2$$



$$\frac{(\sigma_1 \cdot q)(\sigma_2 \cdot q)}{m_\pi^2 + q^2} = \frac{1}{3}\sigma_1\sigma_2 \left[\frac{m_\pi^2 + q^2}{m_\pi^2 + q^2} - \frac{m_\pi^2}{m_\pi^2 + q^2} \right] + \frac{1}{3} S_{12}(q) \frac{q^2}{m_\pi^2 + q^2}$$

δ 関数　Yukawa　Tensor

$$S_{12}(q) = [[\sigma_1 \sigma_2]_2 \times Y_2(q)]_0$$

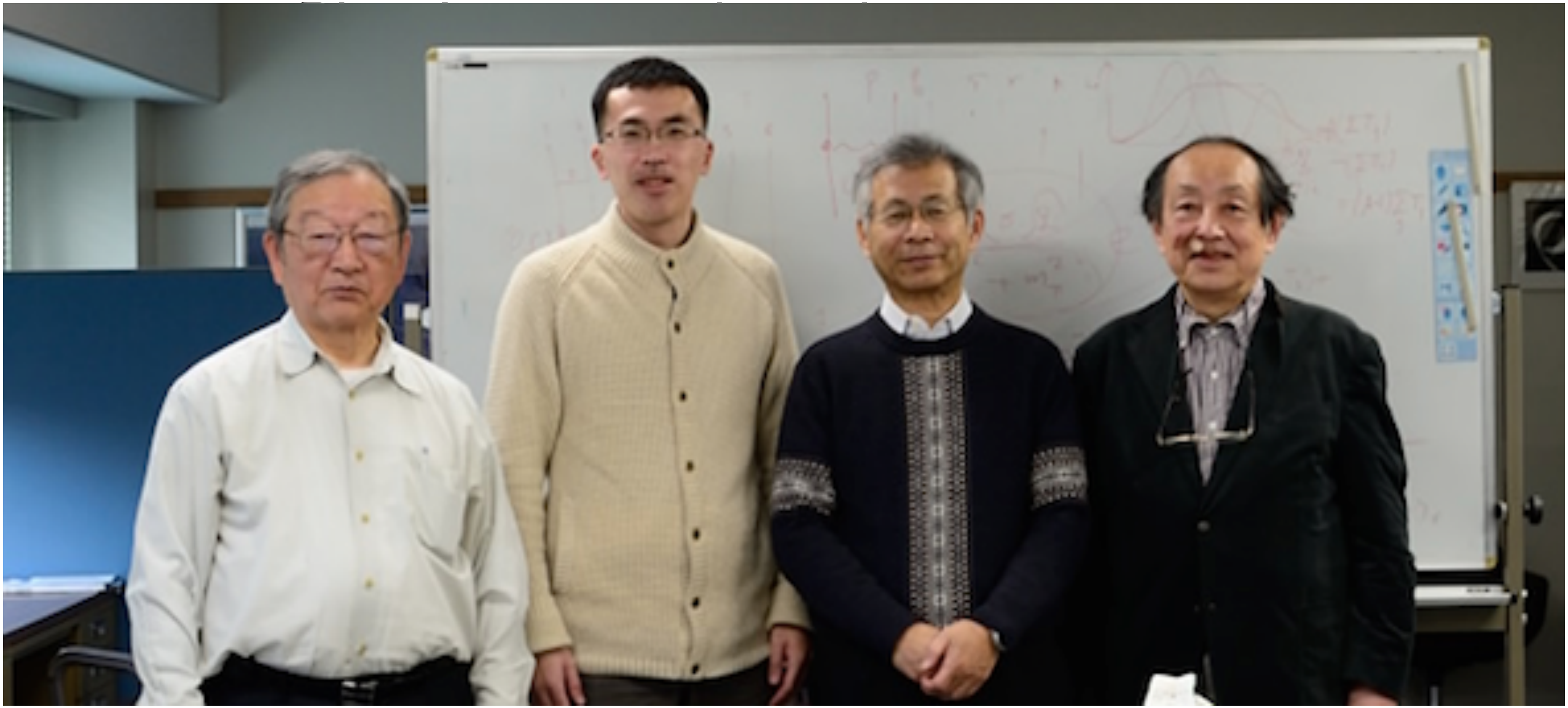


Horiuchi　Myo　Toki　Ikeda

Tensor interaction increases with momentum

Slide from H. Toki

Why tensor interaction is strong?



Tensor interaction increases with momentum

Tensor Optimized Shell Model (TOSM)

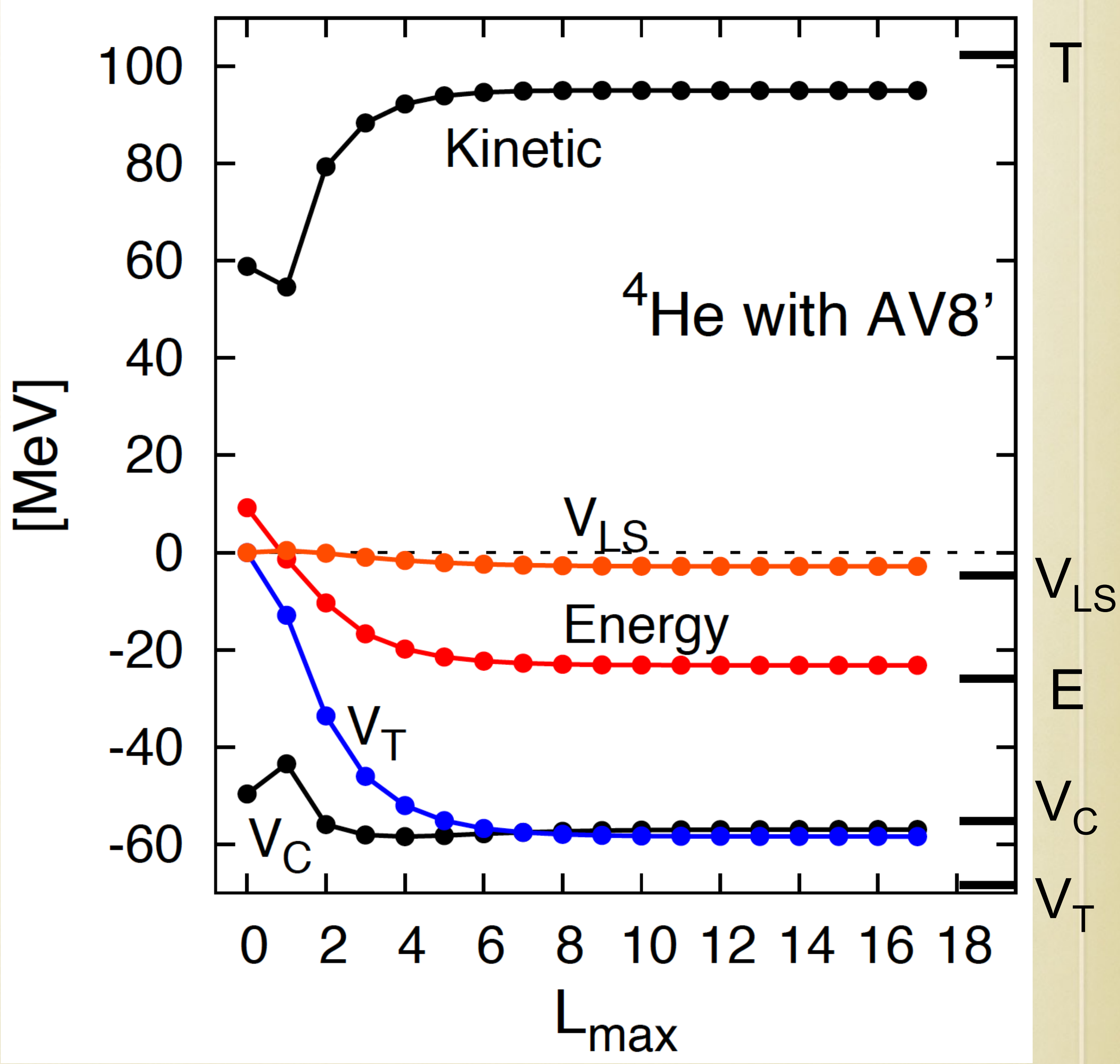
Horiuchi Myo Toki Ikeda

Tensor interaction in ^{4}He

$$\Phi(^4\mathrm{He}) = \Sigma_i C_i \psi_i(\{b_\alpha\}) = C_1 (0s)^4 + C_2 (0s)^2 (\overline{0p_{1/2}})^2 + \cdots$$

- 2p-2h states with high momentum nucleons
- 2p-2h excitations of p-n pair under *ΔS*=2, *ΔL*=2 provide tensor energies.

- Tensor interactions give ~60 MeV of potential energy.
- Remember *l*=1 excitation already gives ~14 MeV of potential energy.
- Higher *l* contribute more but…



Tensor Optimized Shell Model by T. Myo, H. Toki and K. Ikeda, Progr. Theor. Phys. **121** 511 (2009)

The most important 2p-2h configuration

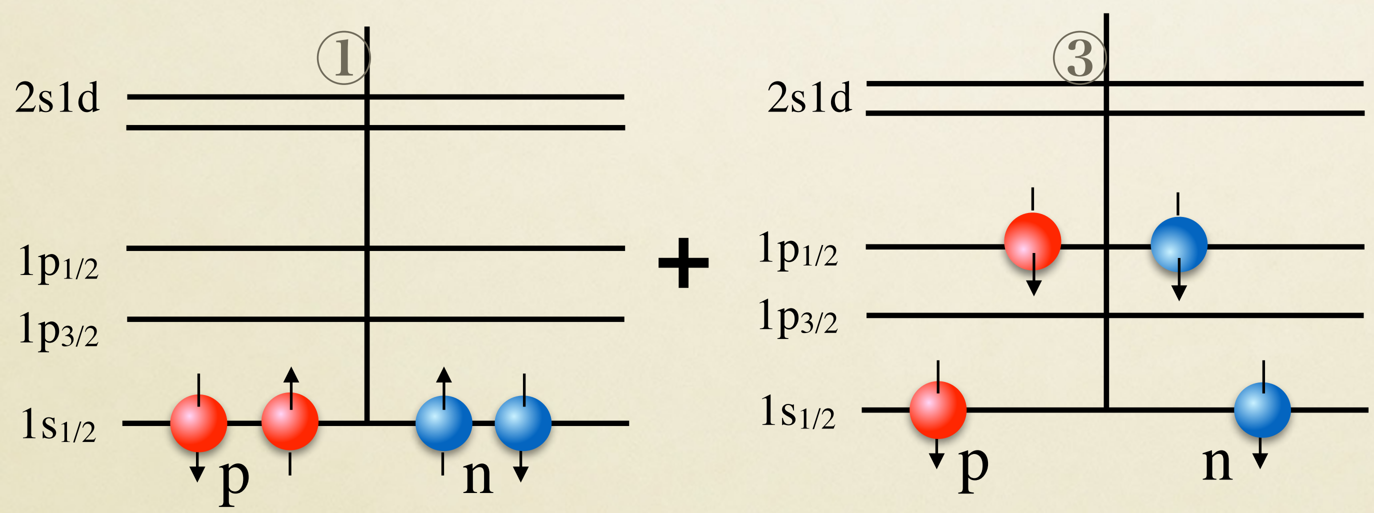
Configurations up to l=1

T. Myo, K. Kato, and K. Ikeda, PTP 113, (2005) 763.

$$\Psi(^4\mathrm{He}) = \sum_{i=1}^{6} a_i\, \Phi_i \ ,$$

$$\begin{aligned}
\Phi_1 &= (0s_{1/2})^4_{00} \ , \\
\Phi_2 &= \left[(0s_{1/2})^2_{01}, (0p_{1/2})^2_{01}\right]_{00} \ , \\
\Phi_3 &= \left[(0s_{1/2})^2_{10}, (0p_{1/2})^2_{10}\right]_{00} \ , \\
\Phi_4 &= \left[(0s_{1/2})^2_{01}, (0p_{3/2})^2_{01}\right]_{00} \ , \\
\Phi_5 &= \left[(0s_{1/2})^2_{10}, (0p_{3/2})^2_{10}\right]_{00} \ , \\
\Phi_6 &= \left[(0s_{1/2})^2_{10}, \left[(0p_{1/2})(0p_{3/2})\right]_{10}\right]_{00}
\end{aligned}$$

^{4}He



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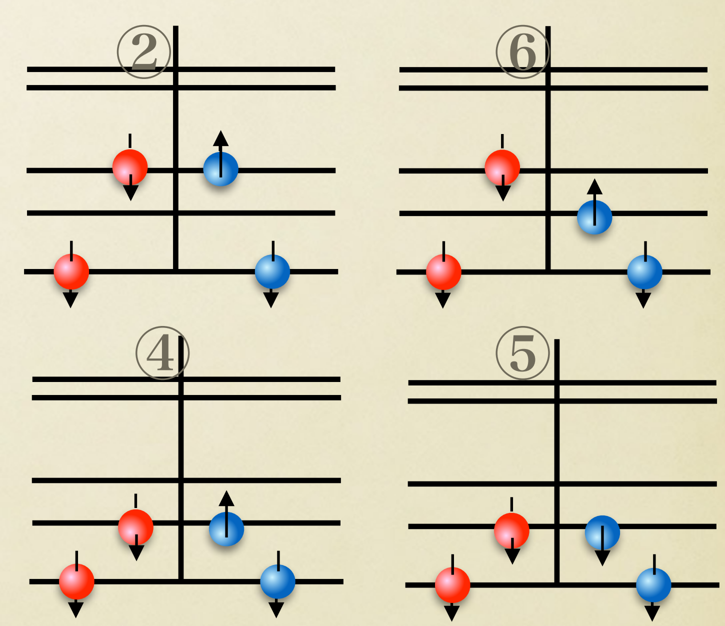

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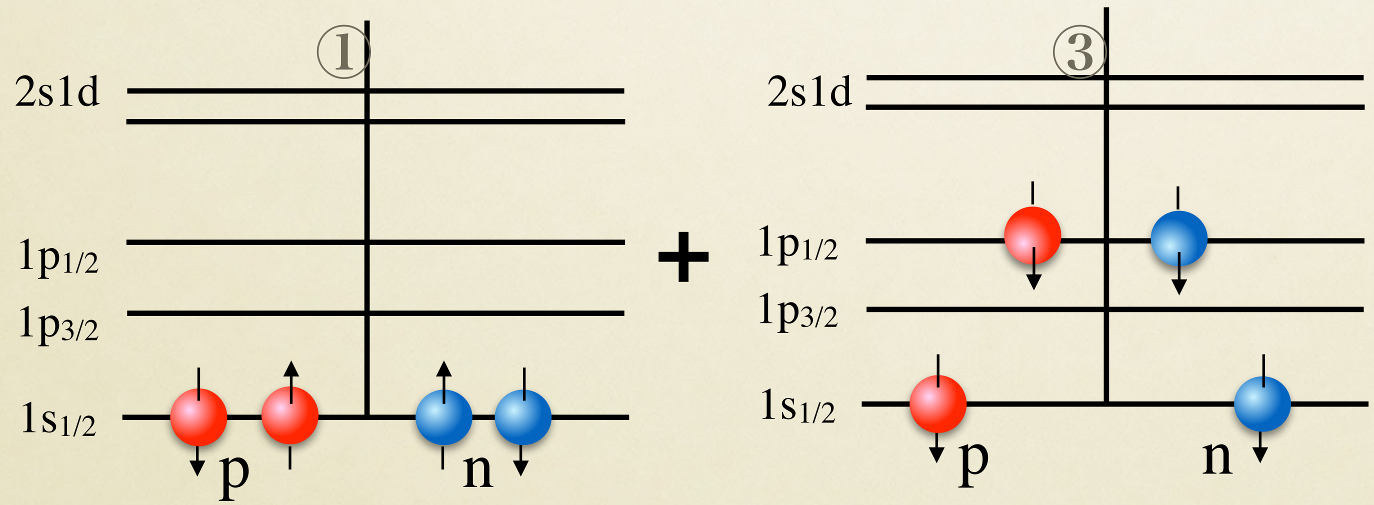
$$\Psi(^4\mathrm{He}) = \sum_{i=1}^{6} a_i\,\Phi_i\ ,$$

	V_T [MeV]
$\Phi_1 = (0s_{1/2})^4_{00}\ ,$	
$\Phi_2 = \left[(0s_{1/2})^2_{01}, (0p_{1/2})^2_{01}\right]_{00}\ ,$	0.37
$\Phi_3 = \left[(0s_{1/2})^2_{10}, (0p_{1/2})^2_{10}\right]_{00}\ ,$	14.49
$\Phi_4 = \left[(0s_{1/2})^2_{01}, (0p_{3/2})^2_{01}\right]_{00}\ ,$	0.19
$\Phi_5 = \left[(0s_{1/2})^2_{10}, (0p_{3/2})^2_{10}\right]_{00}\ ,$	1.67
$\Phi_6 = \left[(0s_{1/2})^2_{10}, \left[(0p_{1/2})(0p_{3/2})\right]_{10}\right]_{00}$	0.09

^{4}He



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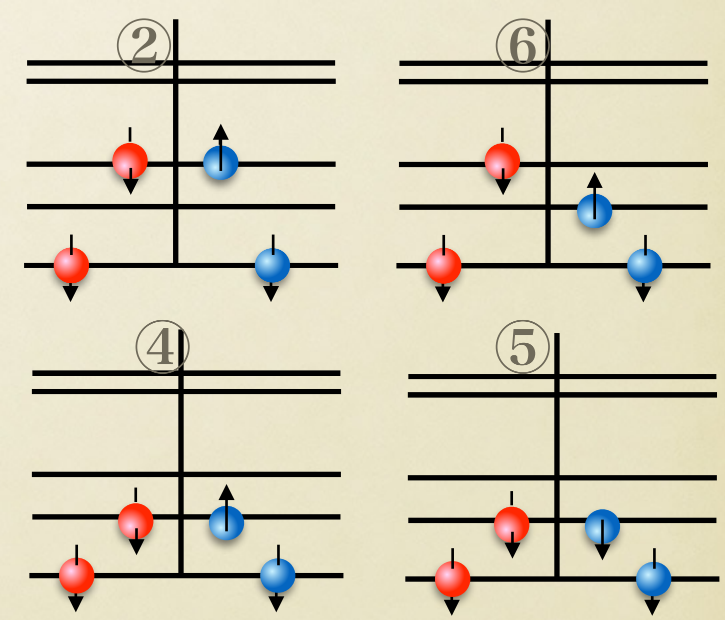

Highest spin orbital ($j_>$) in a major shell is not used for the tensor interaction.
An example is $1p_{3/2}$ orbital in ^{4}He and deuteron.

$$\Psi(^4\mathrm{He}) = \sum_{i=1}^{6} a_i \Phi_i ,$$

V_T [MeV]

$$\Phi_1 = (0s_{1/2})^4_{00} ,$$

$$\Phi_2 = \left[(0s_{1/2})^2_{01}, (0p_{1/2})^2_{01}\right]_{00} , \rightarrow 0.37$$

$$\Phi_3 = \left[(0s_{1/2})^2_{10}, (0p_{1/2})^2_{10}\right]_{00} , \rightarrow 14.49$$

$$\Phi_4 = \left[(0s_{1/2})^2_{01}, (0p_{3/2})^2_{01}\right]_{00} , \rightarrow 0.19$$

$$\Phi_5 = \left[(0s_{1/2})^2_{10}, (0p_{3/2})^2_{10}\right]_{00} , \rightarrow 1.67$$

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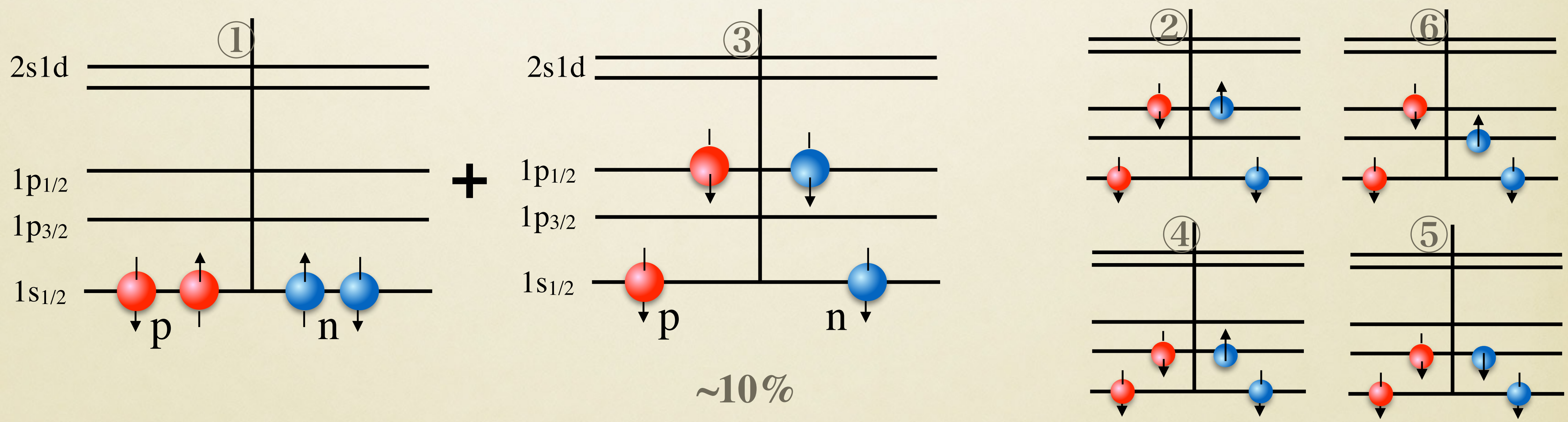
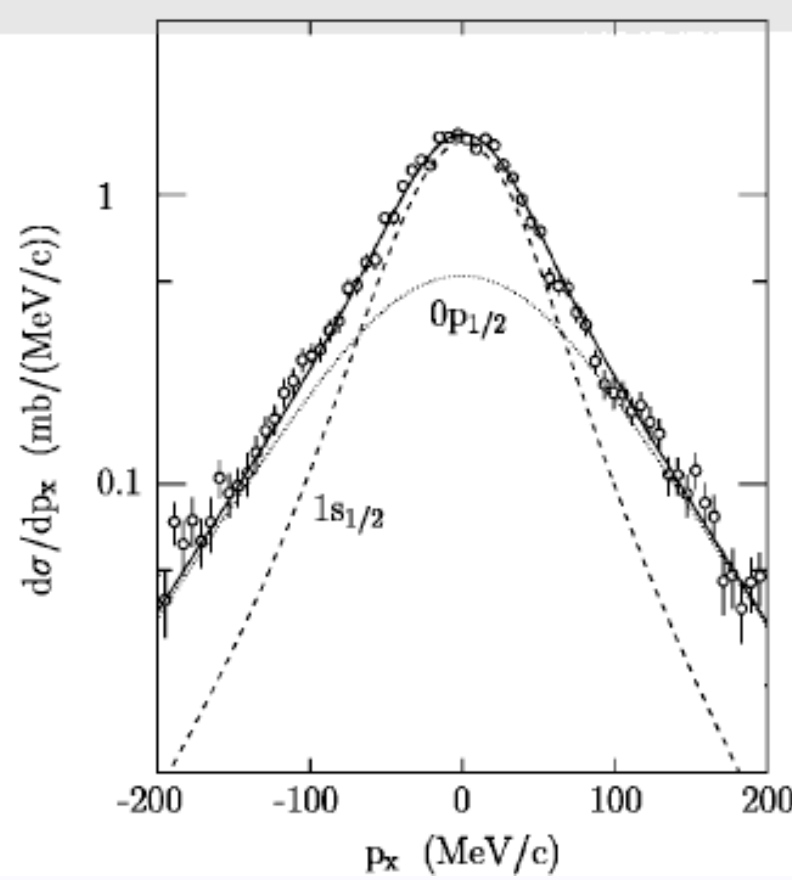
^{4}He

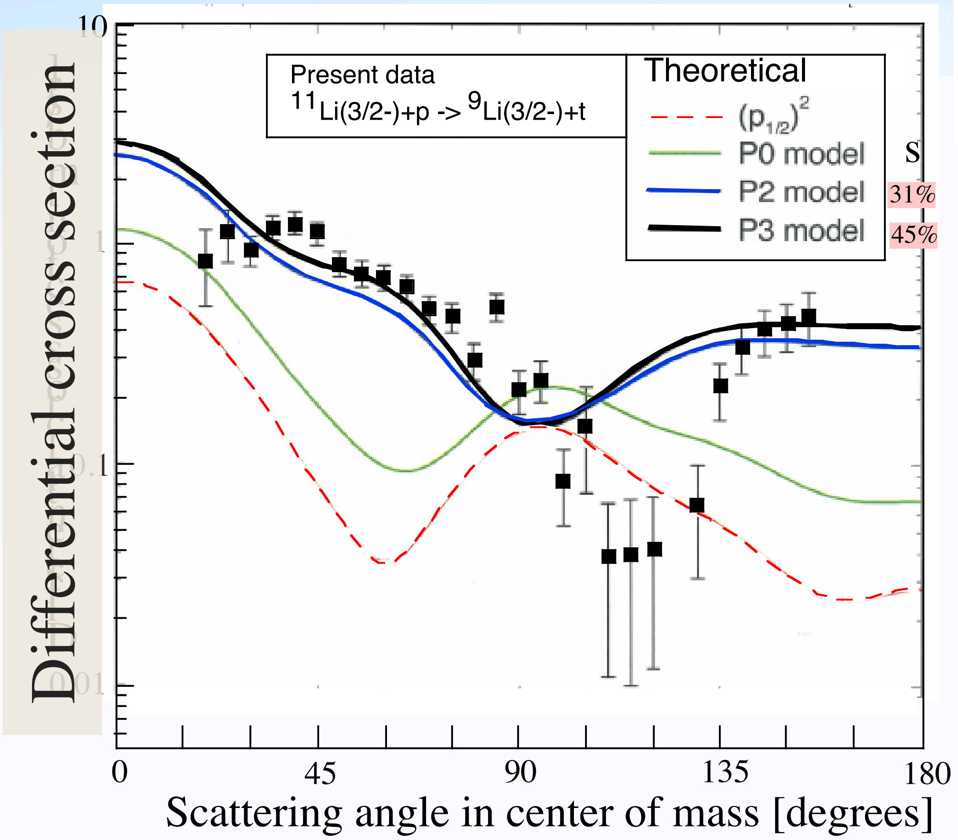


In more general p-n pairs from $(nlj)^2$ configuration to $(n+1,l+1,j)^2$ or $(n+1,l-1,j)^2$

s- and p- wave mixing in ^{11}Li

- Momentum distribution of fragments ^{10}Li
  - *Equal amount of $p_{1/2}$ and $s_{1/2}$. (Simon 1999)*
- Beta-decay
  - *30-40% $s_{1/2}$ wave and small amount of $p_{1/2}$ (Borge 1997)*
- two-neutron transfer reaction
  - *($^{11}Li+p$ --> $^{9}Li+t$)*
  - *31-45% $s_{1/2}$ and $p_{1/2}$*
  - *(Tanihata 2008)*





41% s

35% s

PHYSICAL REVIEW C   VOLUME 49, NUMBER 4   APRIL 1994

Effects of ^{10}Li virtual states on the structure of ^{11}Li

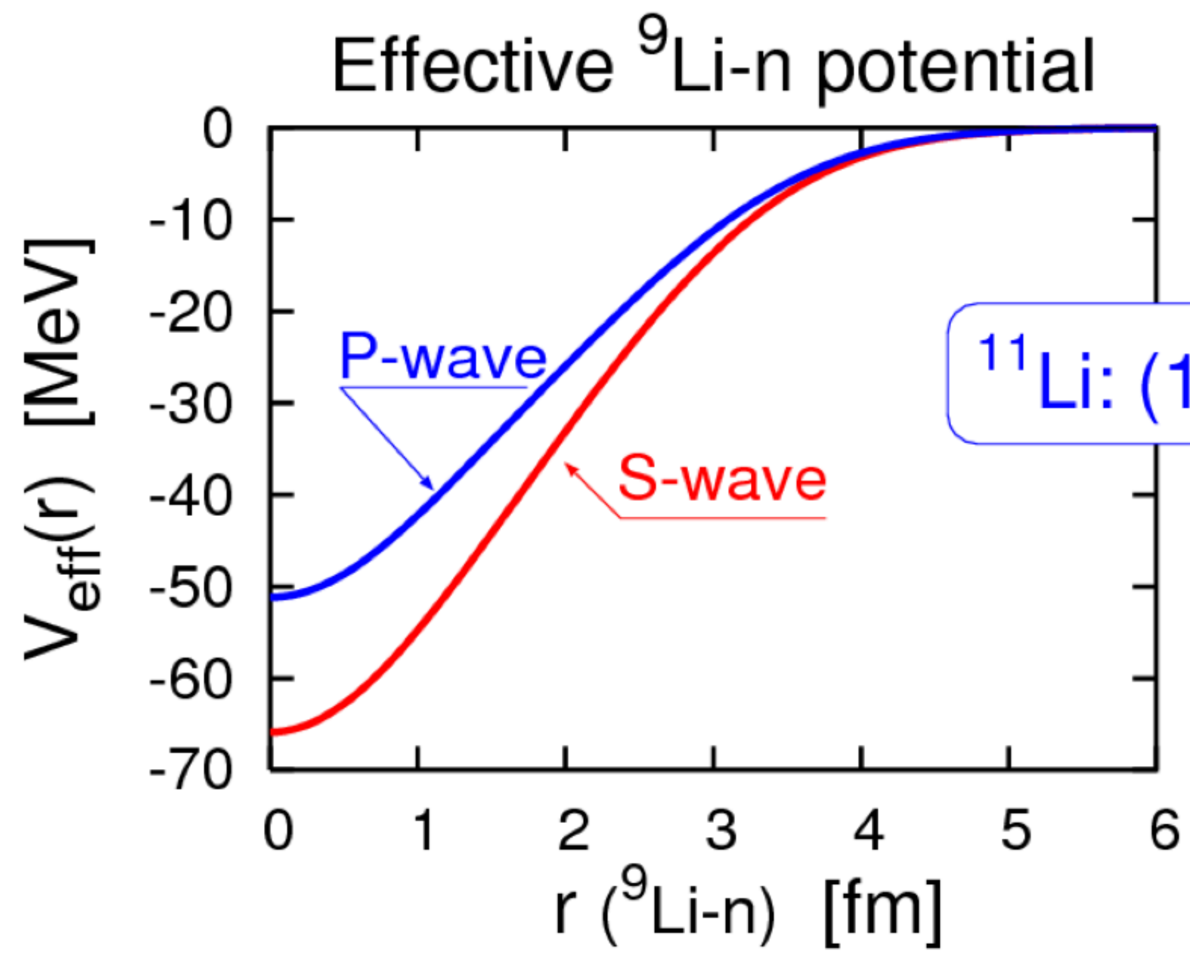
I. J. Thompson
Department of Physics, University of Surrey, Guildford GU2 5XH, United Kingdom

M. V. Zhukov
Department of Physics, Chalmers University of Technology and Göteborg University, S-41296 Göteborg, Sweden
(Received 8 July 1993)

The presence of a low-lying $1s_{1/2}$ virtual state in the $n+{}^9$Li system, when included in Faddeev three-body calculations, has a pronounced effect on the structure of the ^{11}Li halo. The resulting ^{9}Li momentum distributions, calculated in the Serber model, have a narrow width comparable with the experimental data. The structure of ^{11}Li would then have nearly 50% of s-wave motion between the neutrons and the core. The three-body system may also approximately fulfill the conditions for the appearance of Efimov states, and there may exist low-lying excited states near the breakup threshold.

PACS number(s): 21.60.Cs, 27.20.+n

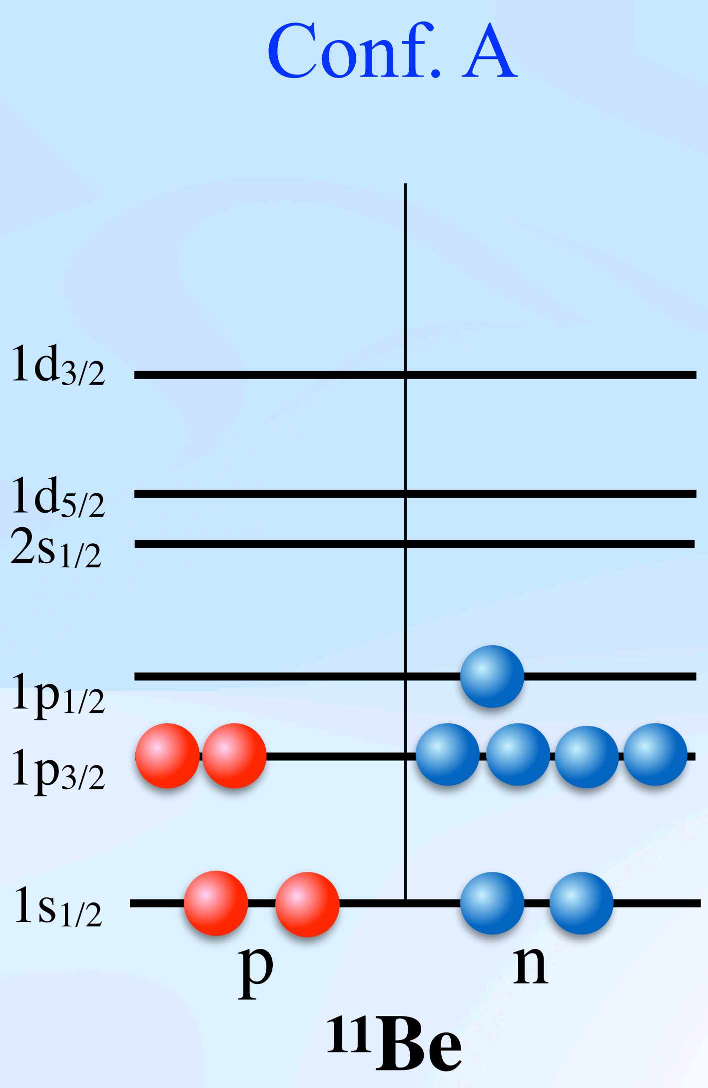
State-dependent potential for ^{9}Li(inert)+n+n



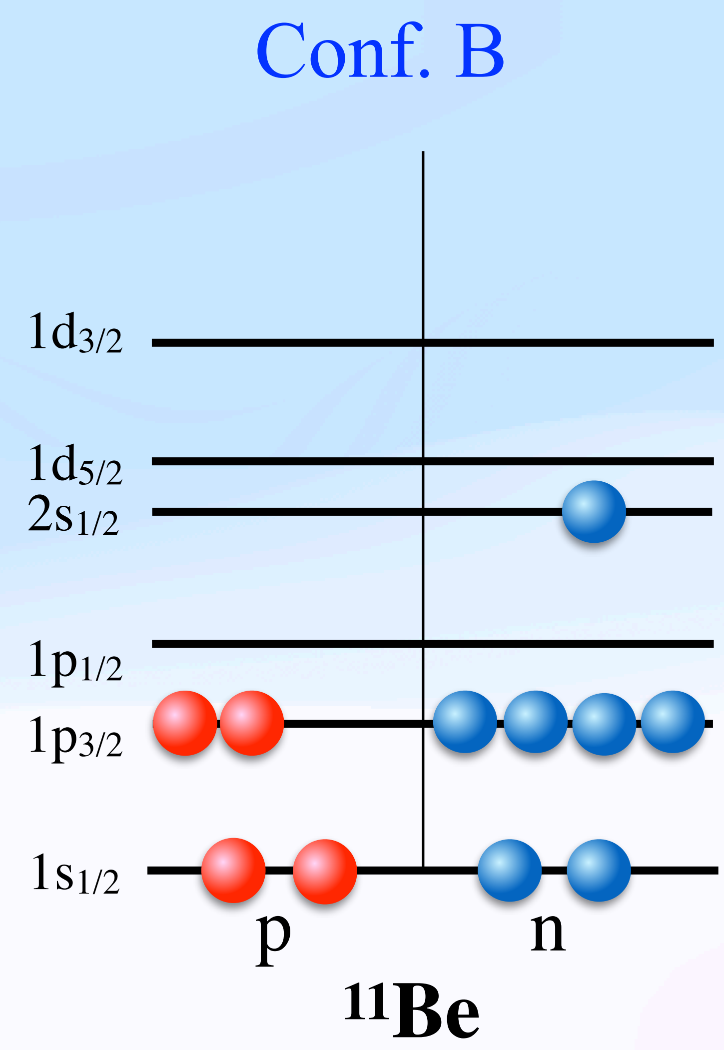
^{11}Li: $(1s)^2$=50%

Cf. I. J. Thompson and M. V. Zhukov PRC49(1994)
E. Garrido, D. V. Fedorov and A. S. Jensen, NPA708(2002)277.

Explanation of $s_{1/2}$ anomaly

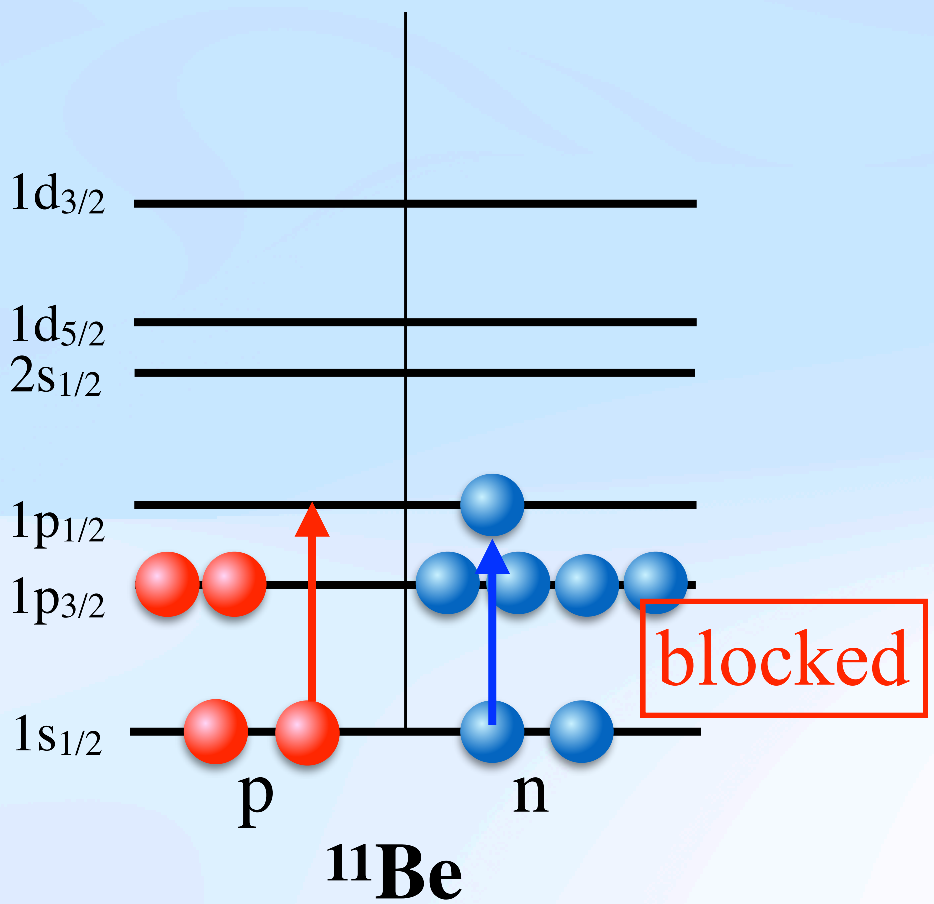


or



Explanation of $s_{1/2}$ anomaly

Conf. A



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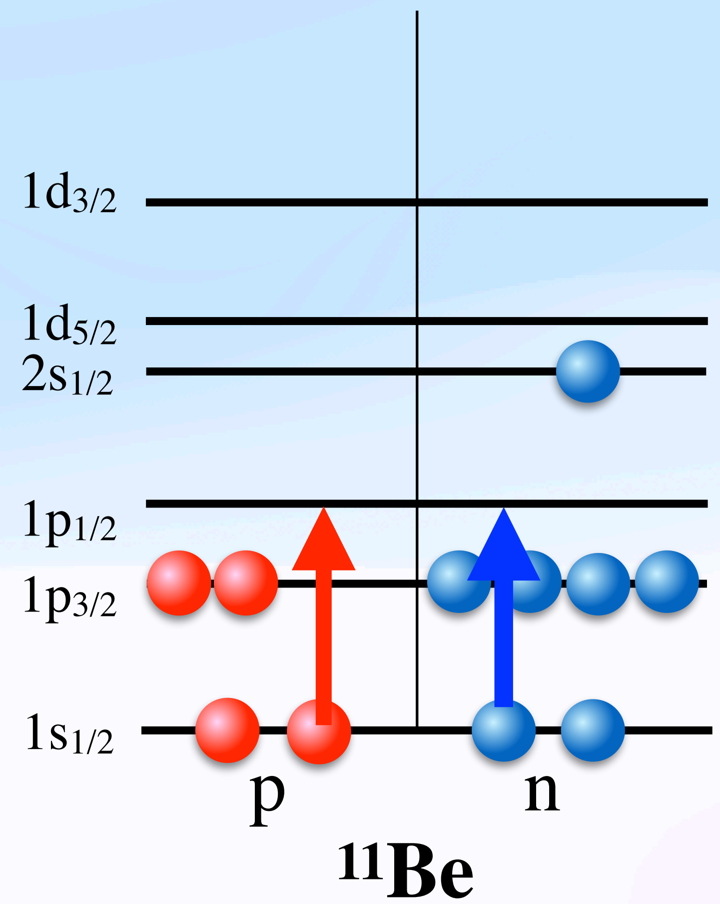
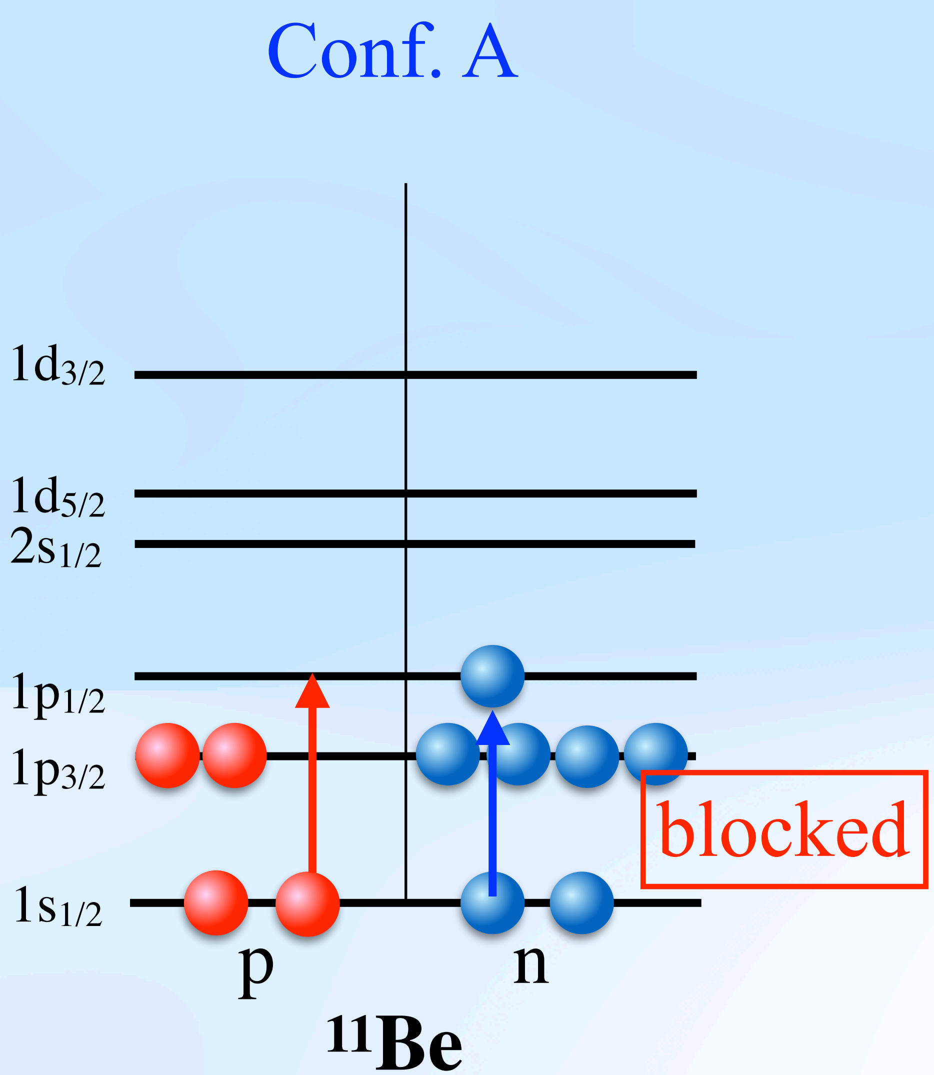
Conf. B



Explanation of $s_{1/2}$ anomaly



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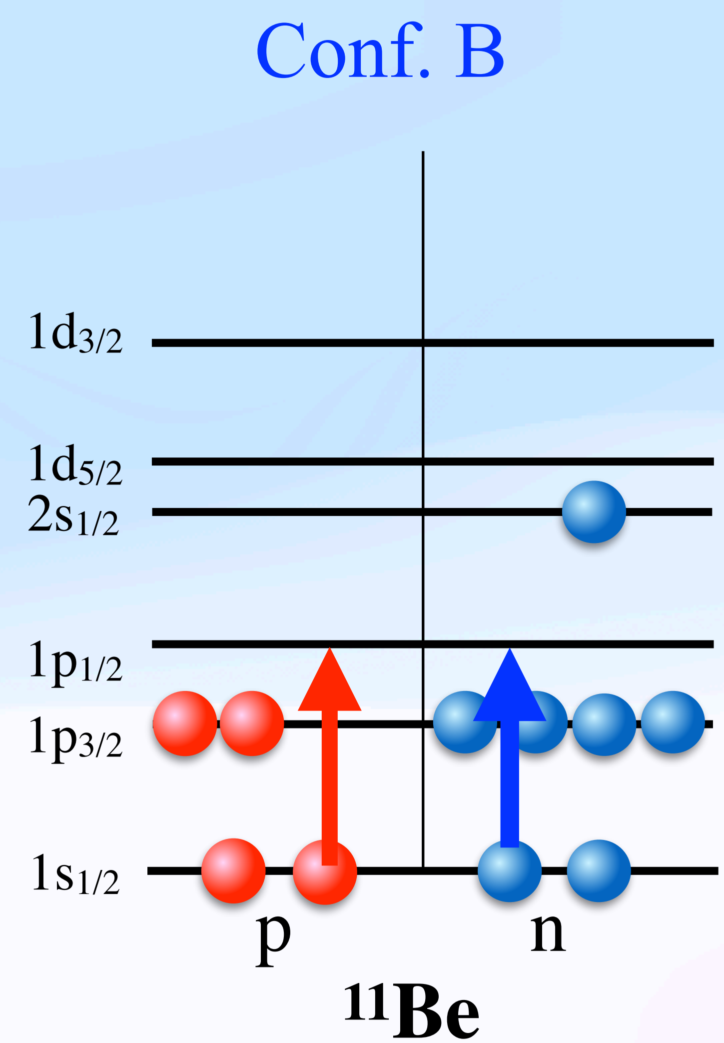
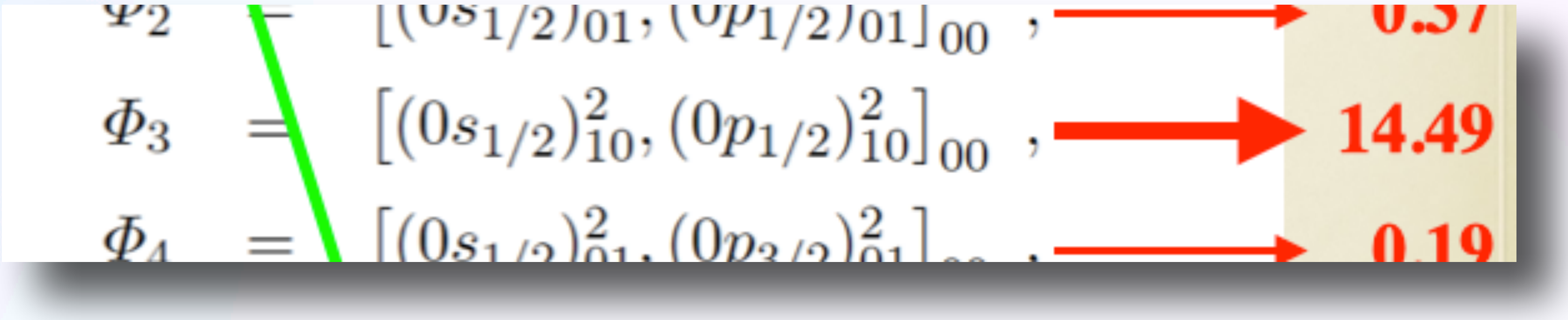




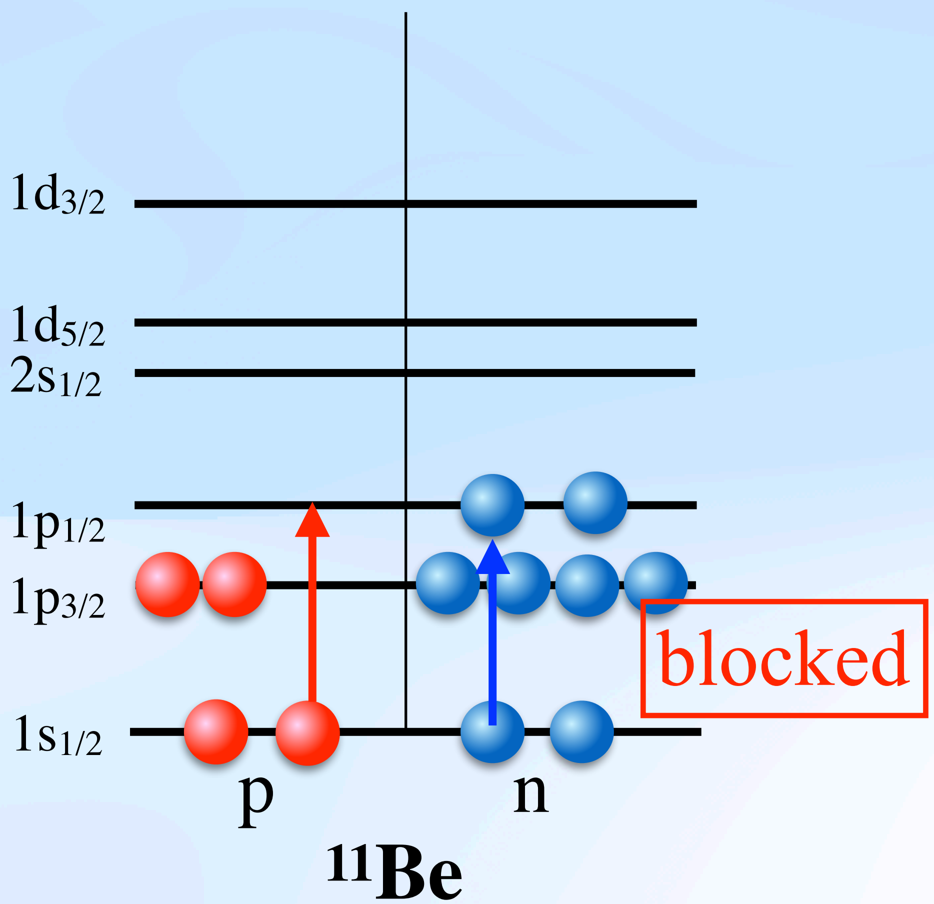
$$\Phi_3 = [(0s_{1/2})^2_{10}, (0p_{1/2})^2_{10}]_{00} \;,\; \rightarrow 14.49$$

$$\Phi_4 = [(0s_{1/2})^2_{01}, (0p_{3/2})^2_{01}]_{00} \;,\; \rightarrow 0.19$$

Explanation of $s_{1/2}$ anomaly

Conf. A

^{11}Li



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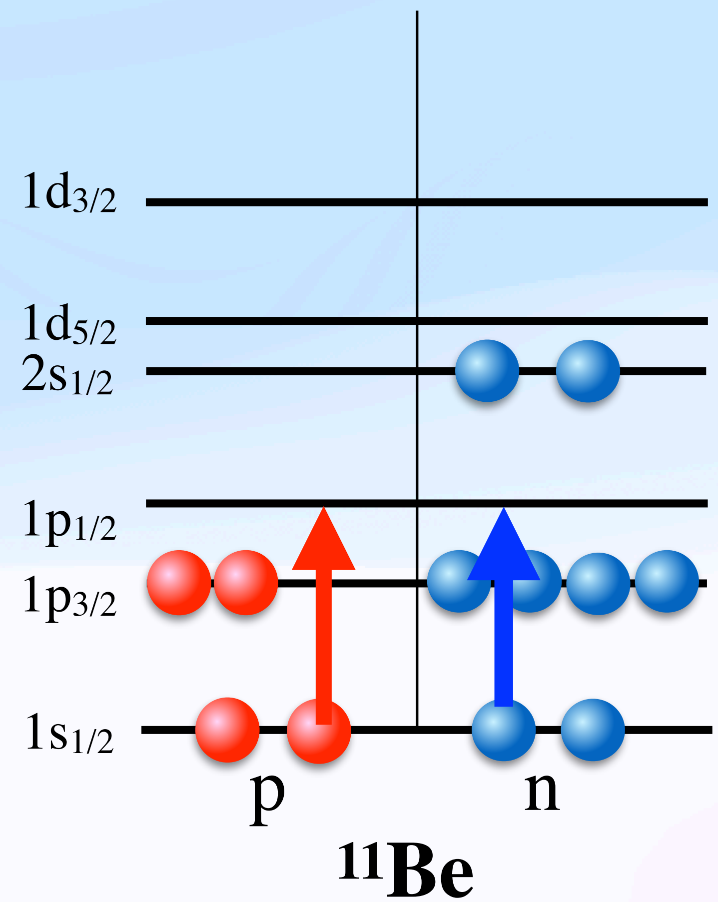

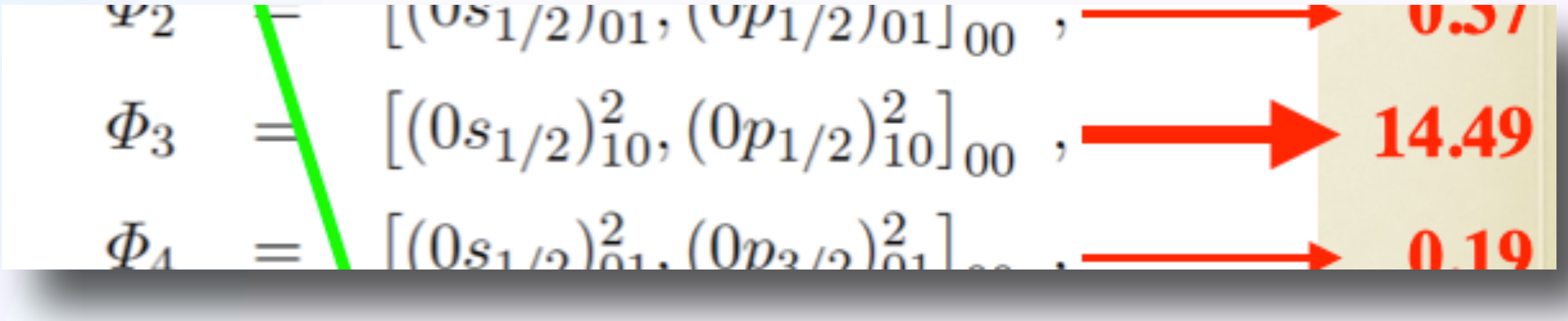

$\Phi_2 = [(0s_{1/2})^2_{01}, (0p_{1/2})^2_{01}]_{00}$, → 0.37

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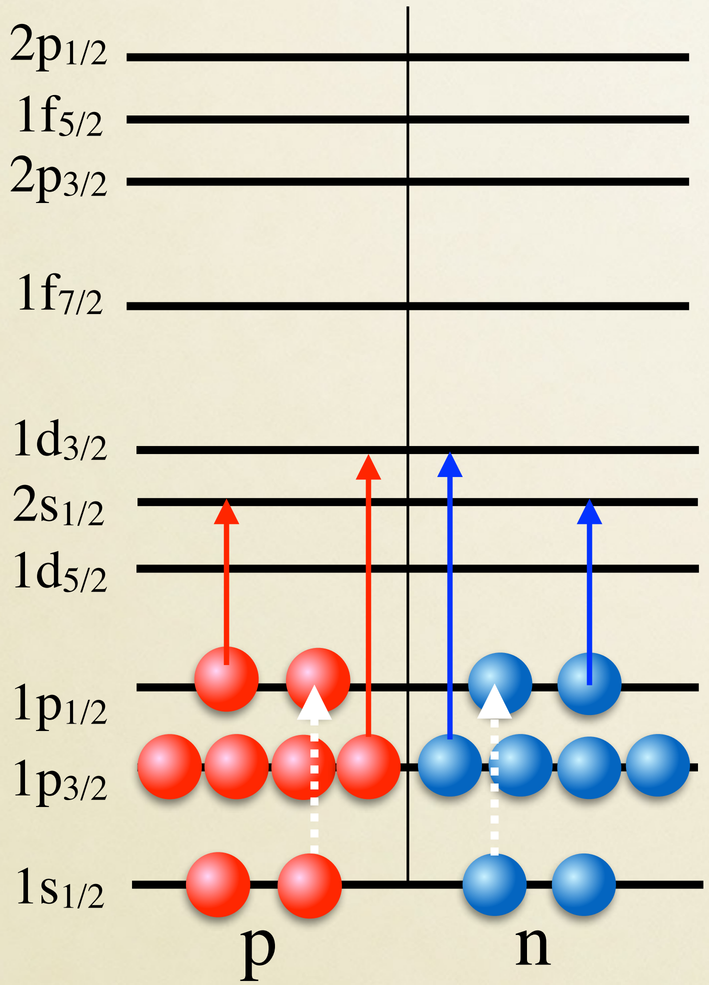
$\Phi_4 = [(0s_{1/2})^2_{01}, (0p_{3/2})^2_{01}]$, → 0.19

Difference between symmetric and neutron rich nuclei?

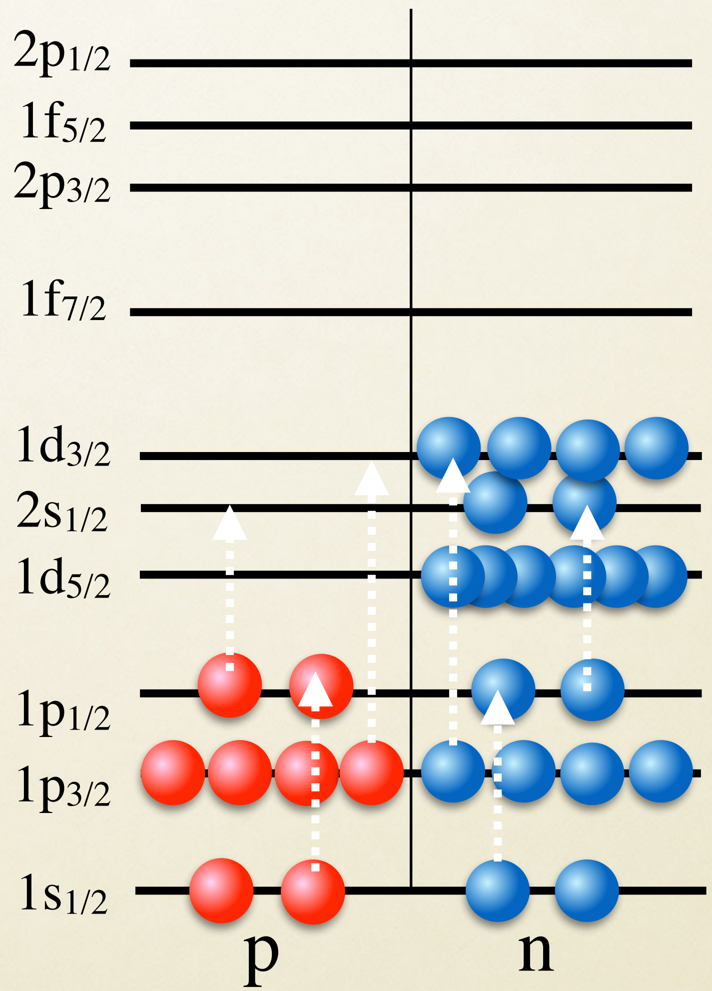
Symmetric nuclei



^{16}O

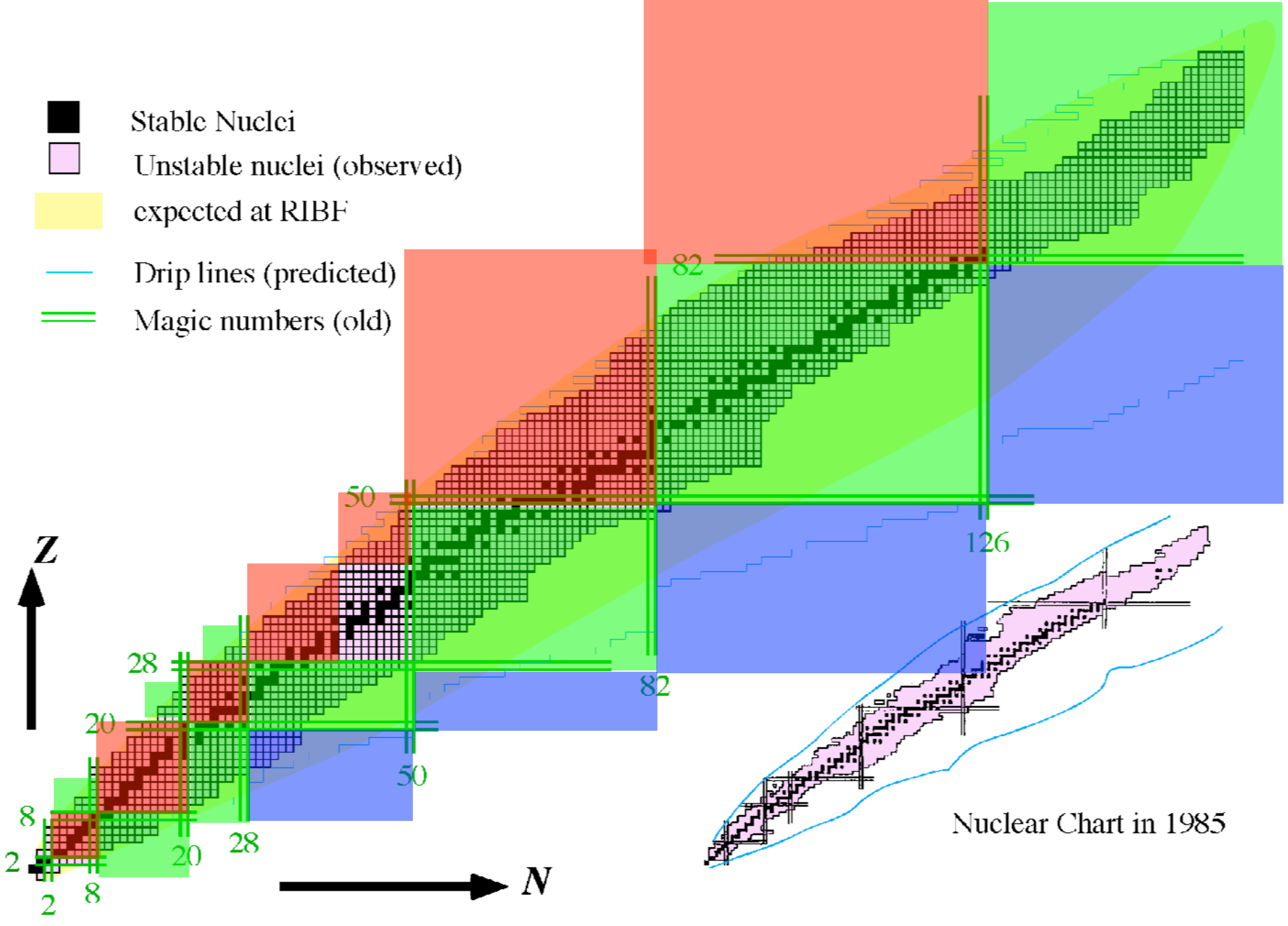
Blocking and Opening occur simultaneously.

Neutron rich nuclei

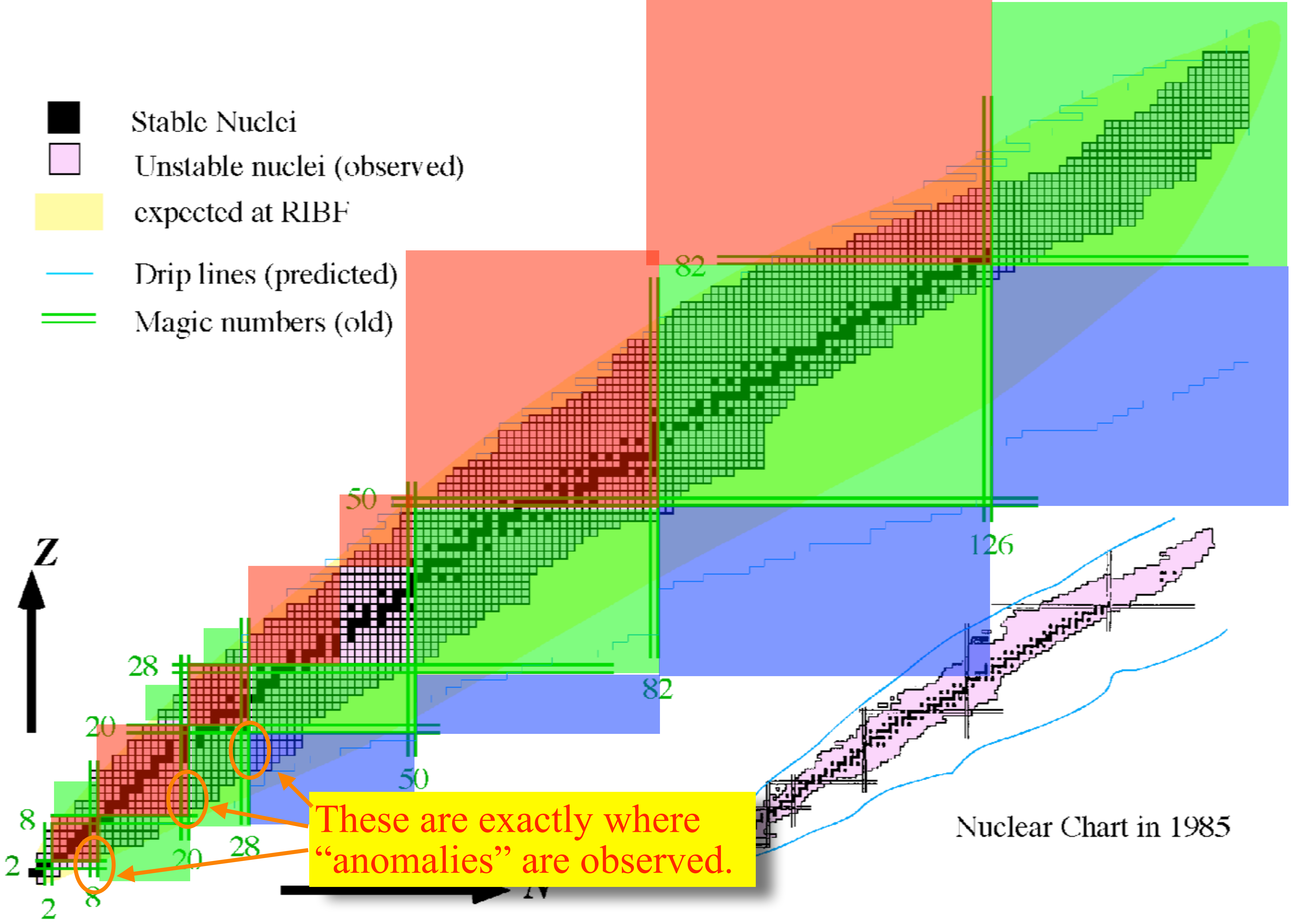


^{28}O

Only tensor blocking occurs.



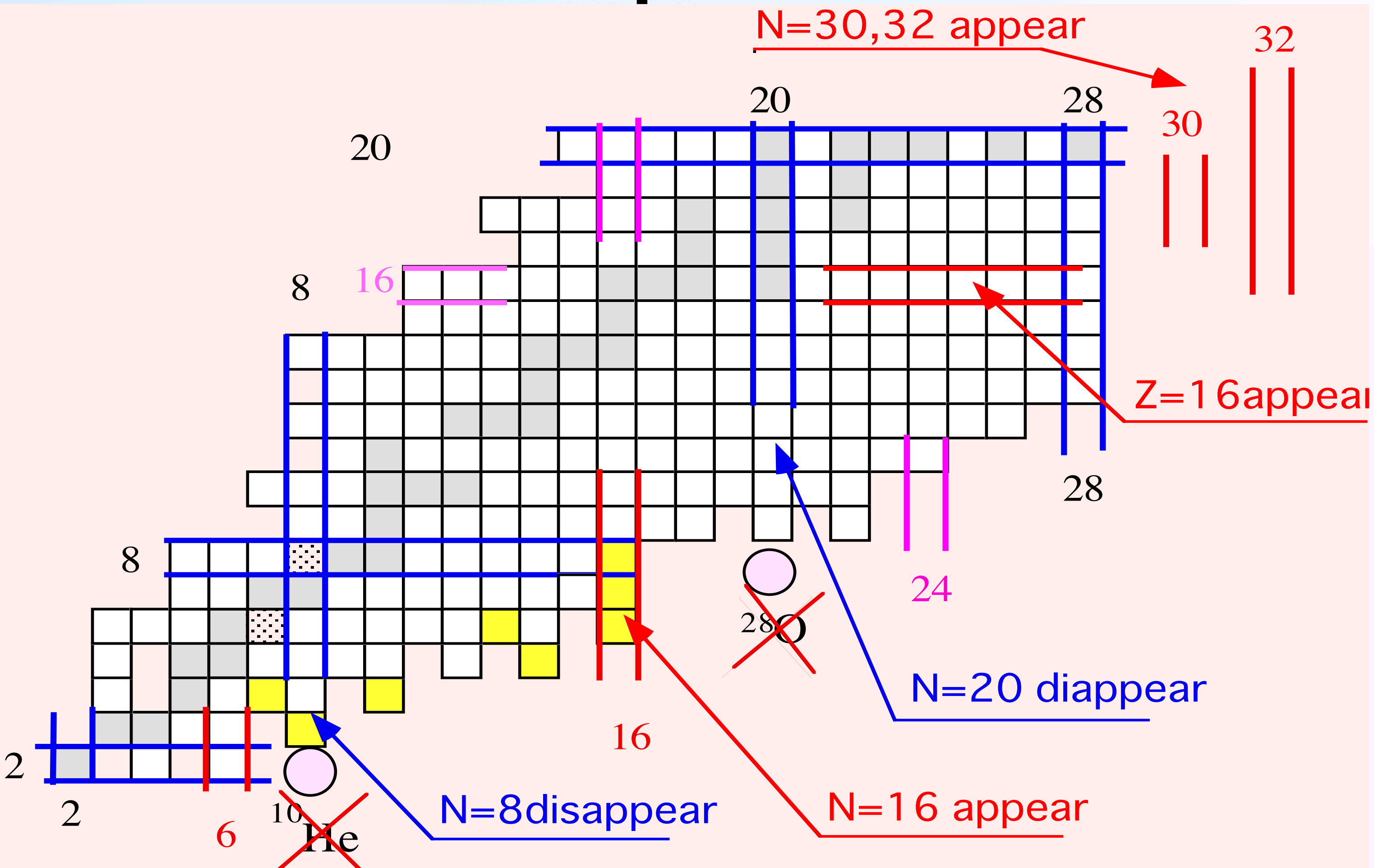
Stable Nuclei
Unstable nuclei (observed)
expected at RIBF
Drip lines (predicted)
Magic numbers (old)
Z
N
2
8
20
28
50
82
126
Nuclear Chart in 1985



Stable Nuclei
Unstable nuclei (observed)
expected at RIBF
Drip lines (predicted)
Magic numbers (old)
Z
N
82
50
126
28
20
8
2
These are exactly where "anomalies" are observed.
Nuclear Chart in 1985

Tensor blocking explains not only the behavior of $s_{1/2}$ orbital but also explains,

- **Why doubly magic number nuclei ^{10}He, ^{28}O is unbound,**
- **Why neutron magic numbers 8, 20 disappears in neutron-rich nuclei,**
- **Appearance of new magic numbers 6, 14, 16, 32, 34,**
- **Why drip line suddenly extend a lot in F isotopes.**



I. Tanihata, J. of Physics. CS vol.1643 (2020) 012109.

High momentum component in ground states of nuclei
= Shell dependent contributions =

- **The existence of high-momentum components in nucleons is observed in e-scattering and proton scattering.**
  - ***J. Arrington, N. Somin, and A. Schmidt, Ann. Rev. Nucl. Part. Sci. 72 (2022) 307.***

- **High momentum pairs are there in ground states of nuclei.**
- **High-momentum pairs are important to provide a large amount of binding energy through tensor interactions.**

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In general this effect is considered just to cut the shell model space restricting only low momentum nucleons. Say Depletion of spectroscopic factors.

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Ground state properties are strongly affected by High-Momentum Nucleons.

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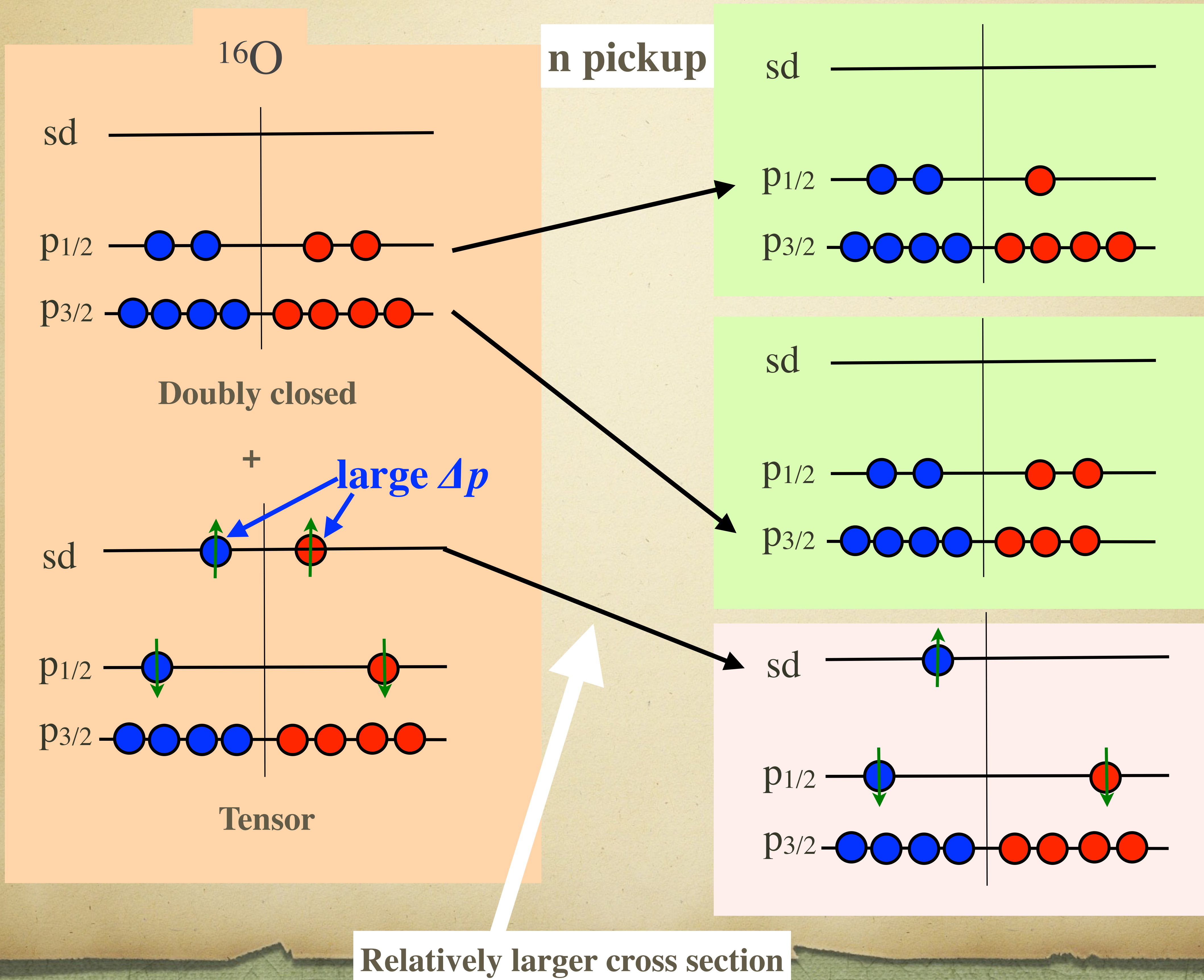
- **High-momentum pairs are important to provi ... of binding energy through tensor interactio**

Can we see enhancement of high-momentum nucleons in 2p-2h excitations?

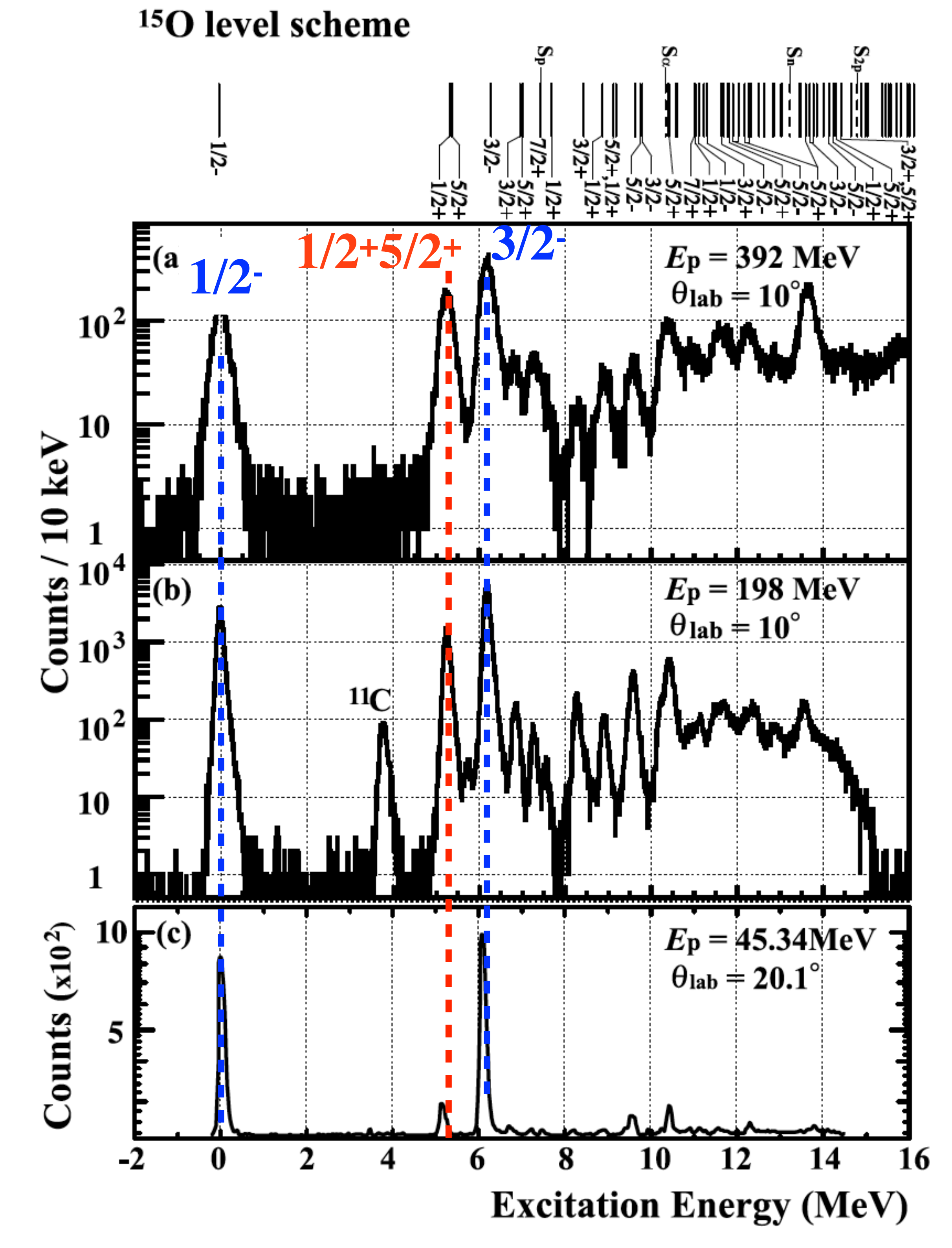
... properties are strongly affected ... y High-Momentum Nucleons.

- **Because of the strong selection rules, tensor interactions affect orbitals differently based on their quantum numbers.**
- **State by state differences of the tensor contributions make exotic behaviors of nuclear structure.**
- **It can be observed as state by state difference of high-momentum components.**

^{16}O and (p,d) reaction



Energy dependence of the cross sections



Study the ratio of the positive parity/negative parity final states

H.-J. Ong et al., Phys. Lett. B 725, 277-281 (2013)

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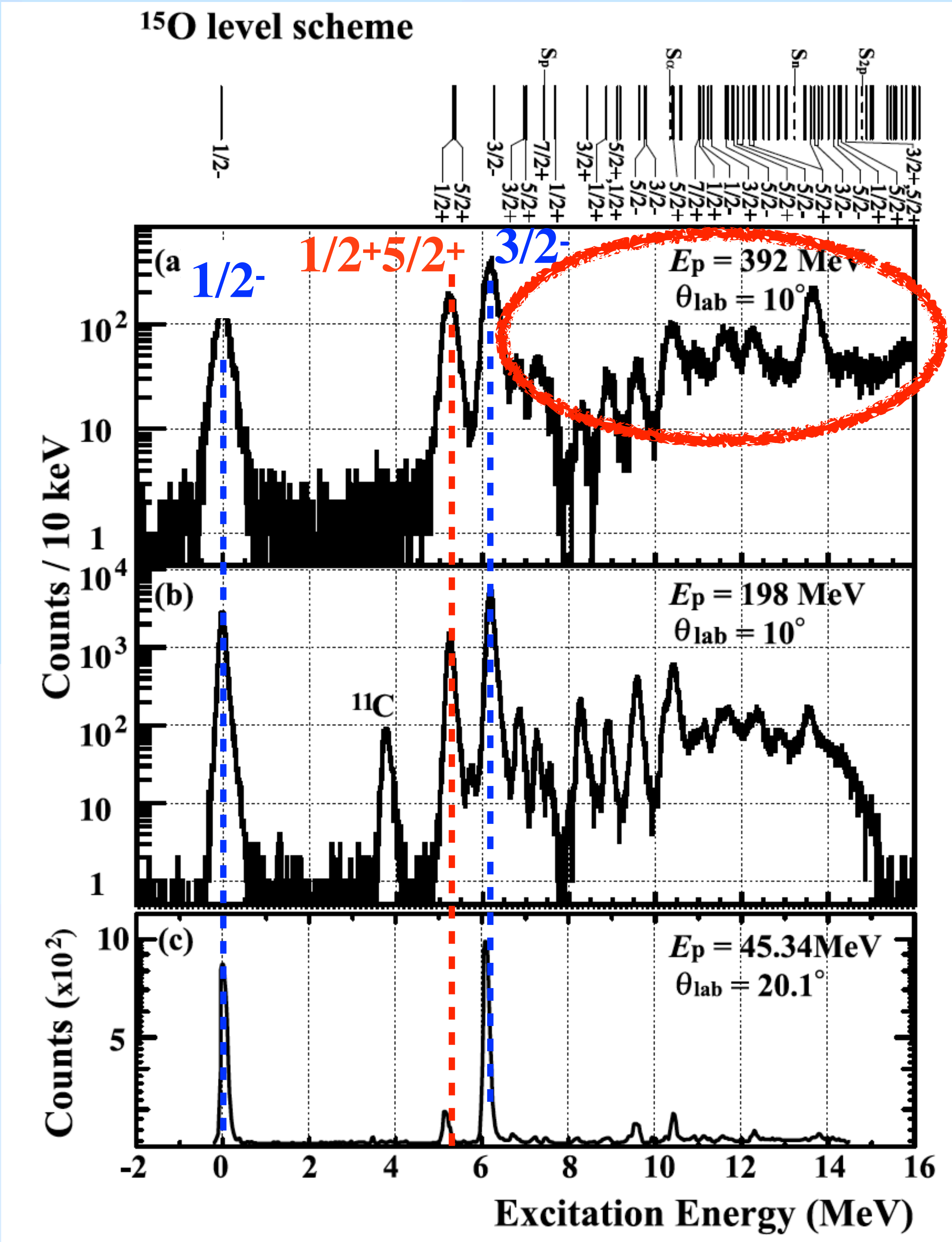

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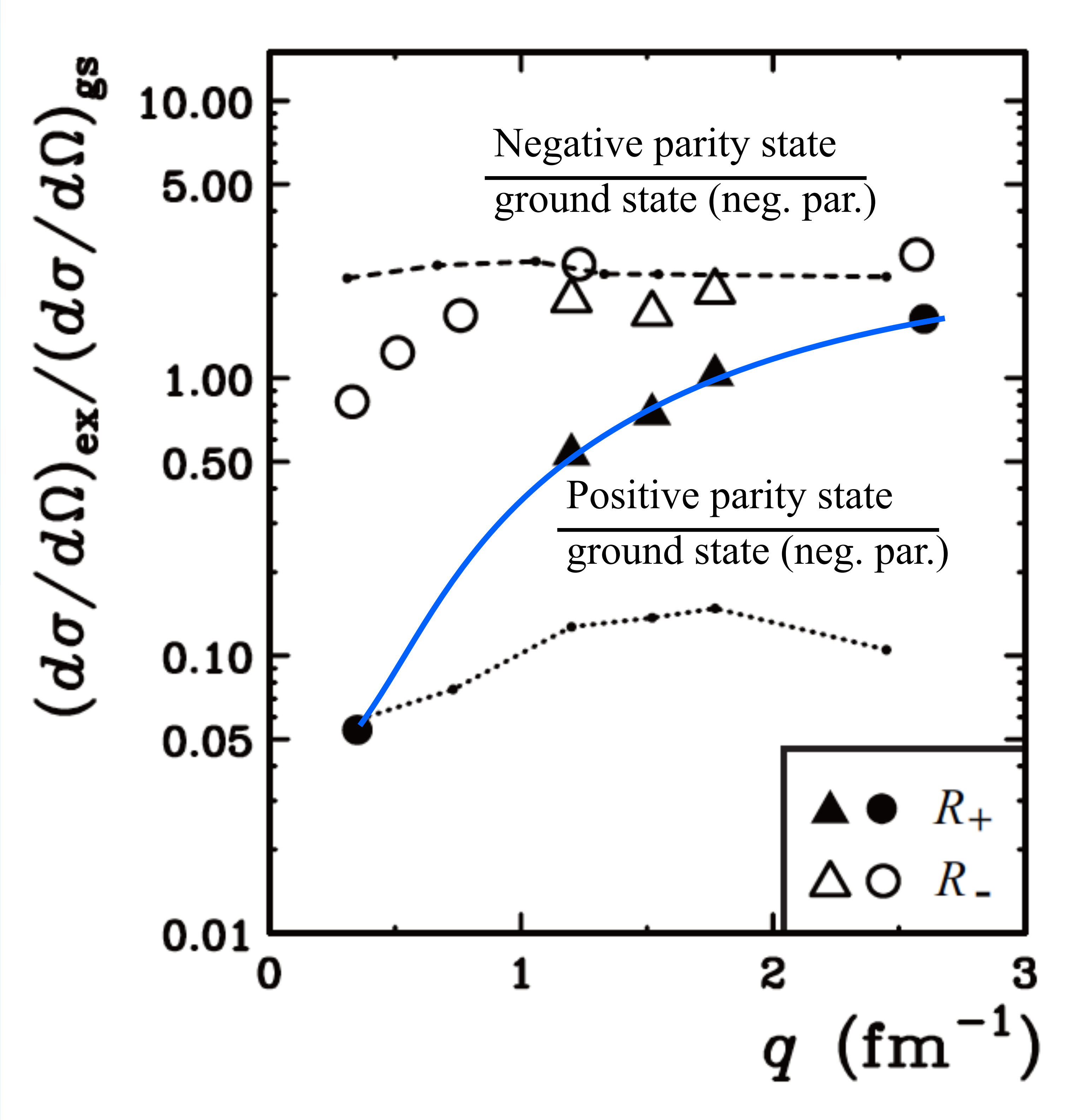
Ratio of the $^{16}O(p,d)^{15}O^*$ cross sections to the gs transitions

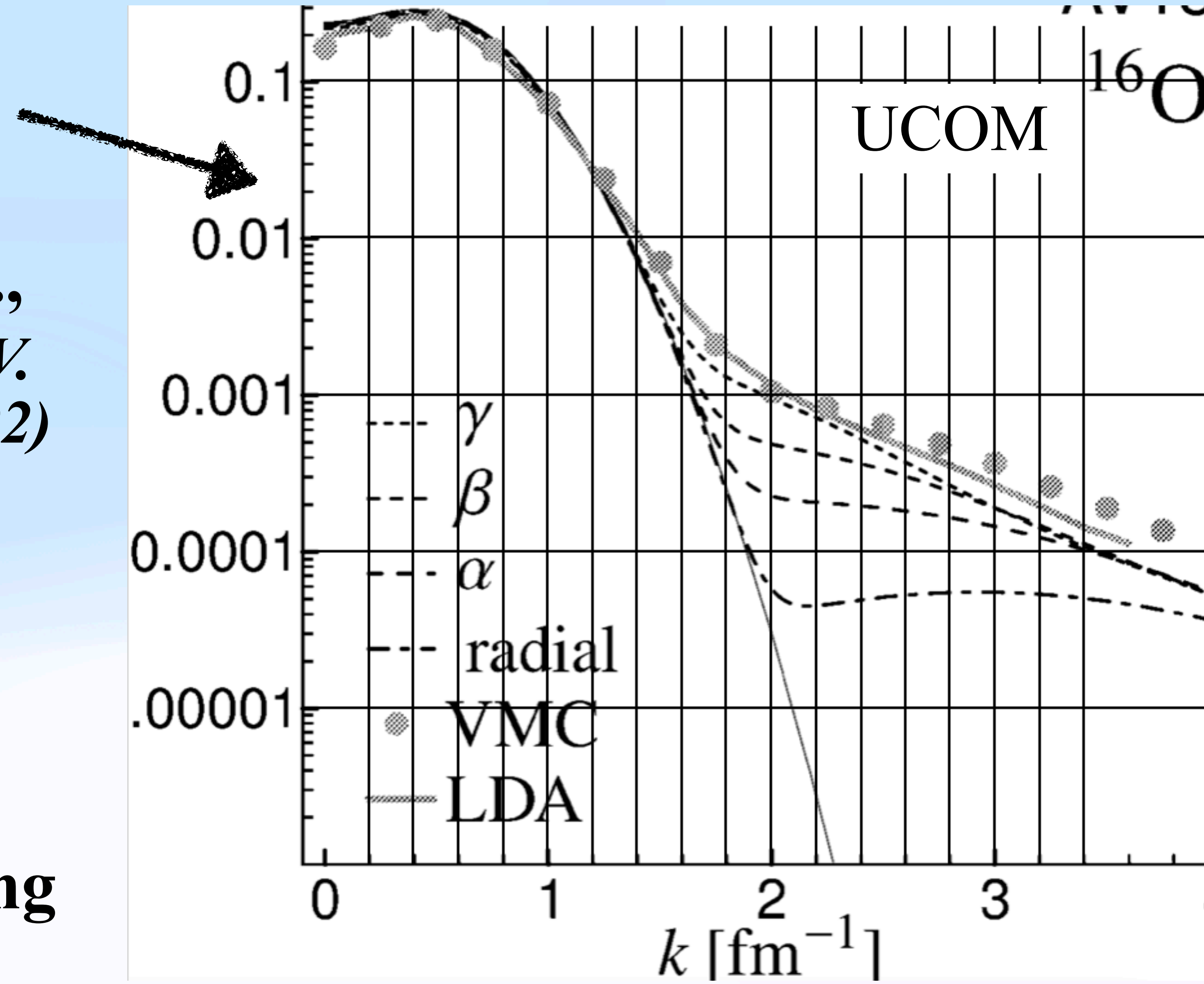


The dashed (dotted) curve represents the ratios of the 1p3/2 (1d5/2) and 1p1/2, obtained by zero-range CDCC-BA calculations with finite-range correction using the Dirac phenomenological potentials. (by K. Ogata)
Wavefuncions are from Wood-Saxon potential.

H.-J. Ong et al., Phys. Lett. B 725, 277-281 (2013)

Theoretical model predictions

- **UCOM calculation,**
  - ***T. Neff and H. Feldmeier, Nucl. Phys. A 713, 311 (2003).***
- **Variational Monte Carlo calc.,**
  - ***S.C. Pieper, R. B. Wiringa, and V. R. Pandharipande, PRC 46 (1992) 1741.***
- **Fermi hyper netted chain integral equation method,**
  - ***A. Fabrocini and G. Go PRC 63 (2001) 044319.***
- **Linked and number conserving cluster expansion method,**
  - ***M. Alvioli, C.C.D. Atti, and H. Morita, PRL 100 (2008) 162503.***



Comparison with models

X. Wang, F.J. Ong, S. Terashima et al., Submitted for publication

- **All models predict peak near 2 fm^{-1}.**
- **Data also show a peak near 2 fm^{-1}.**
- **The height of the peak is strongly depends on the assumptions to obtain the ratio from model momentum amplitudes.**

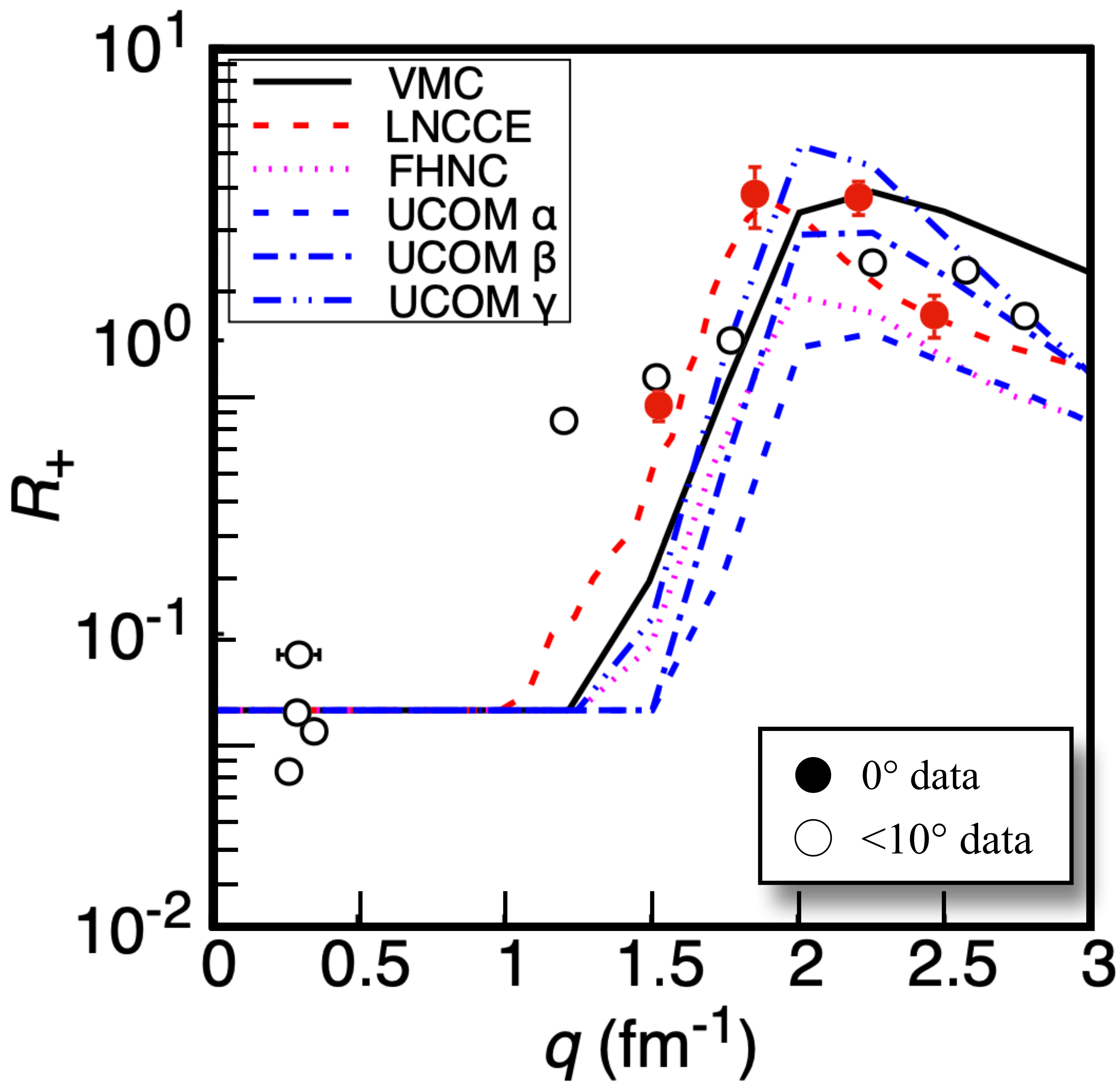
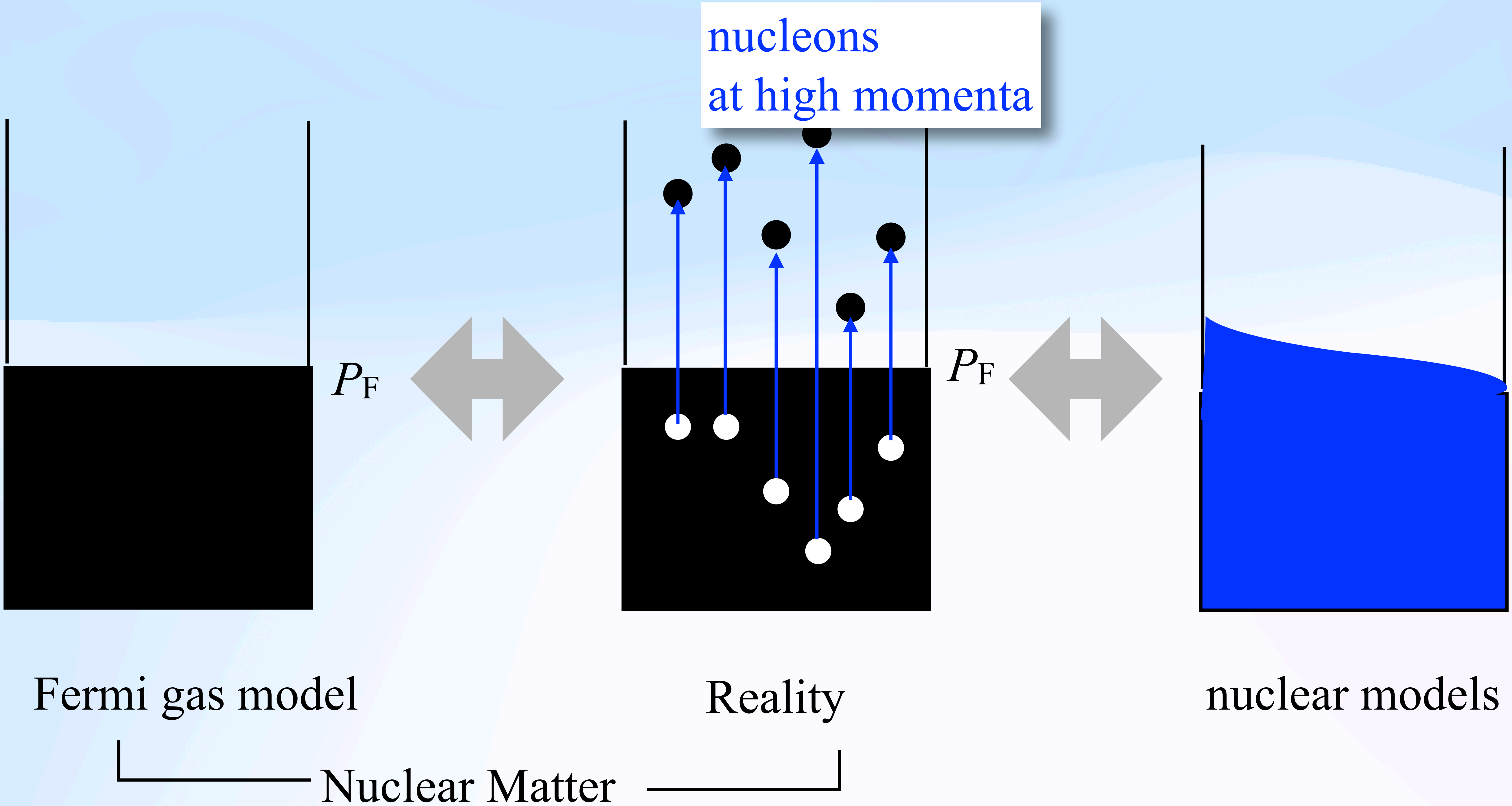


FIG. 4. Comparison of the cross-section ratios between experimental data and theoretical calculations. Filled symbols

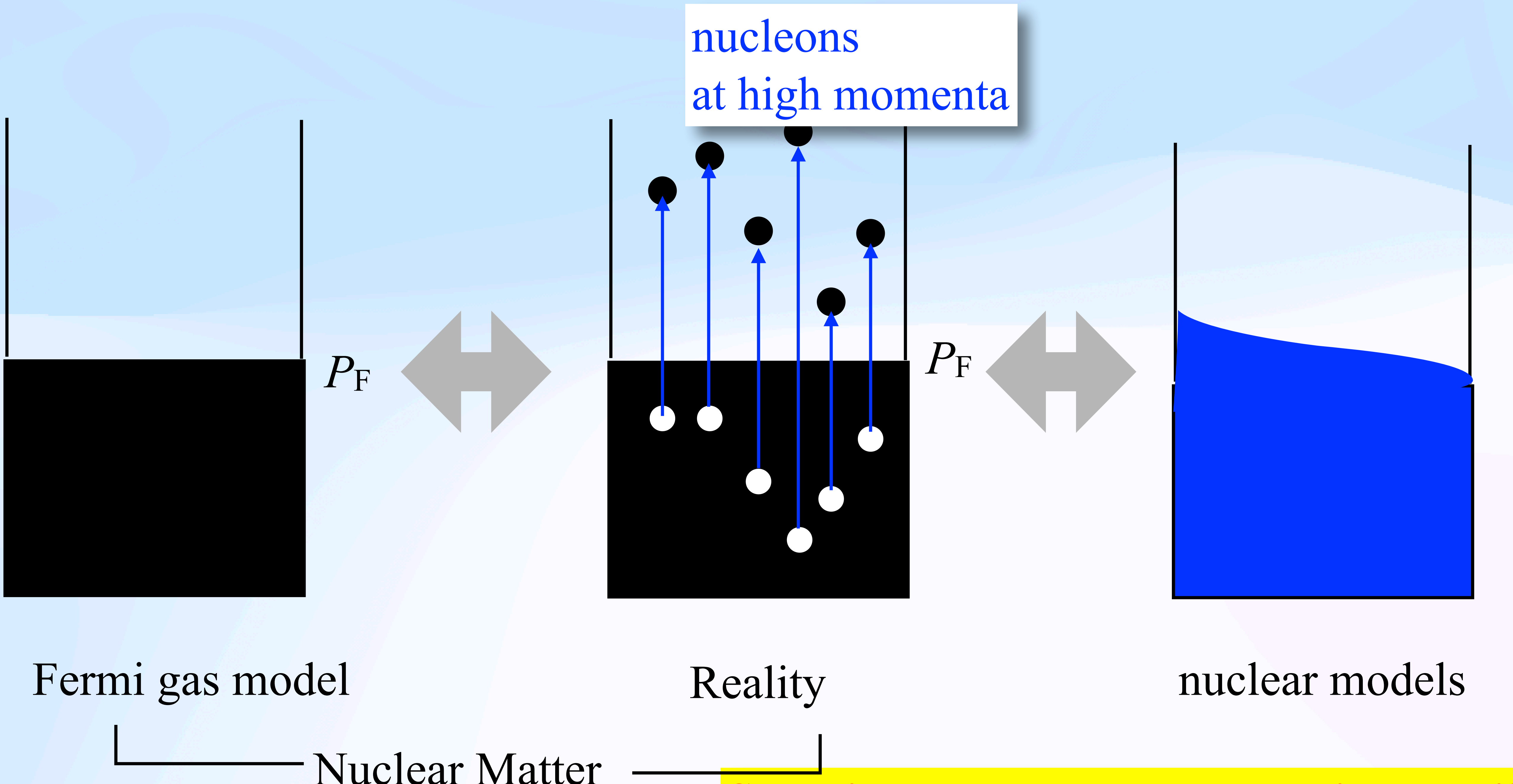
High momentum space in nuclei

- **Nuclear matter**
  - ***E/A = 16 MeV, ρ = 1.6 nucleons/fm³, P_F ~ 1.2 fm⁻¹.***



High momentum space in nuclei

- **Nuclear matter**
  - ***E/A = 16 MeV, ρ = 1.6 nucleons/fm^3, $P_F \sim$ 1.2 fm^{-1}.***



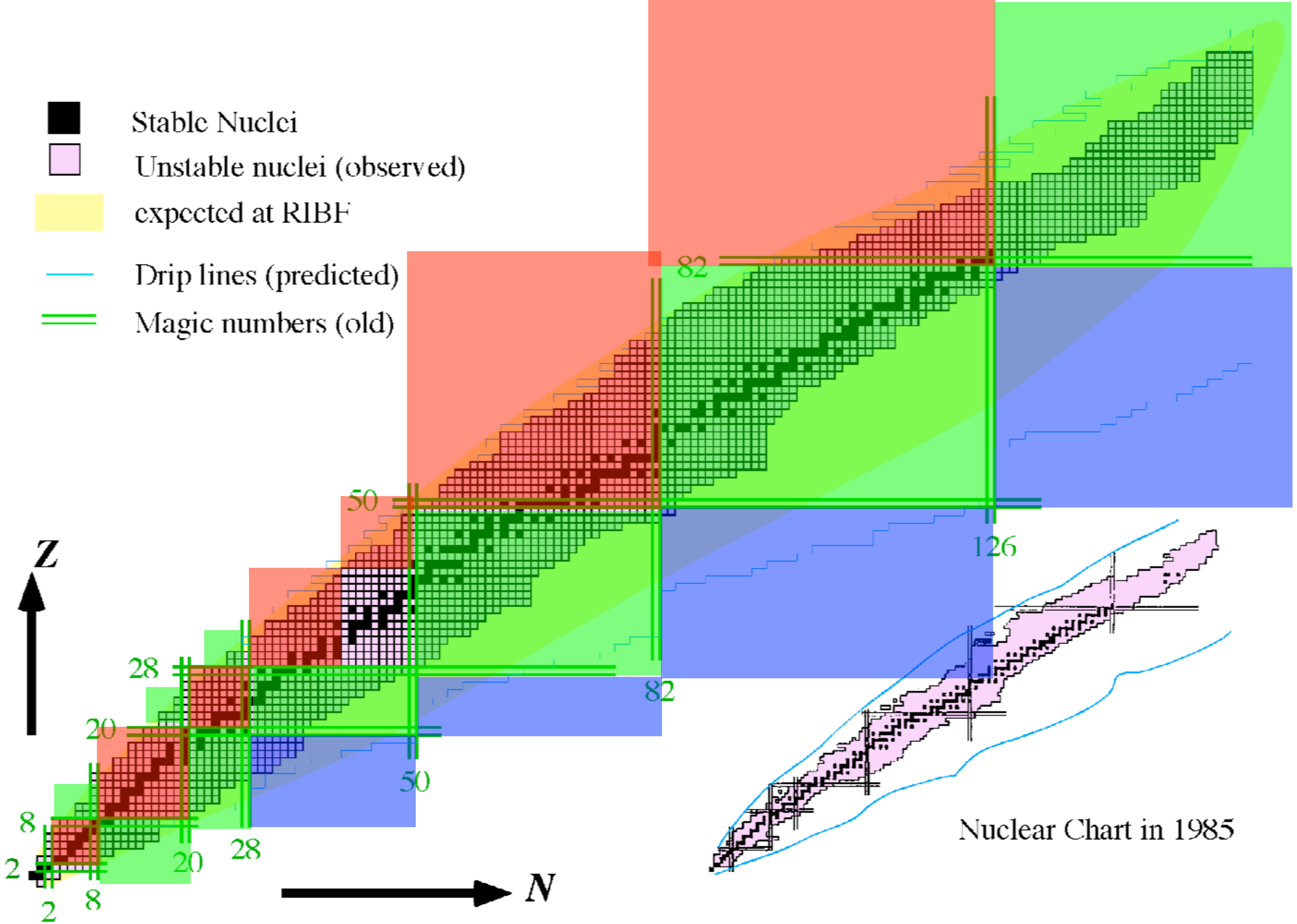
Selection rules apply strongly in nuclei!

Summary

- **Tensor interactions strongly affect the properties of nuclei at ground state and other low lying states.**
- **Blocking of the 2p-2h excitations (Tensor blocking) change the orbitals of g.s. and low-lying states of nuclei.**
- **Those effects are due to high-momentum nucleons in nuclei which contribute strongly to the tensor interactions.**
- **High-momentum neutrons in a 2p-2h state has been observed.**

We need,

- **nuclear-structure theory that includes tensor interactions and high-momentum nucleons to understand nuclei near and far from the stability line simultaneously.**
- **reaction theory that can treat (p, d) reactions well at higher energies.**
- **more experiments directly show tensor effects at low energy properties.**



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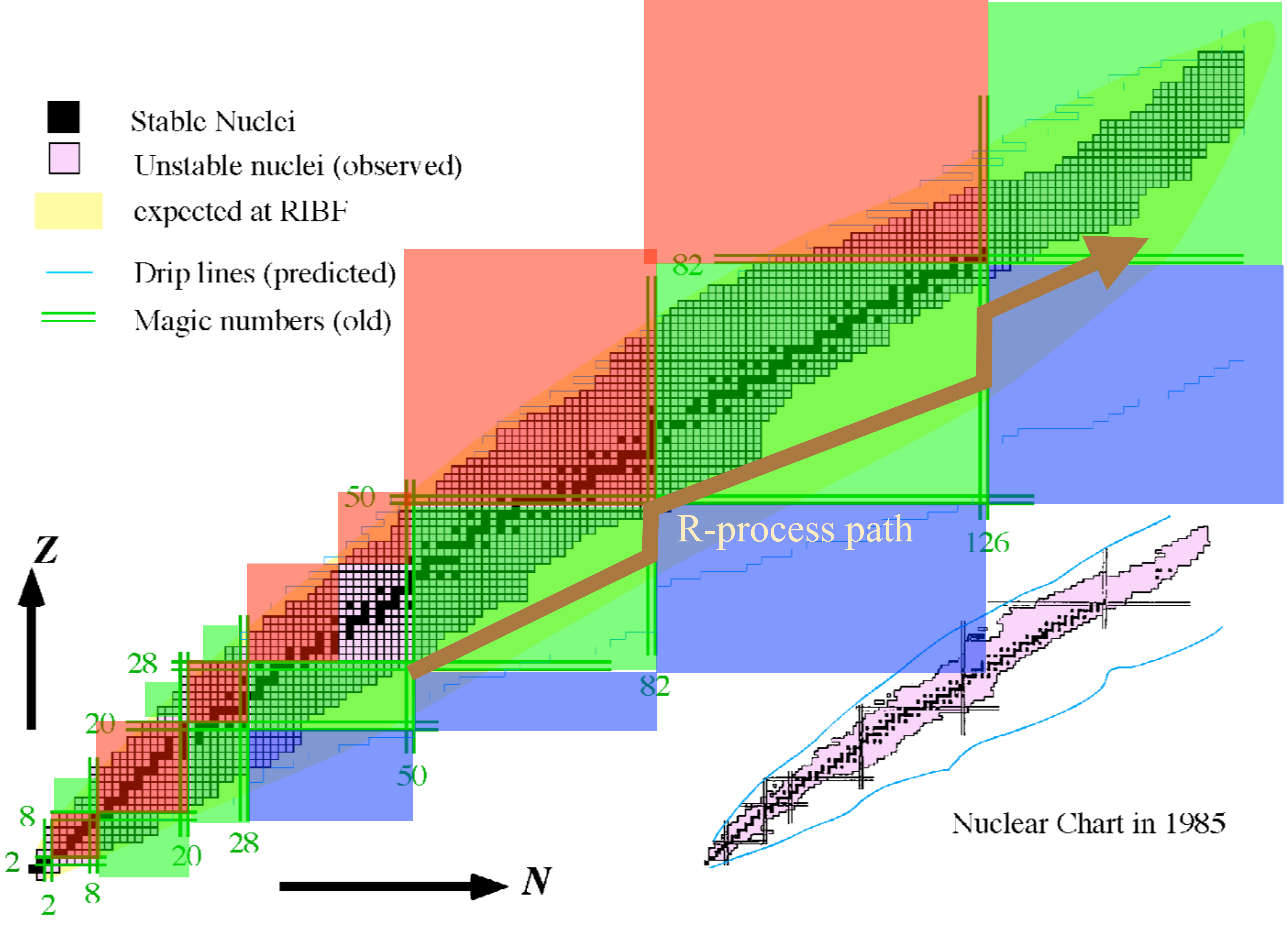

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