Characterizing neutron 0p-1s0d single-particle evolution in neutron-rich nuclei

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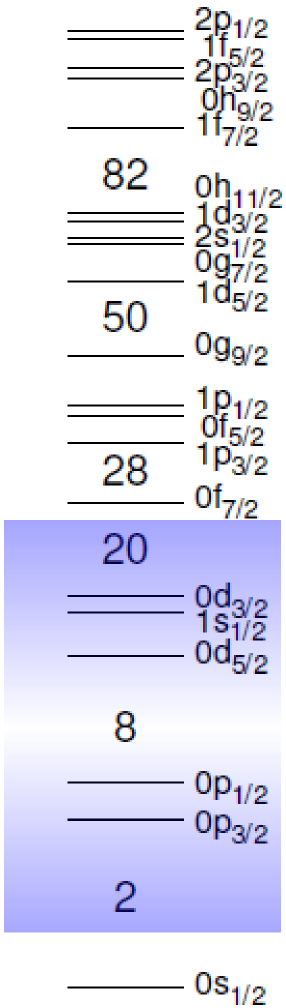
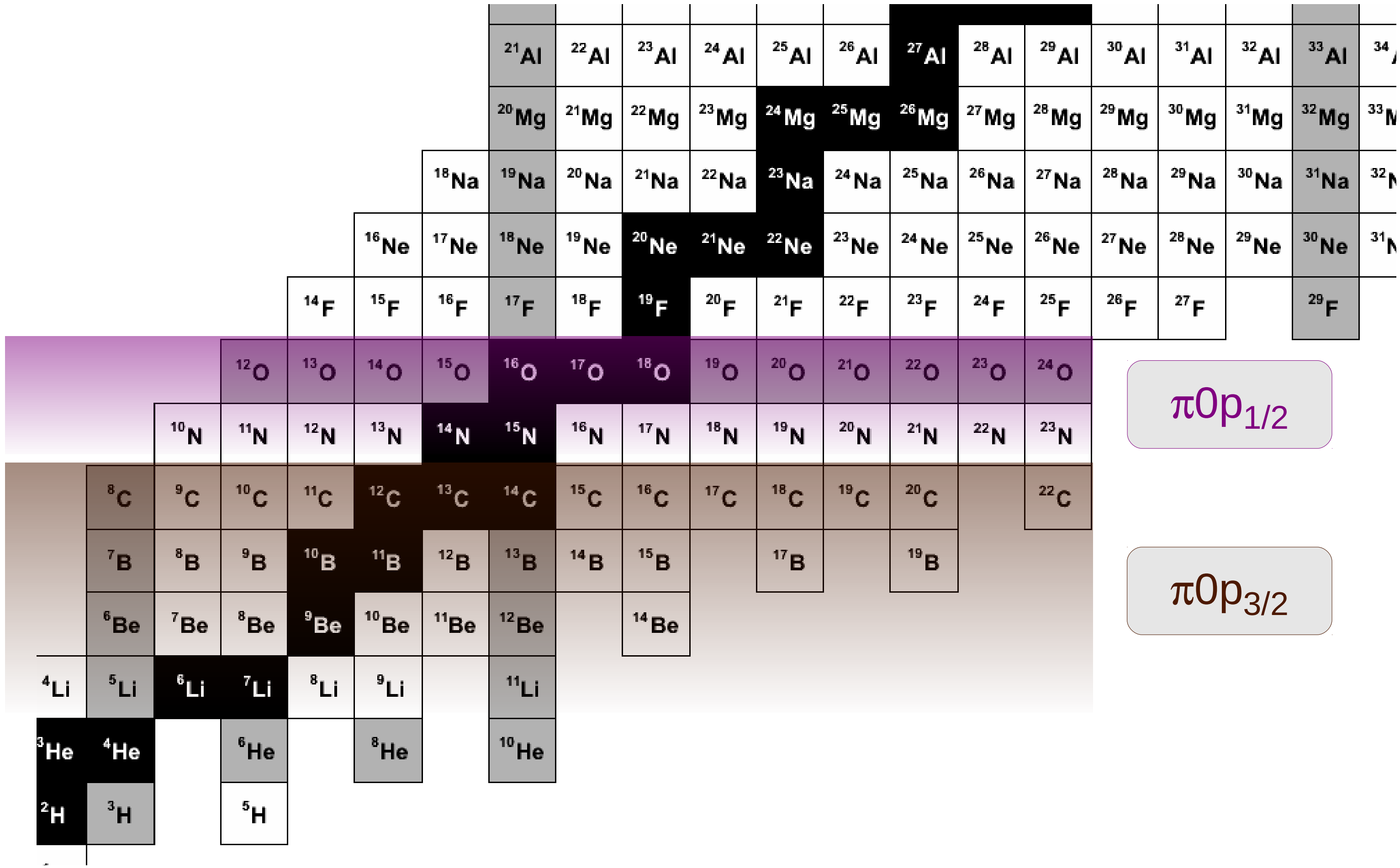
Outline

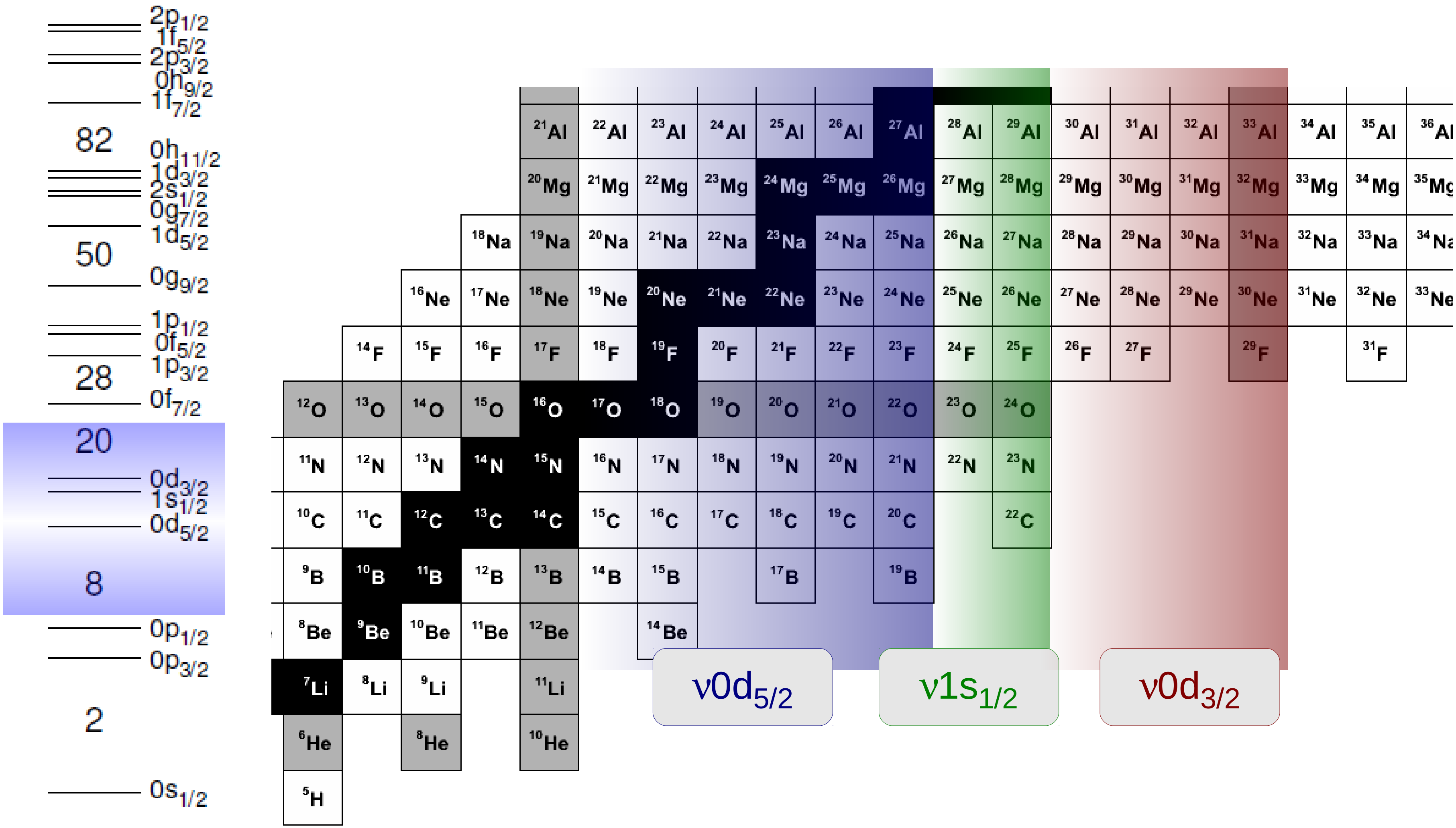
- The 0p-1s0d shell region
- In proximity to the oxygen drip line
  - Drip line anamoly (Z = 8 & 9)
  - Evolution of SPE's
  - Recent measurements
  - Systematics and comparisons with theory
- Direct reactions in 0p-1s0d nuclei
  - ^{19}O(d,p)^{20}O and ^{17}N(d,p)^{18}N
  - SPE's as functions of proton and neutron occupancies
  - HELIOS at Argonne National Laboratory
  - Recent results
- Conclusions, outlook, and future work

The *0p-1s0d* shell region

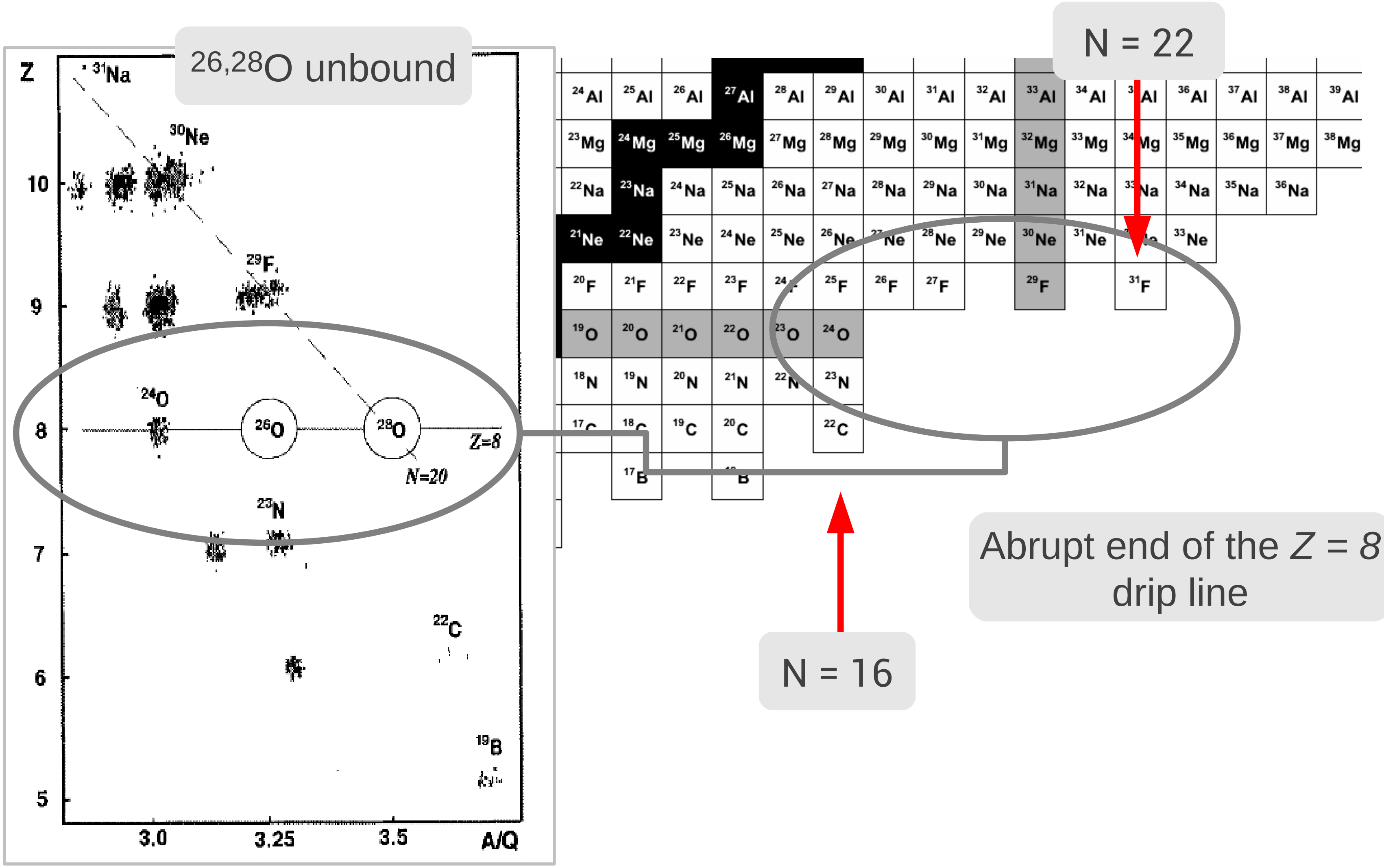




The neutron *sd* shell region (*N* = 9 - 20)



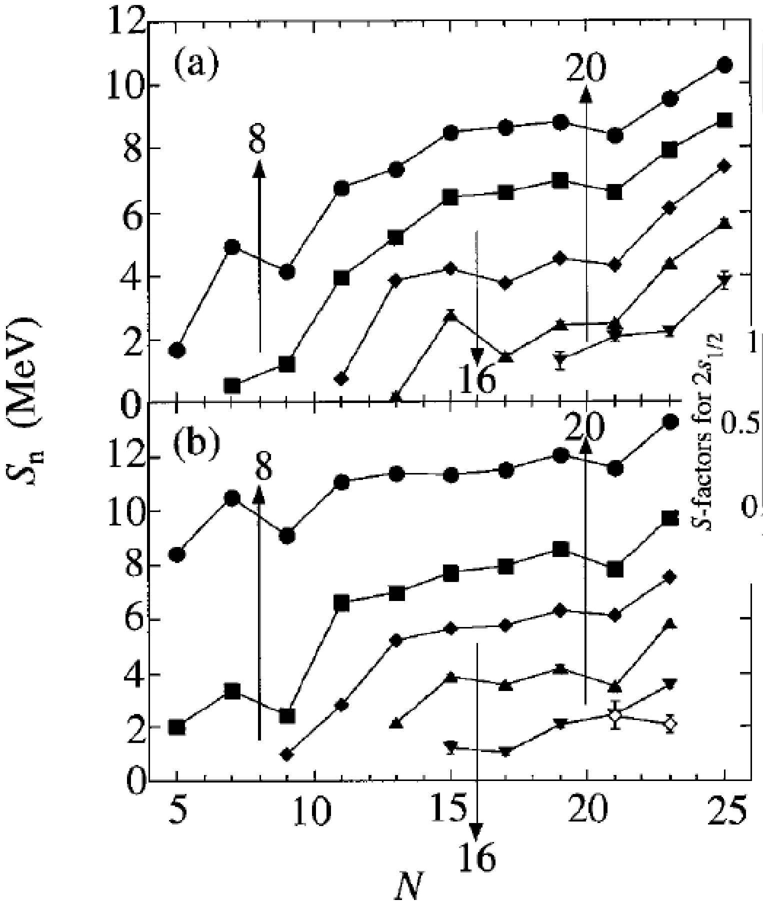
The oxygen-fluorine drip line anomaly



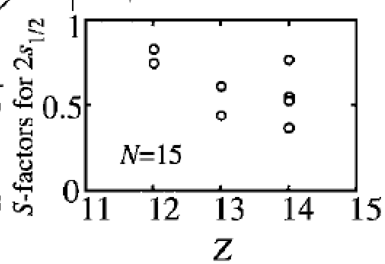
H. Sakurai et al., PLB 448, 180 (1999)
S. M. Lukyanov et al., Phys. At. Nucl. 67, 1627 (2004)

Evidence for an enhanced N = 16 gap

Neutron separation energies



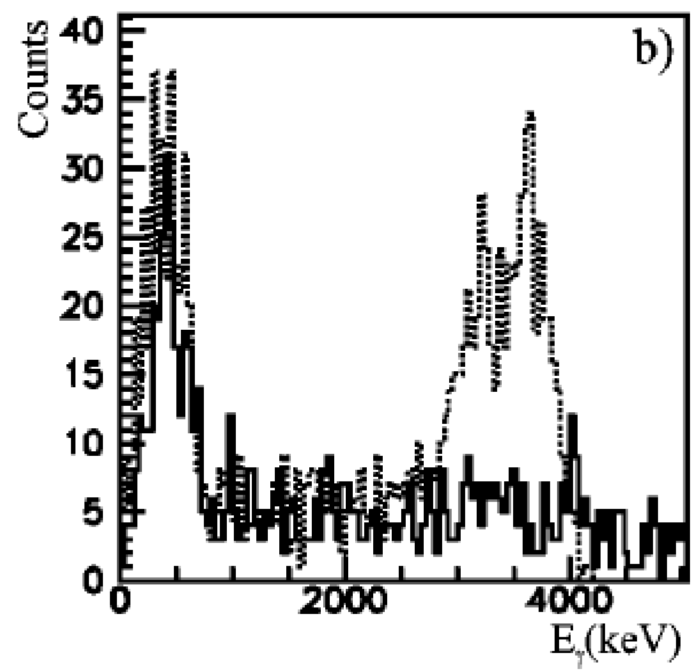
T_z



Ozawa et al., PRL 84, 5493 (2000)
M. Stanoiu et al., PRC 69, 034312 (2004)
B. Jurado et al., PLB 649, 43 (2007)

- S_n = 4.1(1) MeV in ^{24}O
  - ΔE ~ 470 keV from AME2003 (S_n = 3.62(15) MeV)

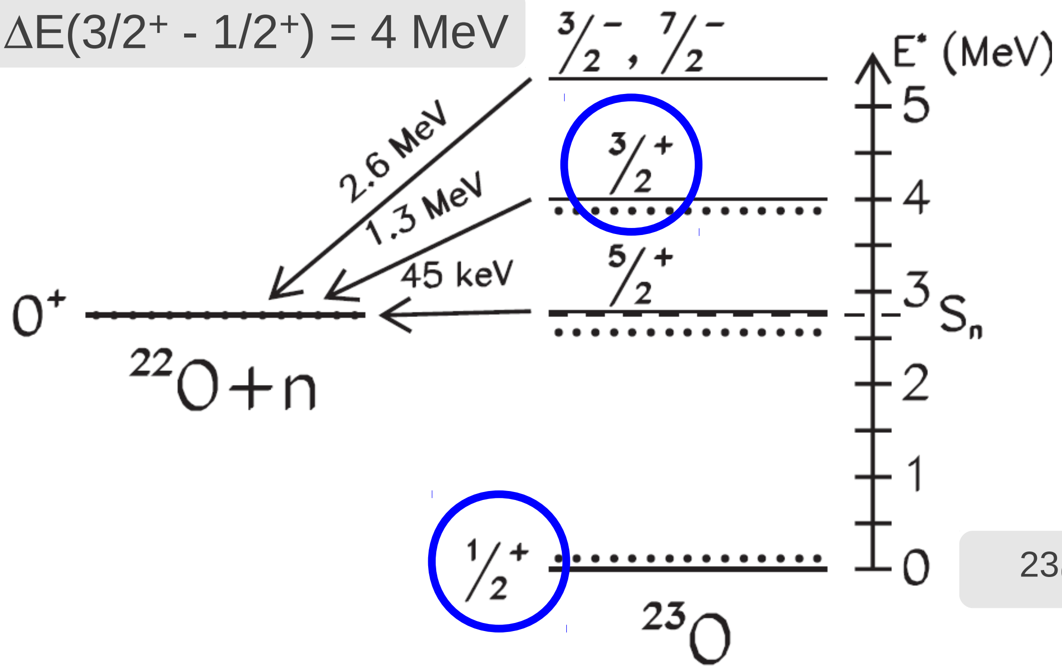
^{24}O lacks a bound excited state



Evidence for an enhanced N = 16 gap

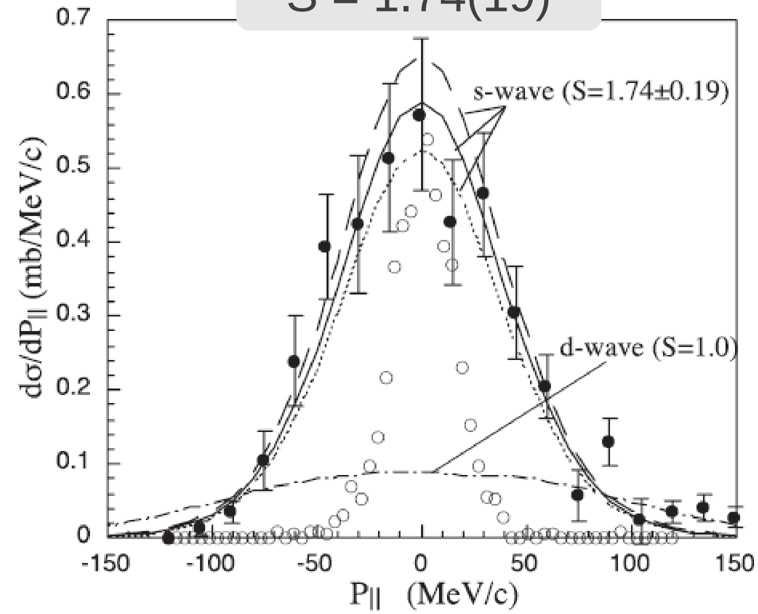
- ^{24}O ground state spectroscopic factor
  - Nearly pure $1s_{1/2}$ (s-wave)
- ~4 MeV gap in ^{23}O (N = 15) and ~4.9 MeV at N = 16

ΔE(3/2⁺ - 1/2⁺) = 4 MeV



$^{23}O(d,p)$ @ 34 MeV/u

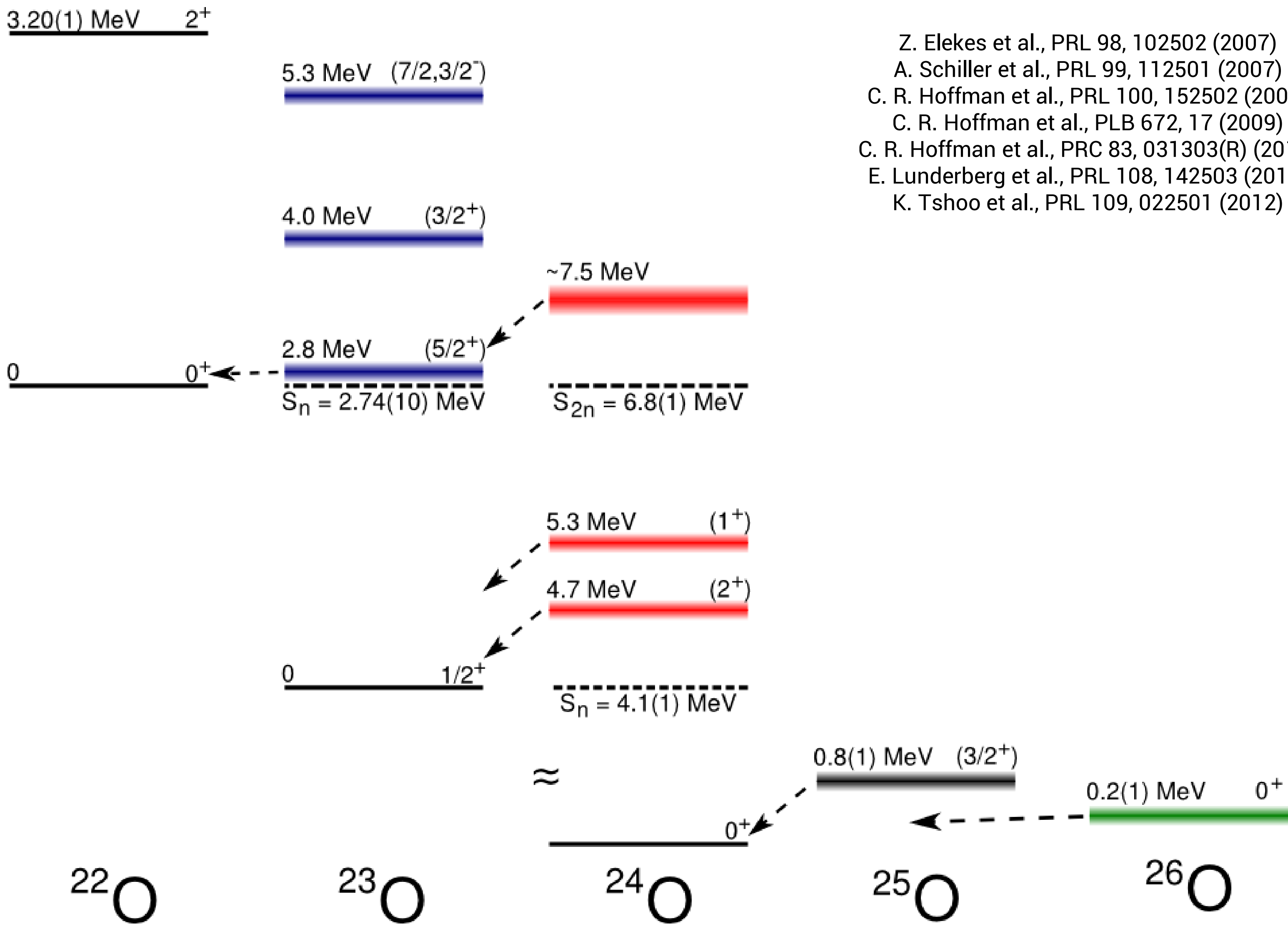
S = 1.74(19)



^{24}O one-neutron removal

A. Schiller et al., PRL 99, 112501 (2007)
R. Kanungo et al., PRL 102, 152501 (2009)
C. R. Hoffman et al., PRL 100, 152502 (2008)

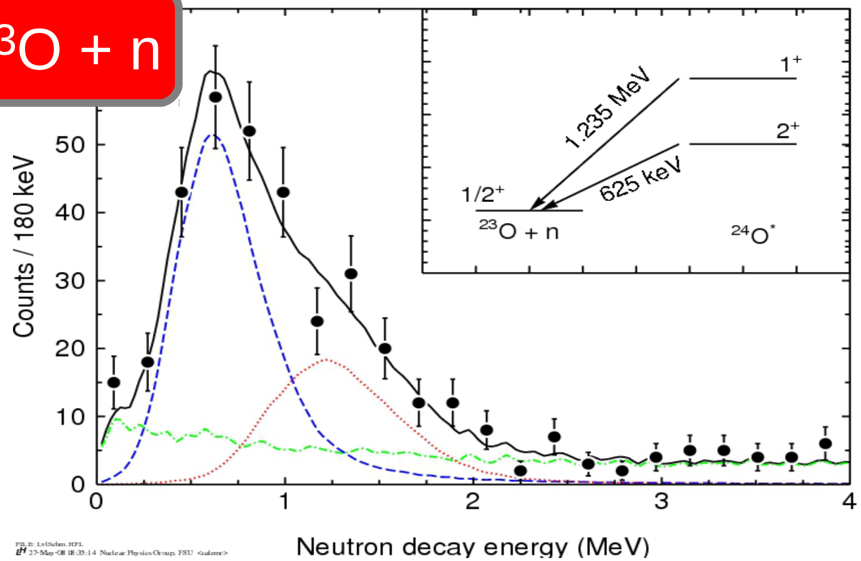
Neutron resonances in the oxygen isotopes

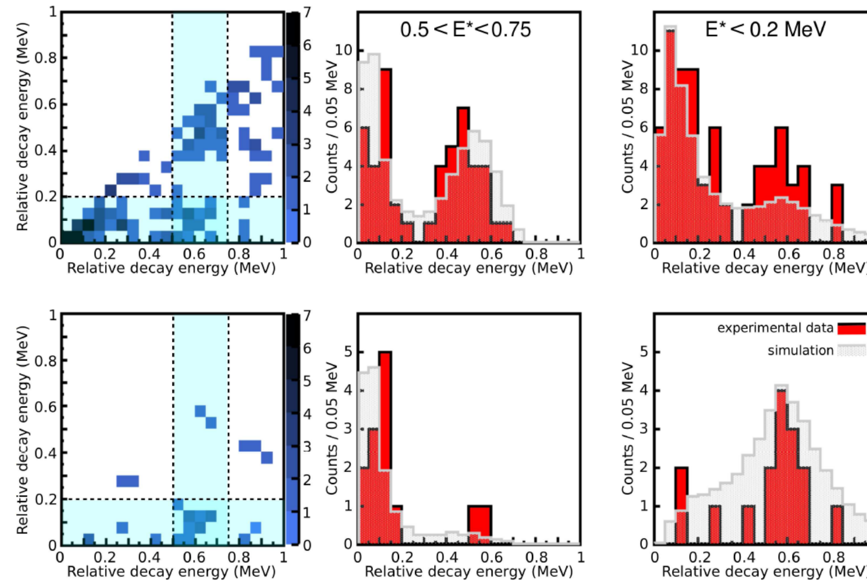


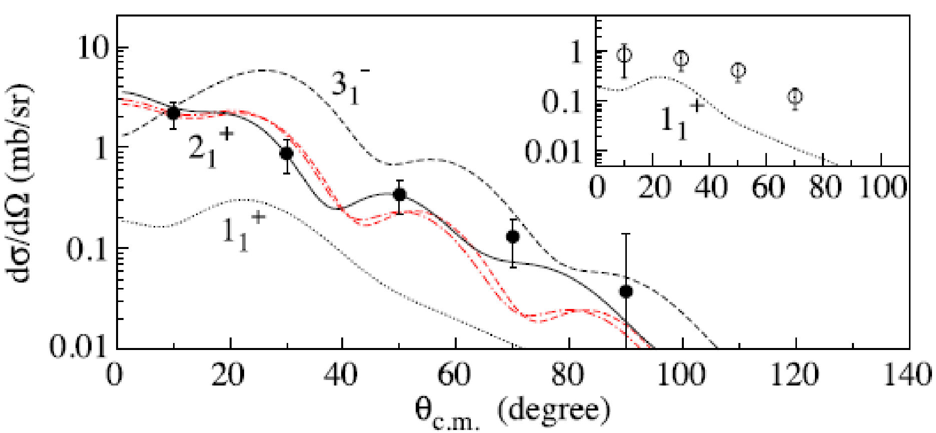
Z. Elekes et al., PRL 98, 102502 (2007)
A. Schiller et al., PRL 99, 112501 (2007)
C. R. Hoffman et al., PRL 100, 152502 (2008)
C. R. Hoffman et al., PLB 672, 17 (2009)
C. R. Hoffman et al., PRC 83, 031303(R) (2011)
E. Lunderberg et al., PRL 108, 142503 (2012)
K. Tshoo et al., PRL 109, 022501 (2012)

Unbound states in ^{24}O

^{23}O + n



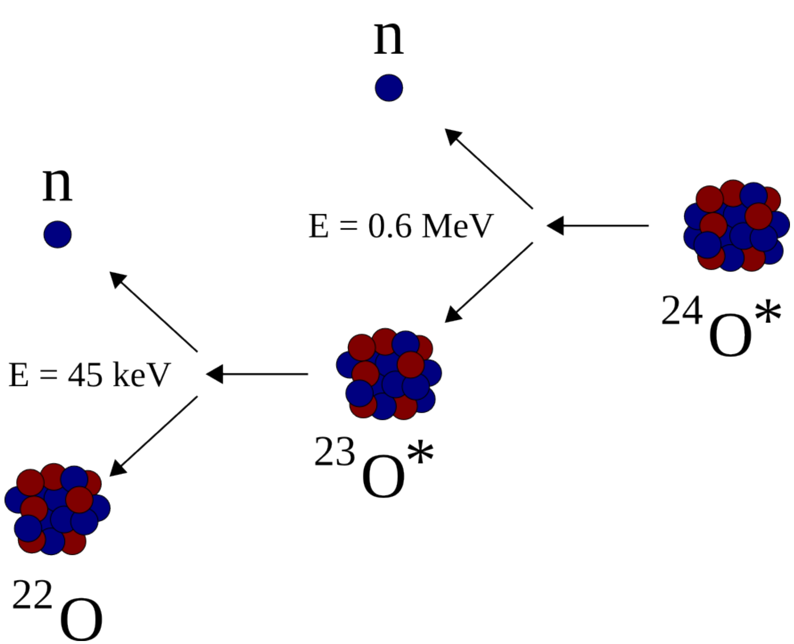


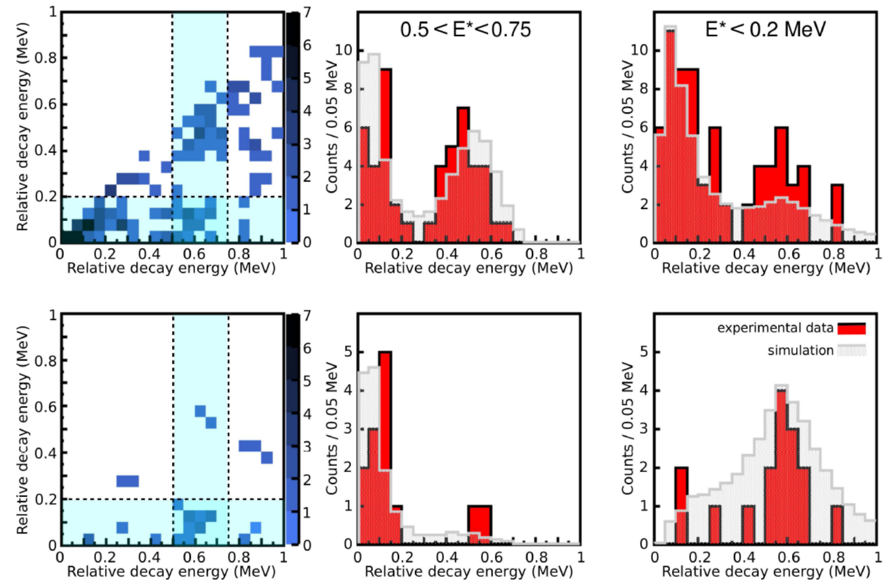


C. R. Hoffman et al., PLB 672, 17 (2009)
K. Tshoo et al., PRL 109, 022501 (2012)

- $^{24}O \rightarrow {}^{23}O + n$ or $^{22}O + n + n$
- 2 Resonances from ^{26}F proton knock-out
- Proton elastic scattering established spin-partiy of lowest level as 2^+

Unbound states in ^{24}O





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- 2 Resonances from ^{26}F proton knock-out
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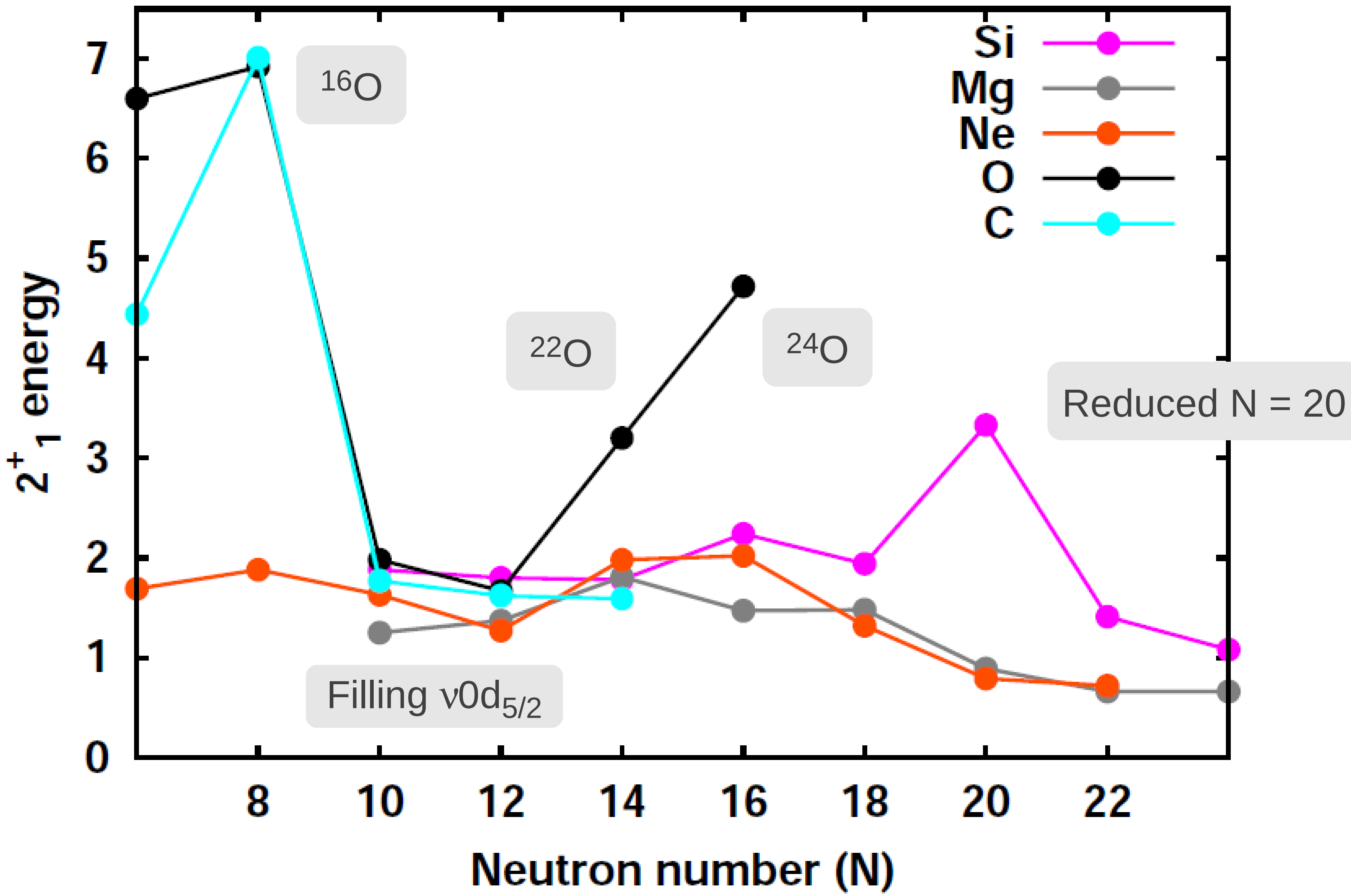
C. R. Hoffman et al., PRC 83,031303 (2011)

Even – Even 2^+ systematics for Z = 6 - 14



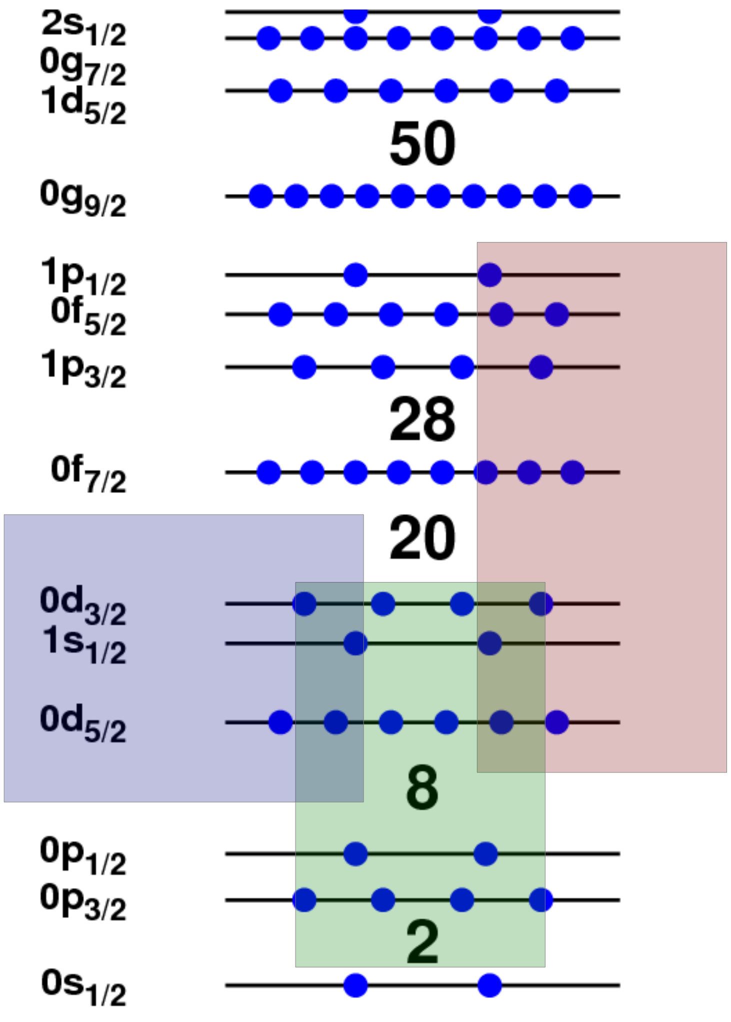
Shell model interactions

- **Two-body Nucleon-Nucleon forces**
  - G-matrix
  - V_{lowk} from chiral *NN* @ N^3LO
- **WBP/T** interactions
  - USD for sd orbitals
- **USD & USDA/B** Interactions
  - Data available at 1988 / 2005
- **SDPF-M** Interaction
  - Reproduce unbound ^{26}O g.s.
  - Monopole + pairing modified

$$\delta V^{T=1,0}_{0d_{5/2},0d_{3/2}} = +0.30, -0.70\,\mathrm{MeV},$$

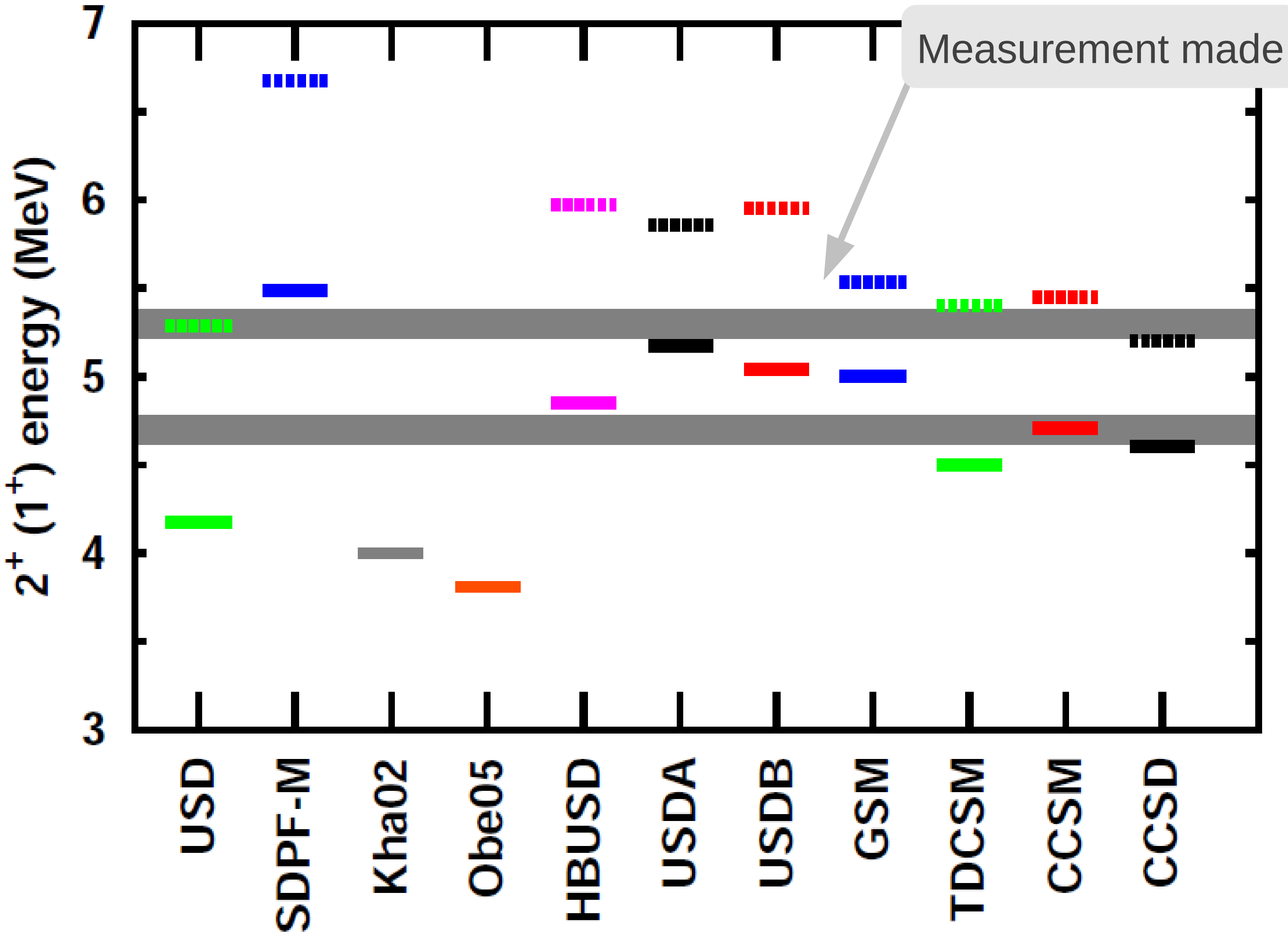
$$\delta V^{T=1,0}_{0d_{5/2},0f_{7/2}} = +0.16, -0.50\,\mathrm{MeV},$$

Single-particle levels



E. K. Warburton and B. A. Brown, PRC 46, 923 (1992)
B. A. Brown and B. H. Wildenthal, Rev. Part. Nucl. Sci. 38, 29 (1988)
B. A. Brown and W. A. Richter, PRC 74, 034315 (2006)
Y. Utsuno et al., PRC 60, 054315 (1999)

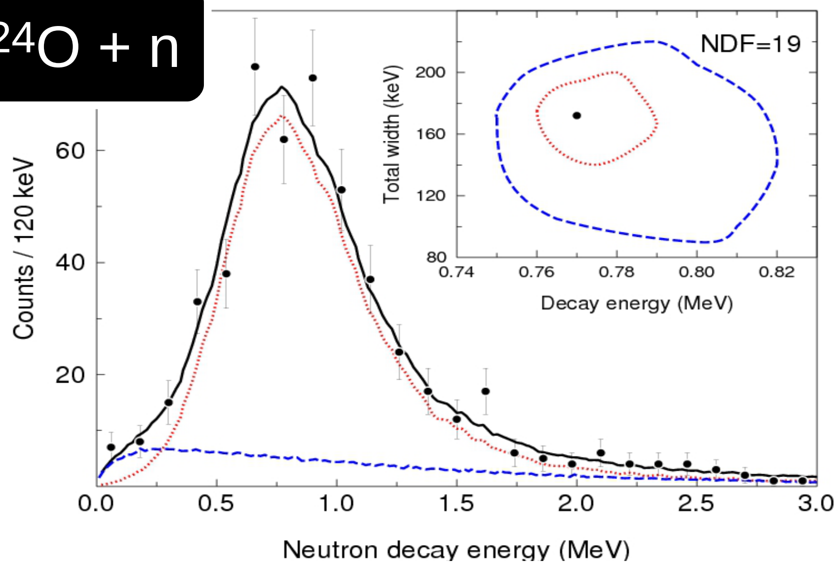
^{24}O calculated 2^+ (1^+) energies



K. Tsukiyama et al., PRC 80, 051301(R) (2009), A. Volya, PRC 79, 044308 (2009); K. Tsukiyama et al., arXiv:1001.0729 (2010), G. Hagen et al., PRL 108, (2012)

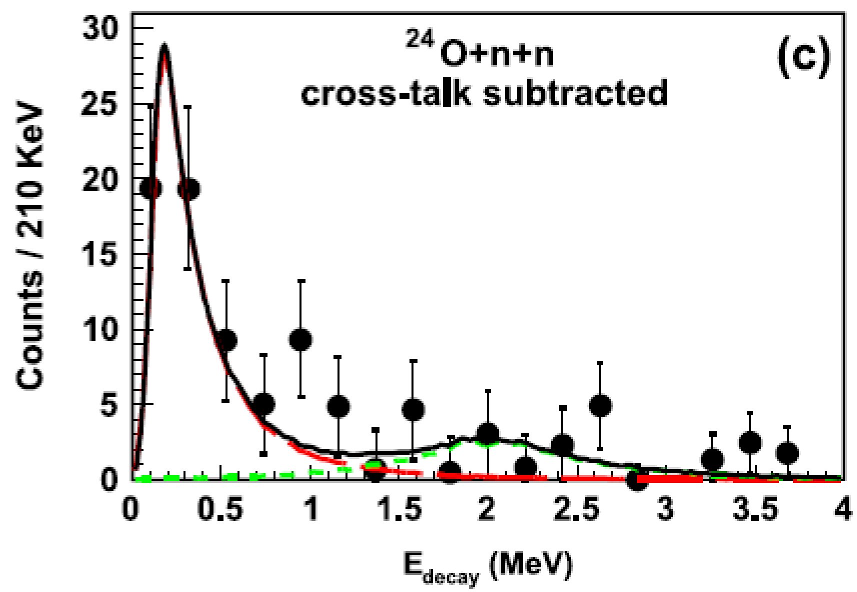
Ground state measurements: ^{25}O & ^{26}O

$^{24}O + n$



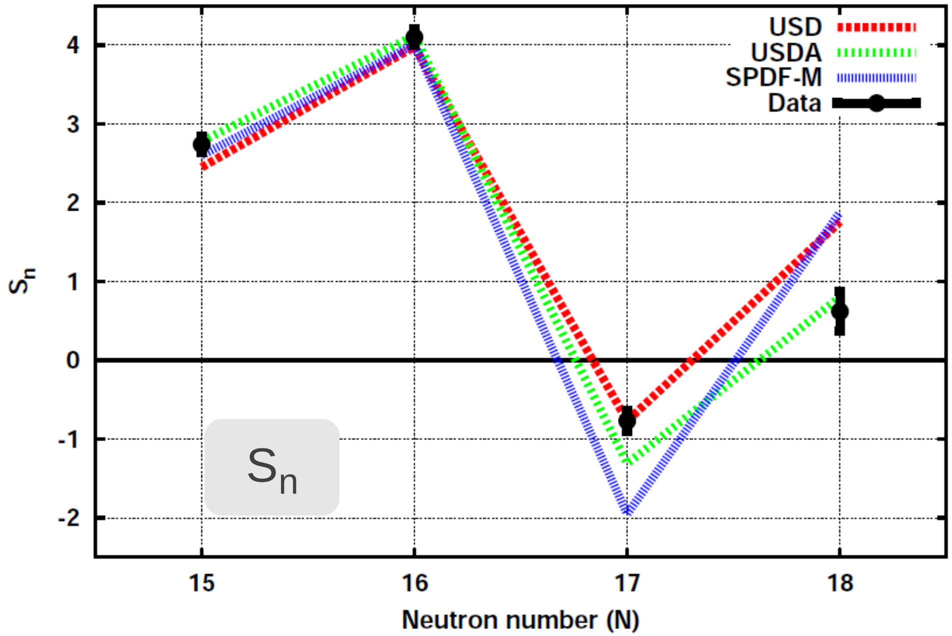
- E = 0.77(30) MeV
- Γ = 0.17(30) MeV
- Mass excess:
  - 27440(110) MeV

- ^{26}O ground state is unbound to 2-neutron decay
- E = 0.15(10) MeV
- Γ = 0.005 MeV

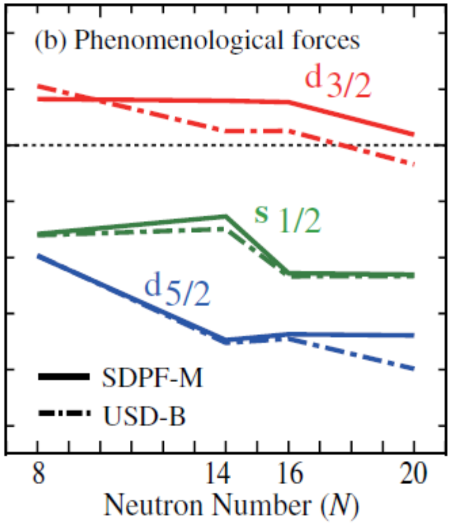


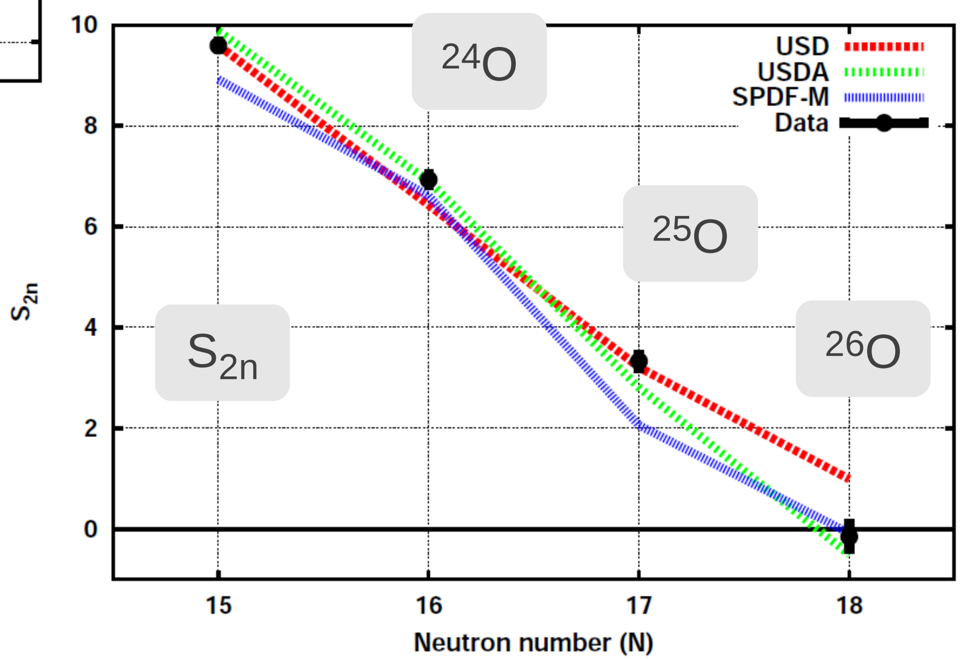
C. R. Hoffman et al., PRL 100, 152502 (2008)
E. Lunderberg et al., PRL 108, 142503 (2012)

Neutron separation energies



- USD, USDA, SDPF-M interactions
- ^{25}O g. s. → USD
- ^{26}O g.s. → USDA, SDPF-M (S_{2n})

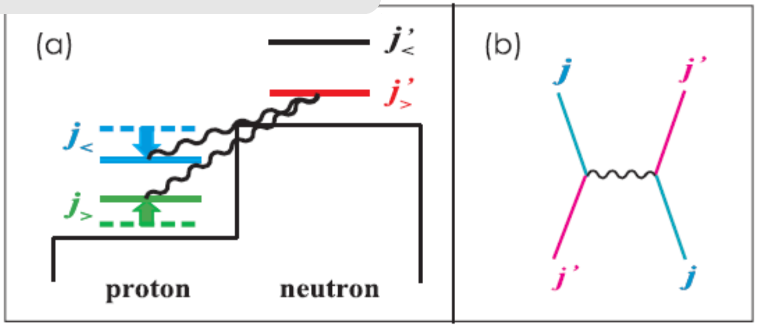


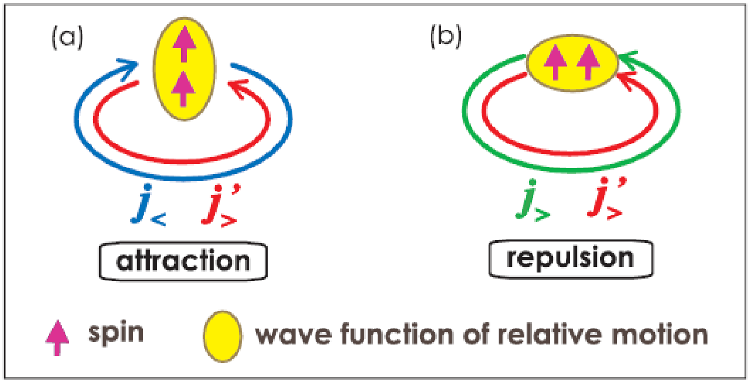


C. R. Hoffman PLB 672, 17 (2009), E. Lunderberg et al., PRL 108, 142502 (2012)

What is driving the shell evolution?

Tensor force





Components of the *NN* interaction

$$V(1,2) = V(\vec{r}_1, \vec{\sigma}_1, \vec{\tau}_1; \vec{r}_2, \vec{\sigma}_2, \vec{\tau}_2).$$

$$V_T(1,2) = \left(V_T^{is}(r) + V_T^{iv}(r)\vec{\tau}_1 \cdot \vec{\tau}_2\right) S_{12}(r),$$

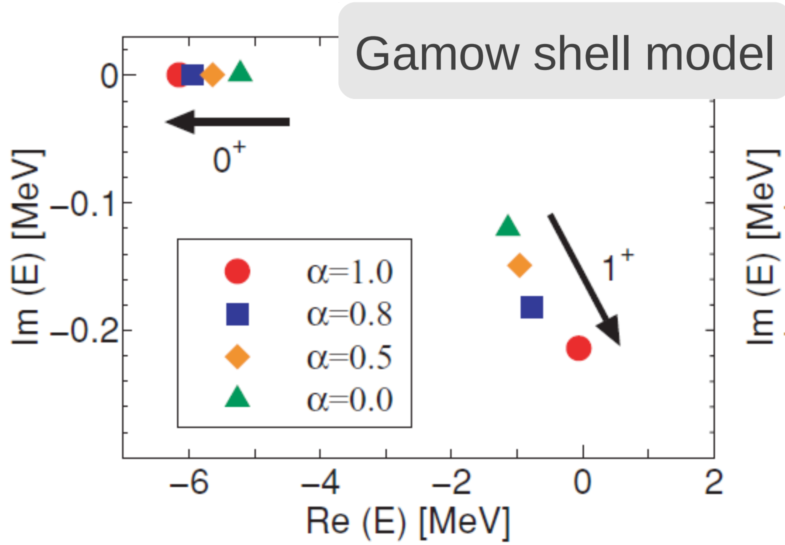
$$S_{12}(r) = \frac{3}{r^2}(\vec{\sigma}_1 \cdot \vec{r})(\vec{\sigma}_2 \cdot \vec{r}) - \vec{\sigma}_1 \cdot \vec{\sigma}_2.$$

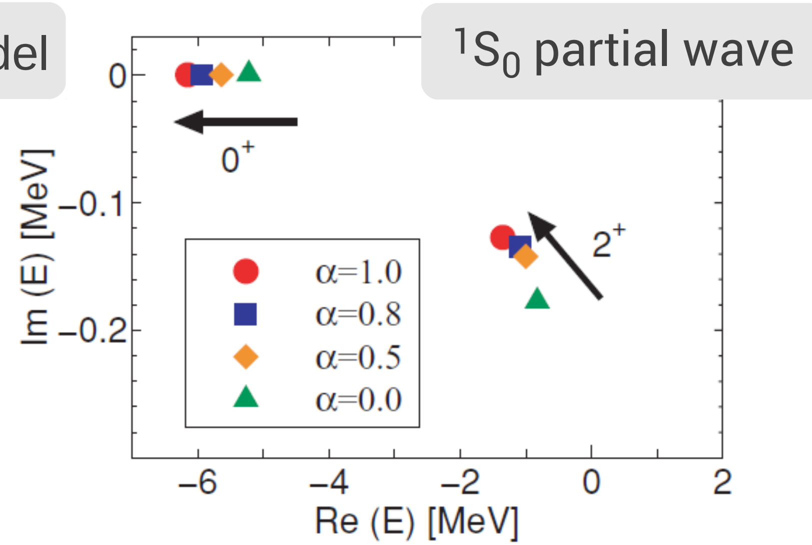
Spin-isospin interaction

$$V_c(1,2) = V_0(r) + V_\sigma(r)\vec{\sigma}_1 \cdot \vec{\sigma}_2 + V_\tau(r)\vec{\tau}_1 \cdot \vec{\tau}_2 + V_{\sigma\tau}(r)\vec{\sigma}_1 \cdot \vec{\sigma}_2 \vec{\tau}_1 \cdot \vec{\tau}_2$$

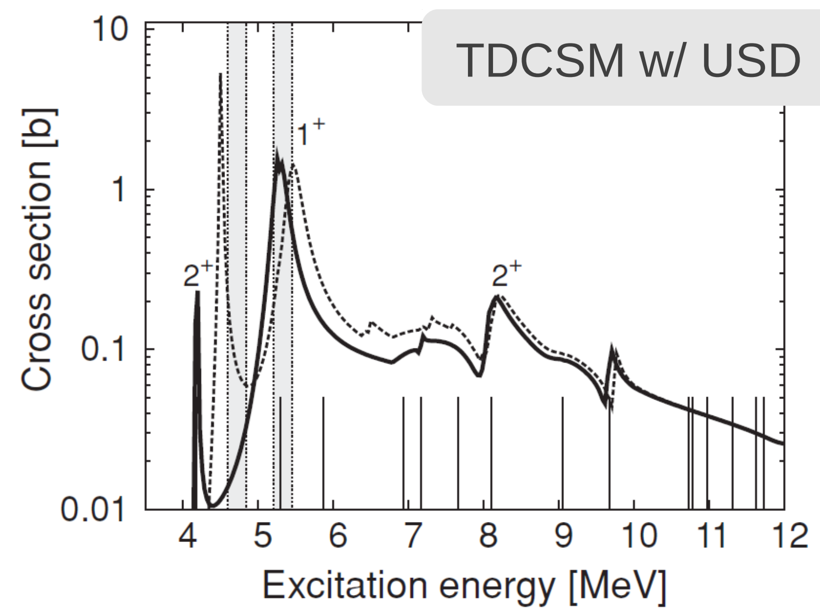
T. Otsuka et al., PRL 87, 082502 (2001), 95, 232502 (2005), 97, 162501, 104, 012501 (2010)

What is driving the shell evolution?





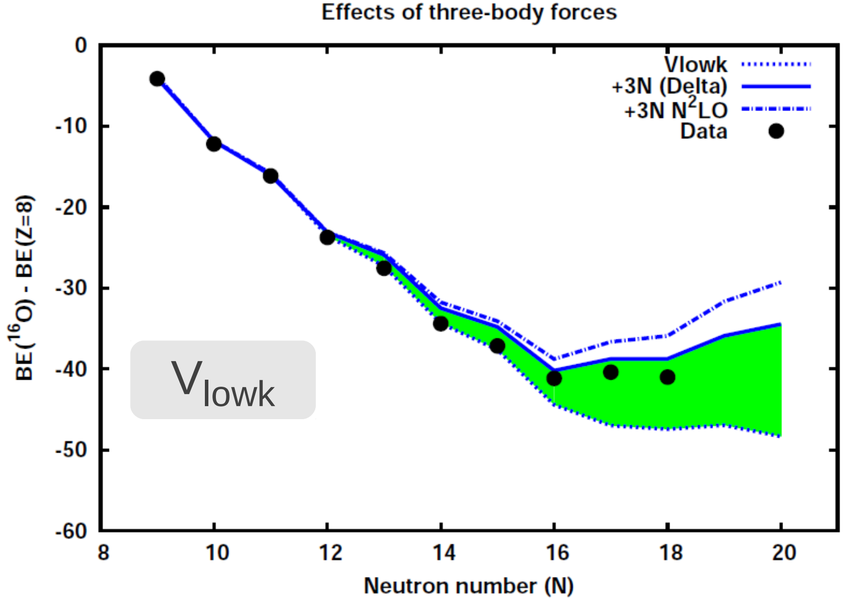
- Coupling to the continuum
  - Time dependent continuum shell model (TDCSM)
  - Gamow shell model calculations (GSM)
  - Continuum Coupled Shell Model (CCSM)
- Impact felt on excited states not binding energies

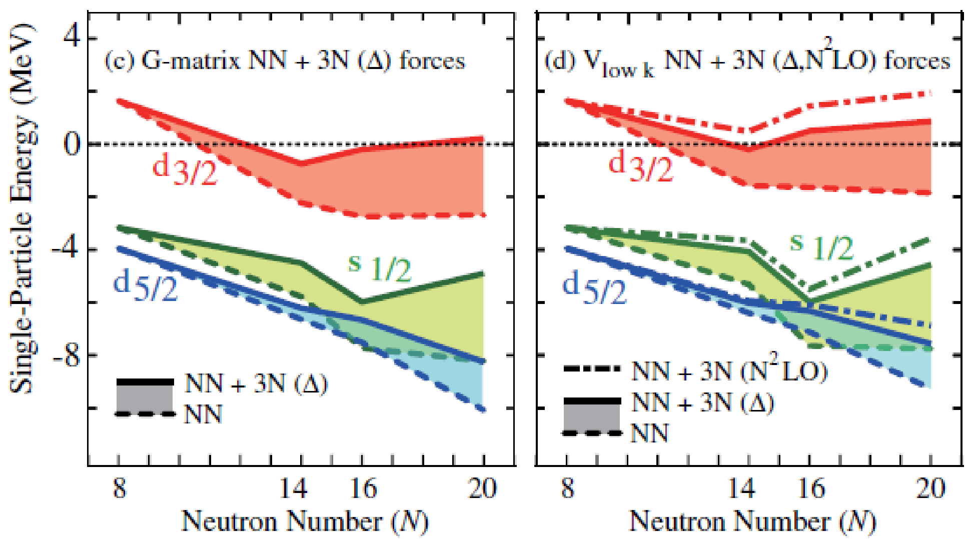


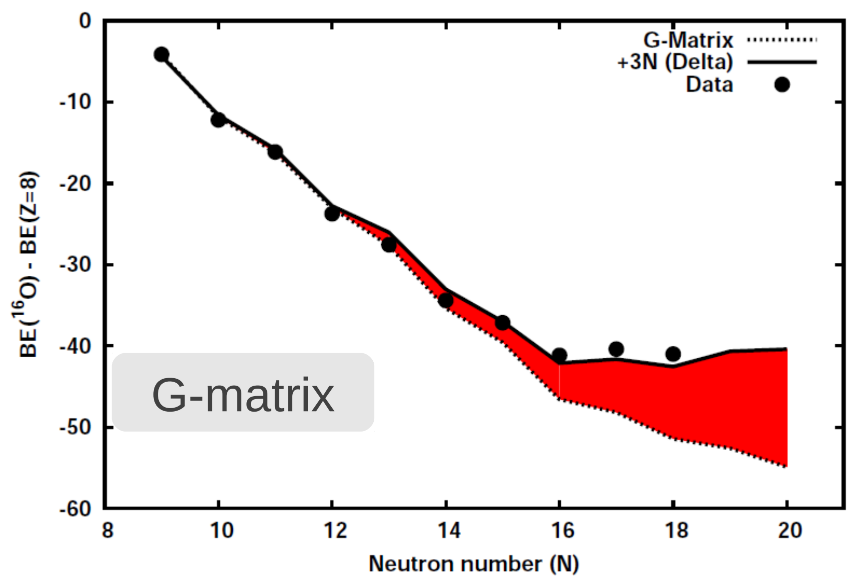
A. Volya, PRC 79, 044308 (2009)
K. Tsukiyama et al. PRC 80, 051301(R); arXiv:1001.0729

Three-body effects at the drip line

- Qualitative reproduction of the drip line & binding energies
- 2N + 3N forces needed for neutron-rich nuclei
- Slight difference in 3N force used
  - Long-range two-pion exchange dominates

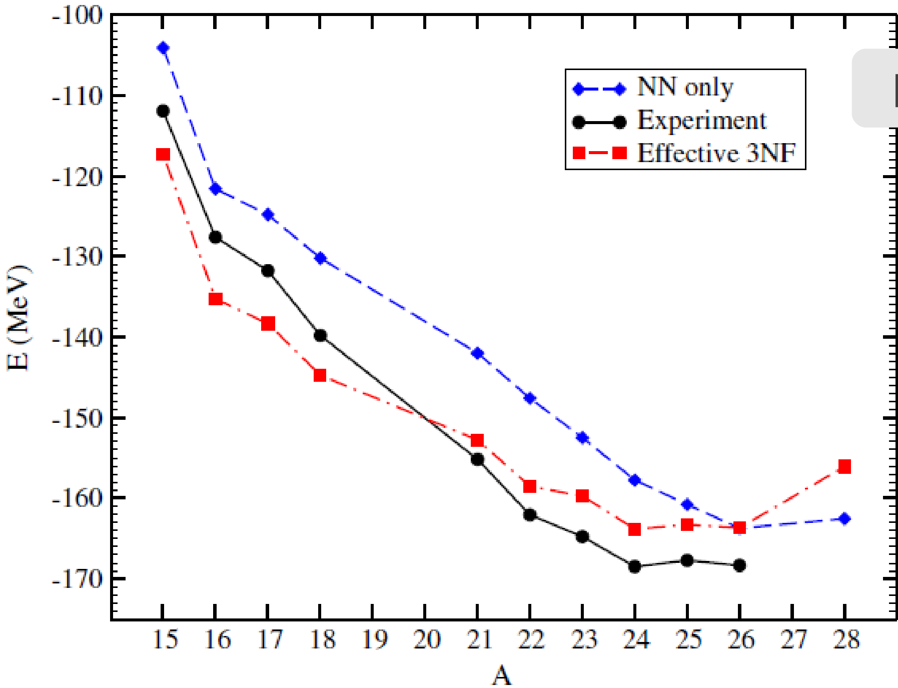






T. Otsuka et al., PRL 105, 032501 (2010)

Coupled-Cluster Method



Both 3-N and continuum contributions

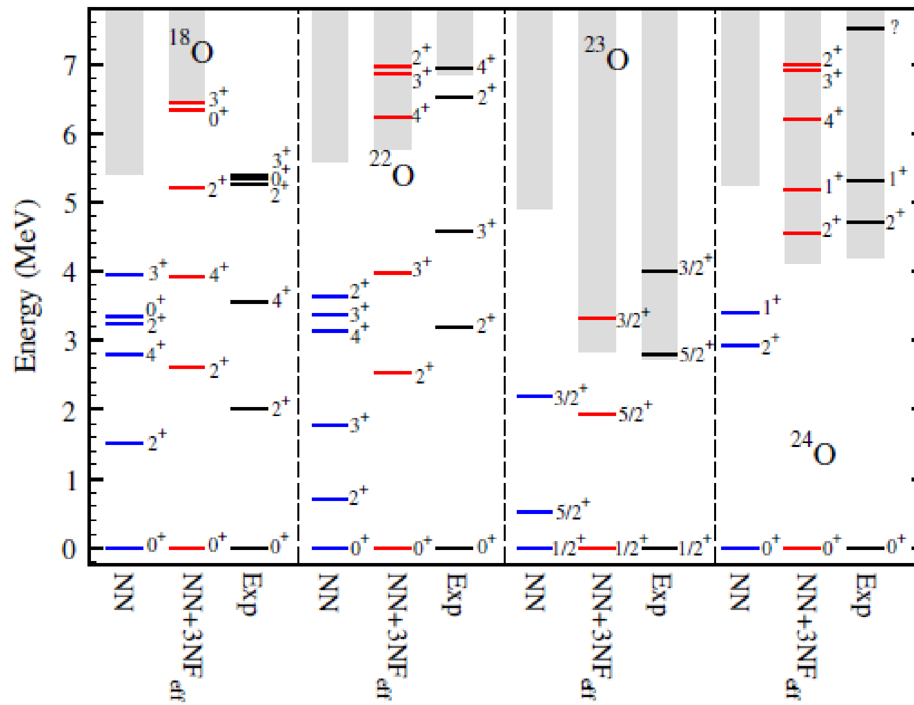
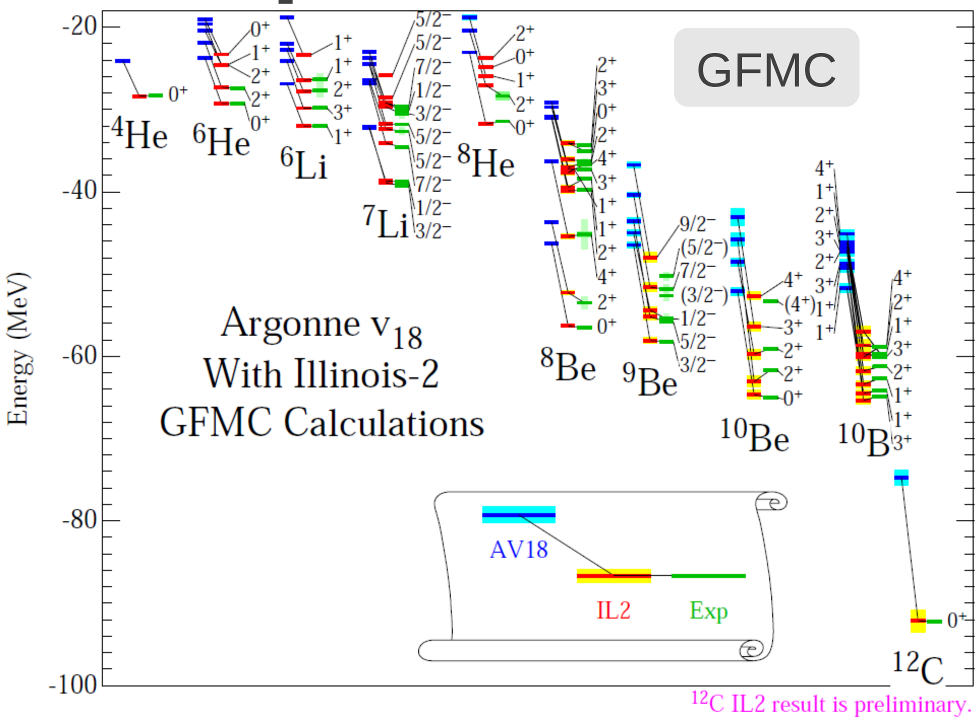


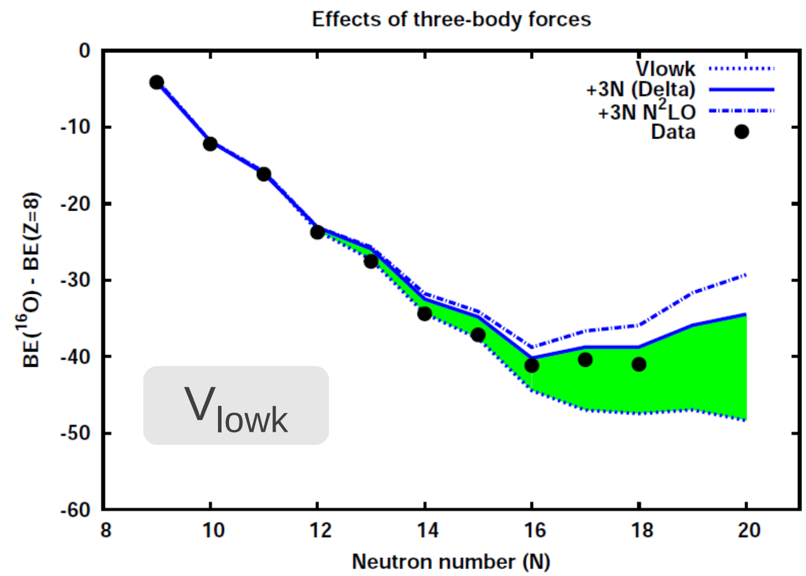
TABLE I. Excited states in ^{24}O computed within EOM-CCSD compared to experimental data from Ref. [6]. Energies and widths are in MeV.

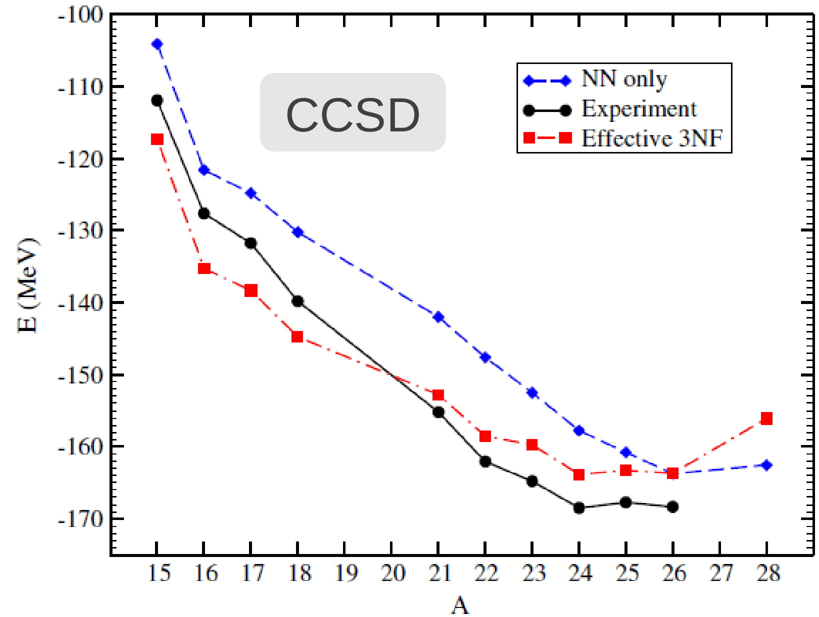
J^π	2_1^+	1_1^+	4_1^+	3_1^+	2_2^+	1_2^+
E_{CC}	4.56	5.2	6.2	6.9	7.0	8.4
E_{Exp}	4.7(1)	5.33(10)				
Γ_{CC}	0.03	0.04	0.005	0.01	0.04	0.56
Γ_{Exp}	$0.05^{+0.21}_{-0.05}$	$0.03^{+0.12}_{-0.03}$				

G. Hagen et al., PRL 108, 242501 (2012)

Comparisons of different 3N forces





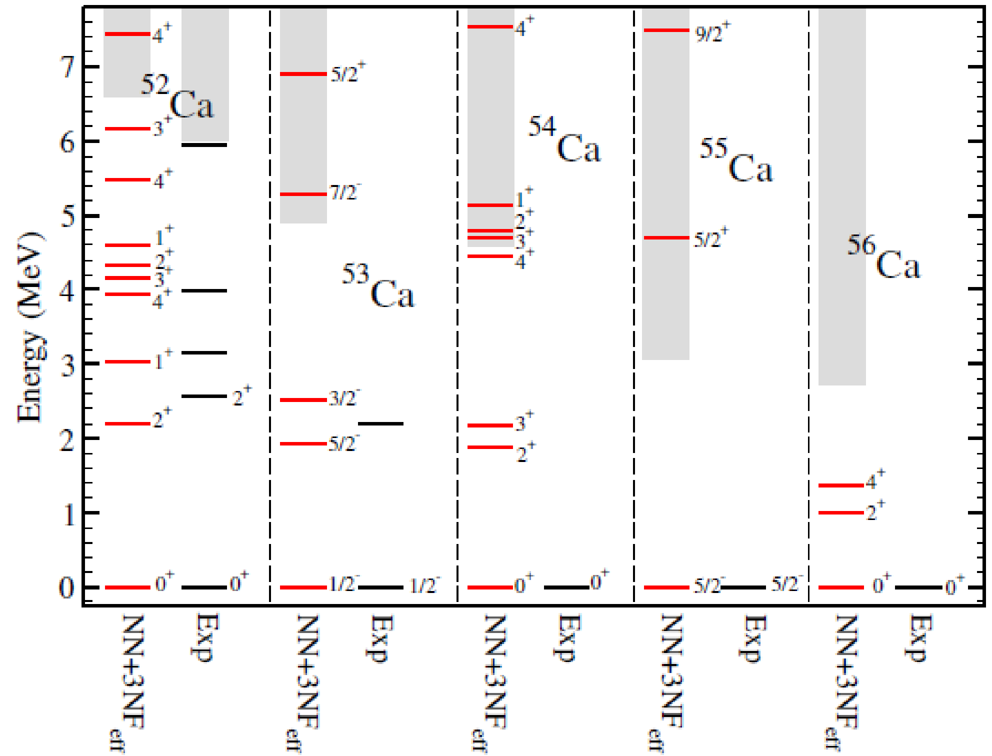


- Increased ground state binding
  - GFMC & Coupled Cluster Calculations
- Reduced binding relative to ^{16}O core
- Impact of scattering into the continuum

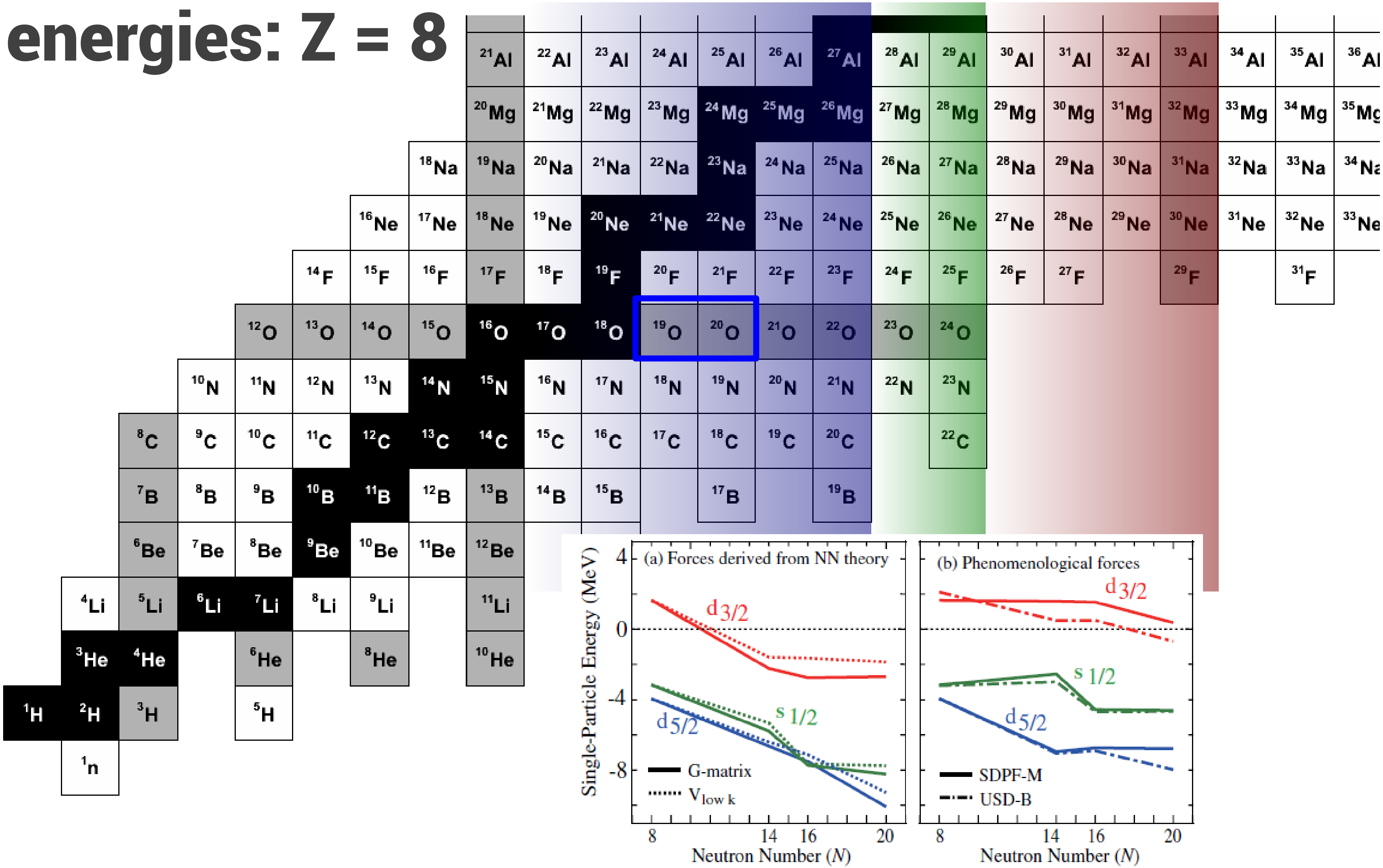
S. C. Pieper and R. B. Wringa, Annu. Rev. Nucl. Part. Sci. 51, 53 (2001)
T. Otsuka et al., PRL 105, 032501 (2010)
G. Hagen et al., PRL 108, 242501 (2012)

Future work

- ^{28}O ground state binding energy
  - Extremely difficult
  - ^{24}O + n + n + n + n
  - Need ^{27}O first
- ^{26}O 2^+ state
  - Above ^{25}O g.s.
- Neutron angular correlations
  - High-lying states
- Unbound states in the Ca region
  - Unlikely to reach drip line with current facilities

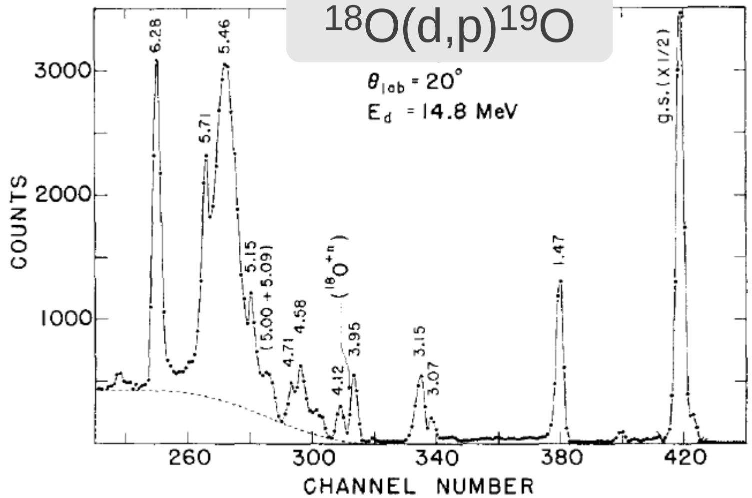


Direct reactions to track single-particle energies: Z = 8

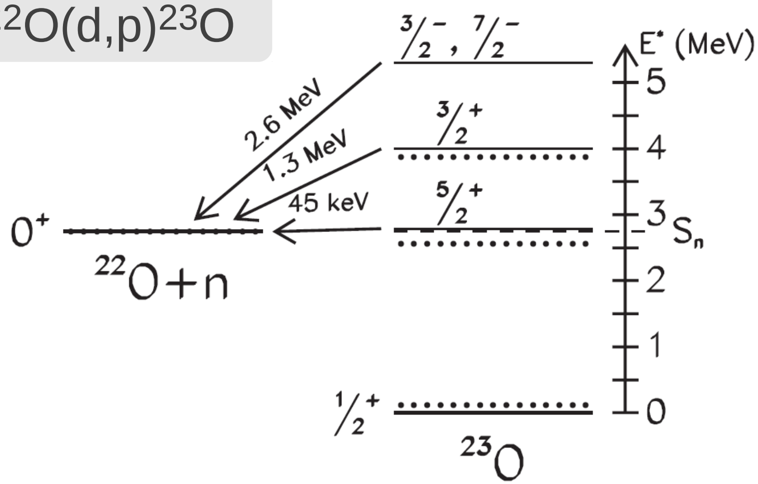


Previous direct reaction work (d,p)

$^{18}O(d,p)^{19}O$

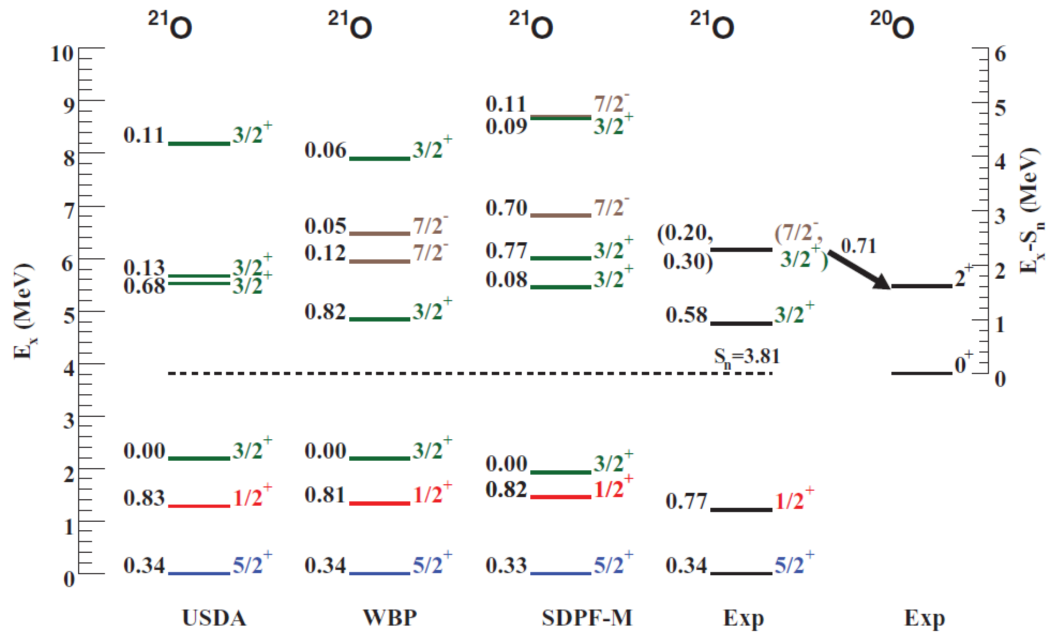


$^{22}O(d,p)^{23}O$



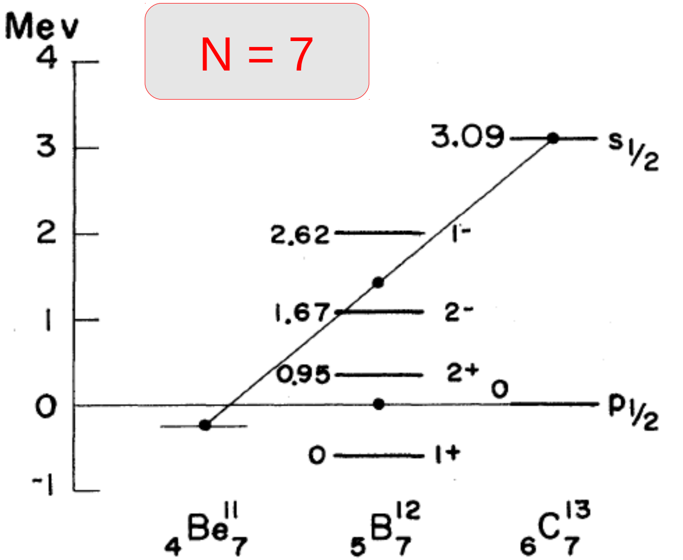
S. Sen et al., NPA 219, 429 (1974)
B. Fernandez-Dominguez et al., PRC 84, 011301R (2011)
Z. Elekes et al., PRL (2007)

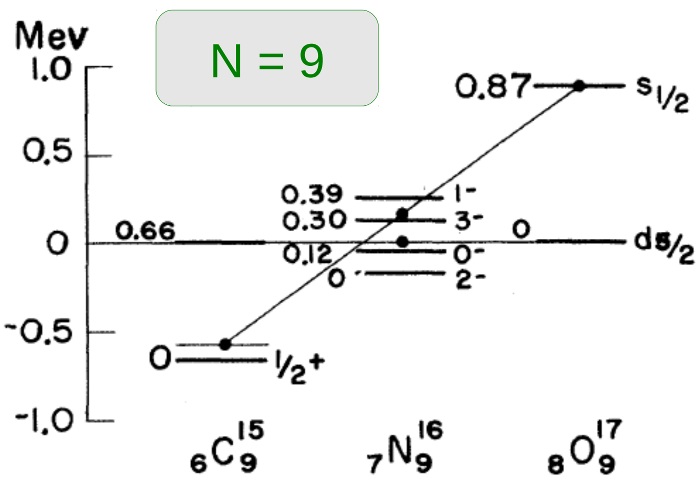
$^{20}O(d,p)^{21}O$

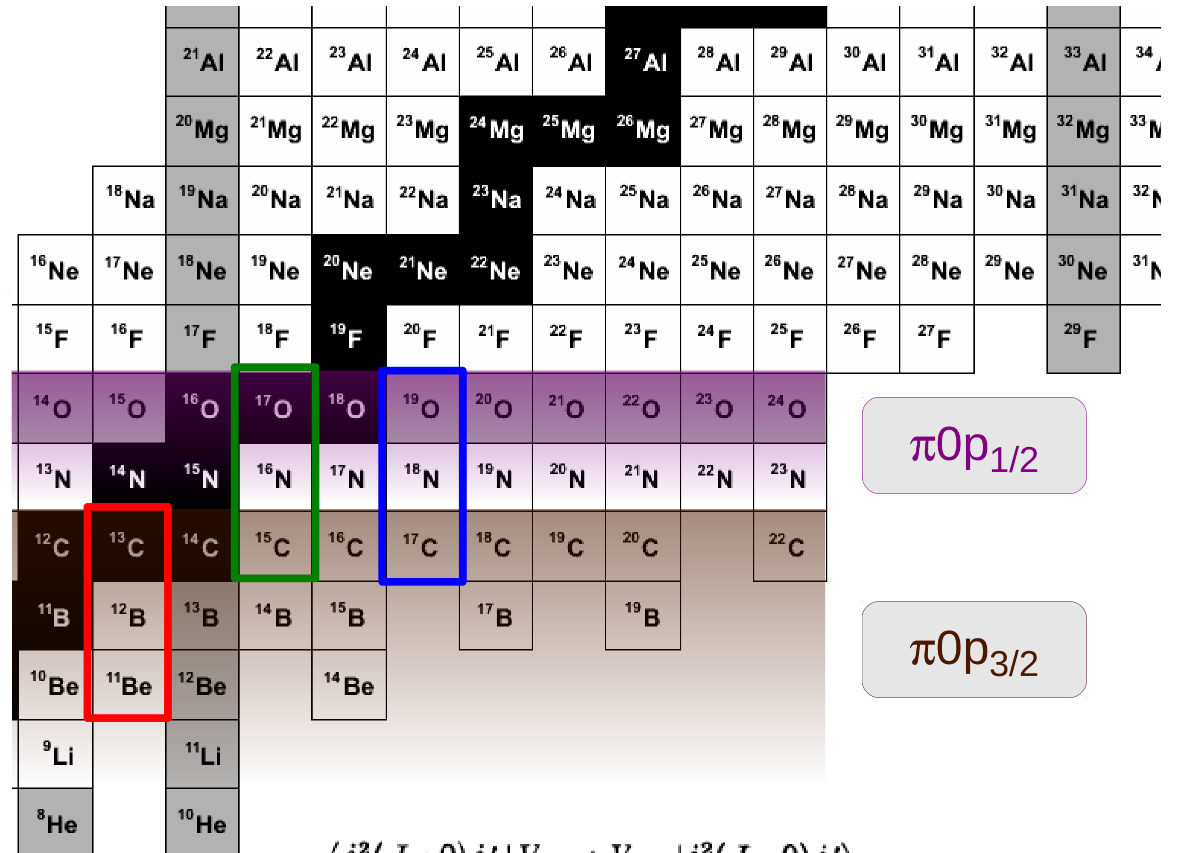


- Excellent reproduction of the neutron $0d_{5/2}$ and $0s_{1/2}$ levels
- The neutron $0d_{3/2}$ is ok
- Heaviest elemental chain with such complete information

Single-particle evolution across isotones



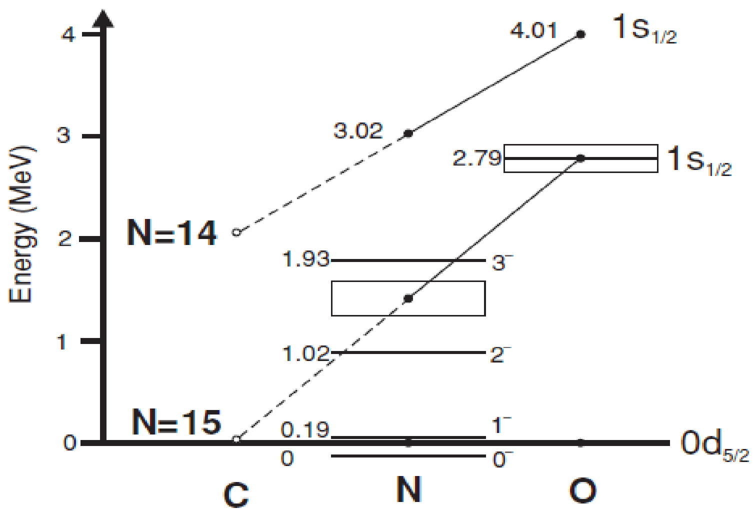


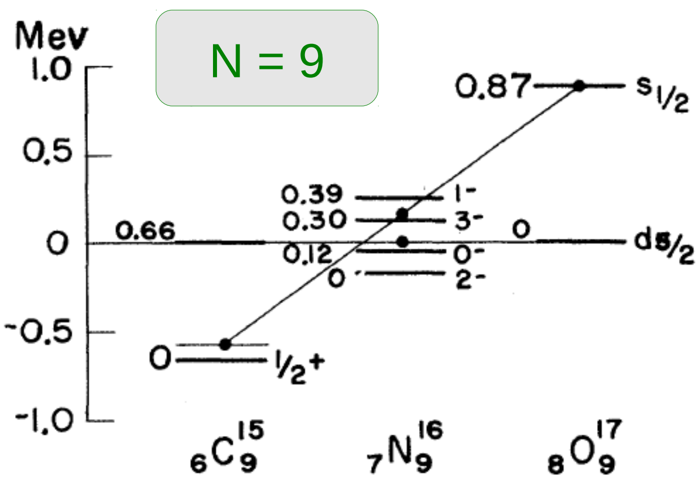


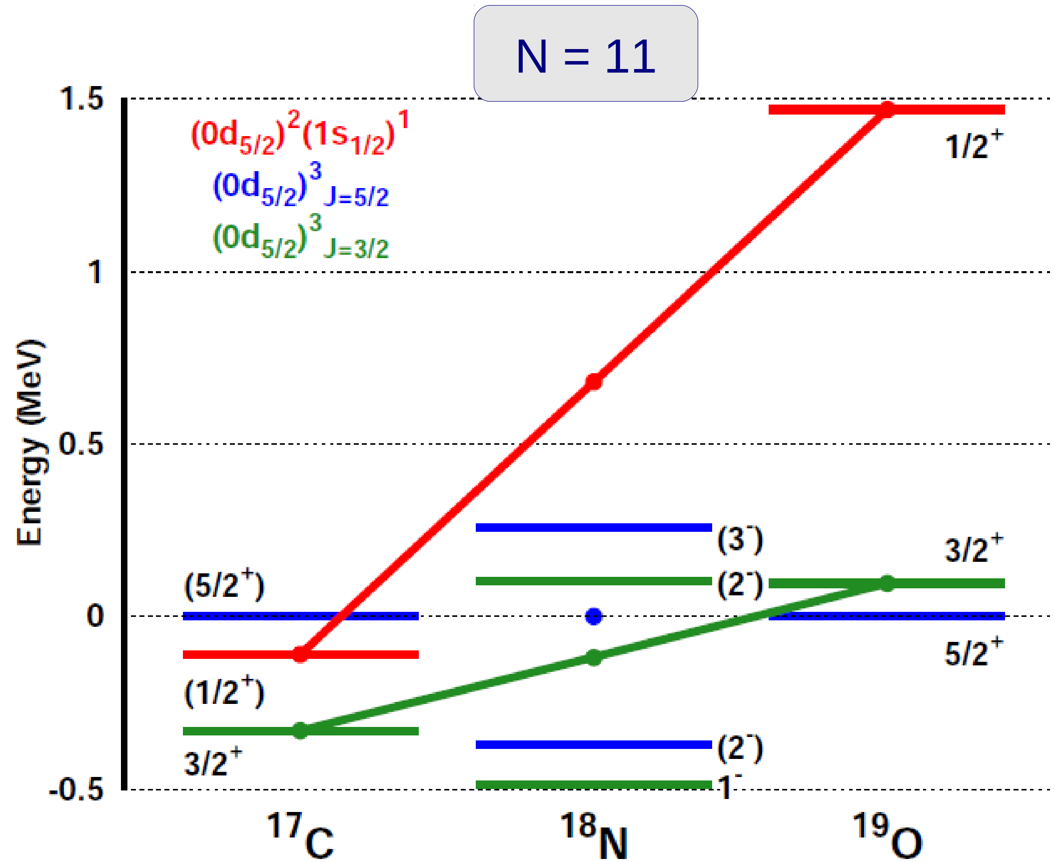
$$\langle j^2(J=0)j'|V_{1n}+V_{2n}|j^2(J=0)j'\rangle = 2\sum_{J=|j-j'|}^{J=j+j'}(2J+1)\langle jj'J|V|jj'J\rangle \Big/ \sum_{J=|j-j'|}^{J=j+j'}(2J+1). \quad (1)$$

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

Single-particle evolution across isotones



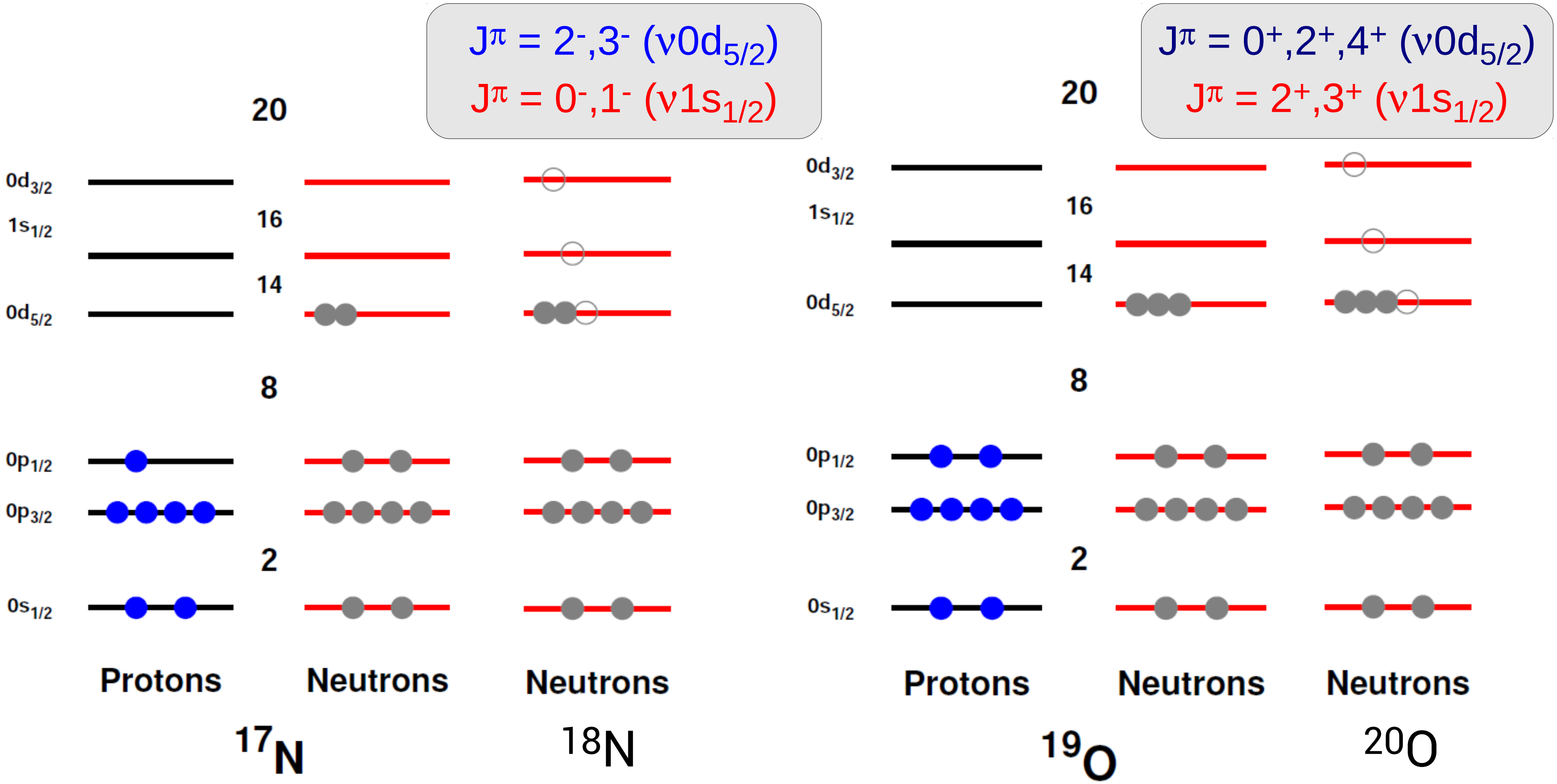




I. Talmi and I. Unna, PRL 4, 469 (1960)

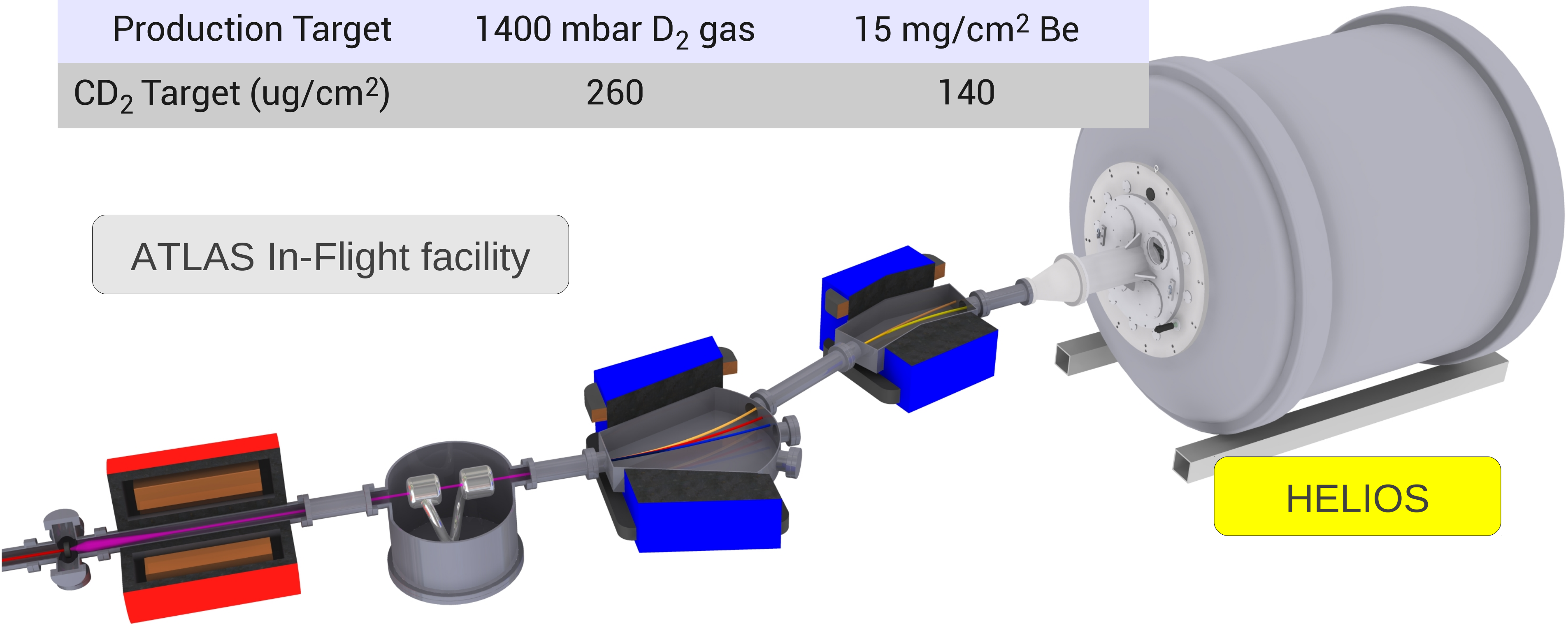
Location of the $1s_{1/2}$-$0d_{5/2}$ neutron orbitals

- Neutron adding (d,p) reaction
  - $^{19}O(d,p)^{20}O$ – neutron *sd* orbitals as a function of N
  - $^{17}N(d,p)^{18}N$ – neutron *sd* orbitals as a function of Z



Experimental details

Reaction	$^{19}O(d,p)^{20}O$	$^{17}N(d,p)^{18}N$
RIB Beam:	^{19}O	^{17}N
Energy (MeV/u)	6.9	13.5
Rate (pps)	$>10^5$	$>10^4$
Production Target	1400 mbar D_2 gas	15 mg/cm^2 Be
CD_2 Target (ug/cm^2)	260	140

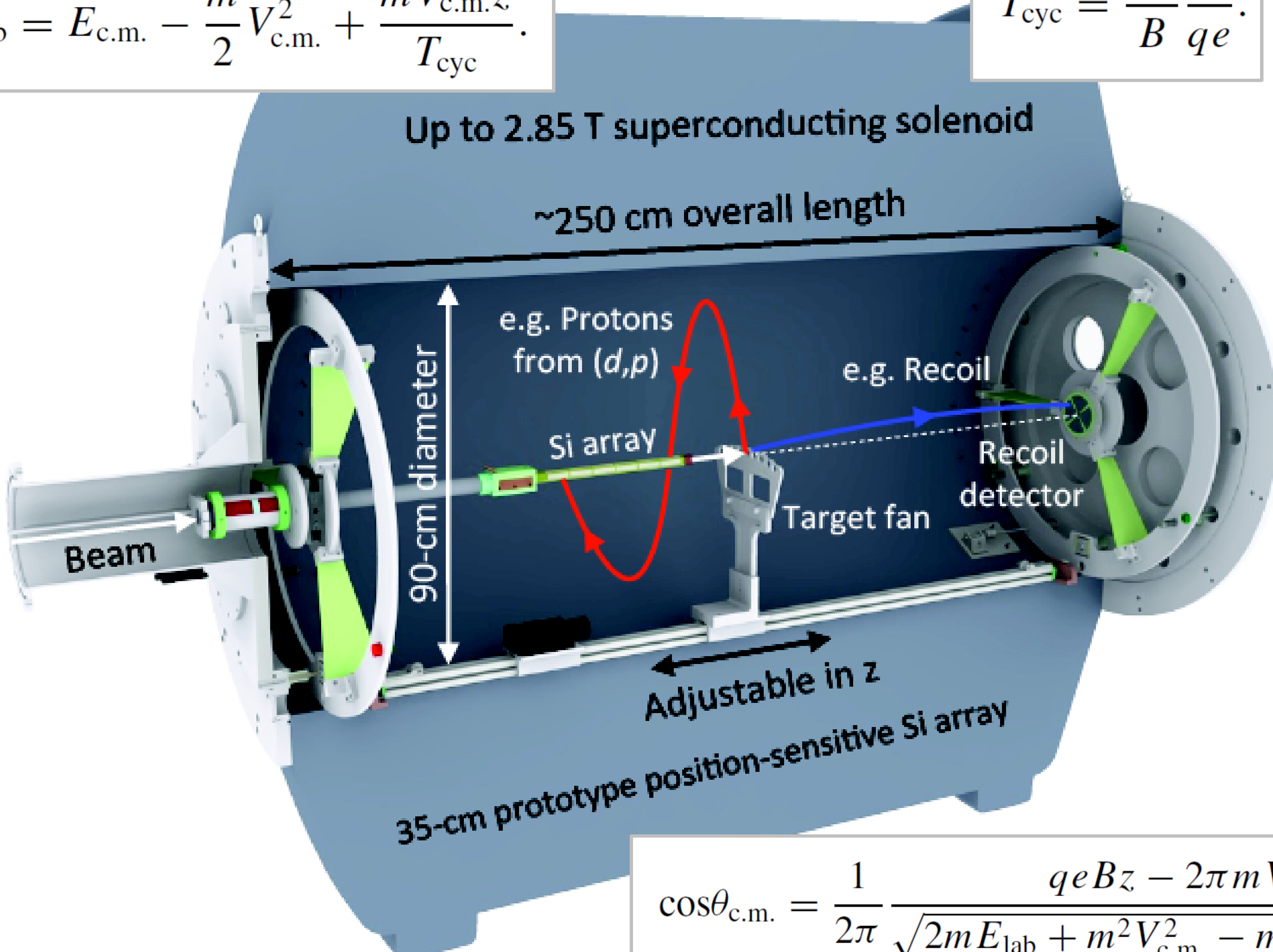


B. Harss et al., Rev. Sci. Instrum. 71, 380 (2000)

HELIcal Orbit Spectrometer (HELIOS)

$$E_{\rm lab} = E_{\rm c.m.} - \frac{m}{2}V_{\rm c.m.}^2 + \frac{m V_{\rm c.m.} z}{T_{\rm cyc}}.$$

$$T_{\rm cyc} = \frac{2\pi}{B}\frac{m}{qe}.$$

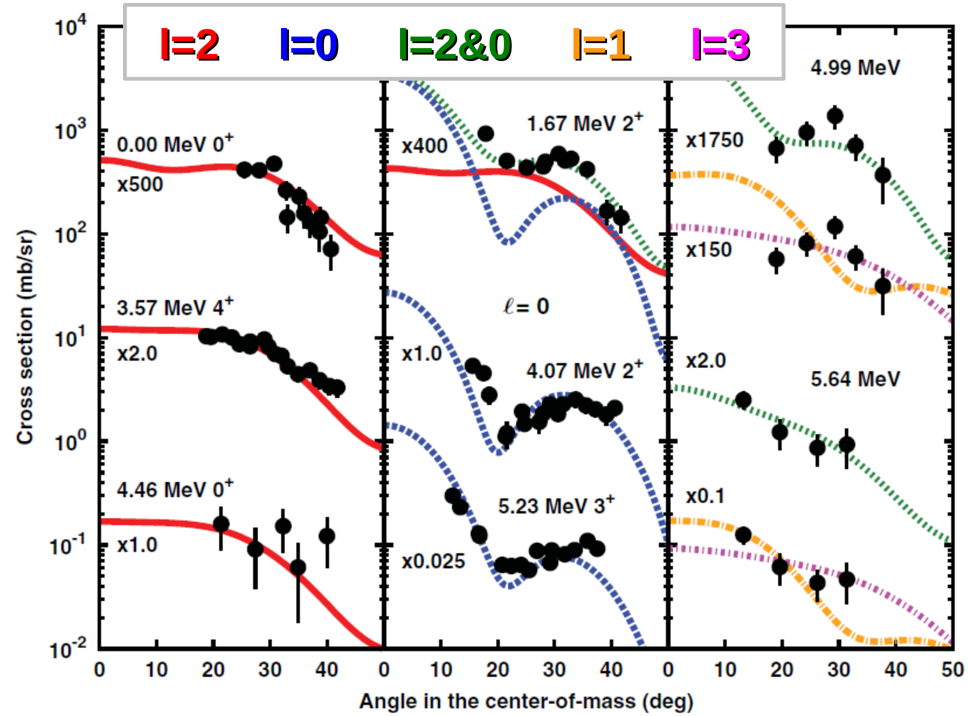


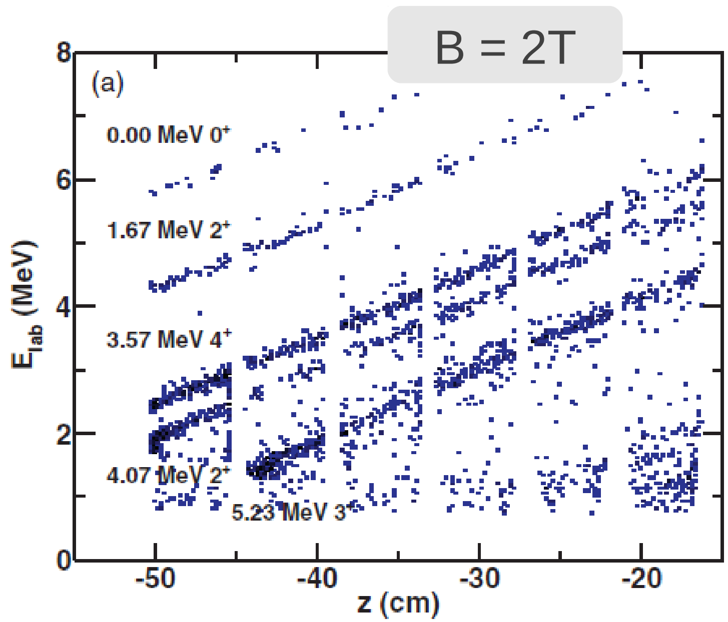
$$\cos\theta_{\rm c.m.} = \frac{1}{2\pi}\frac{qeBz - 2\pi m V_{\rm c.m.}}{\sqrt{2mE_{\rm lab} + m^2 V_{\rm c.m.}^2 - m V_{\rm c.m.} qeBz/\pi}}.$$

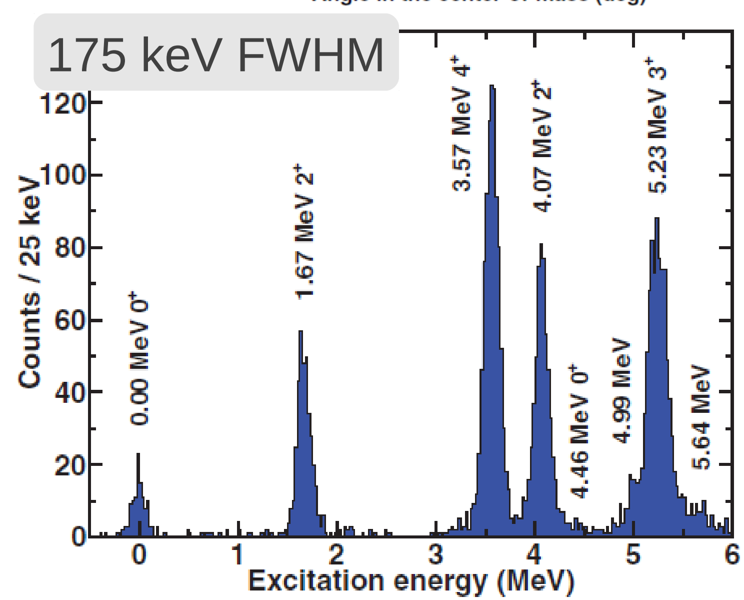
A. H. Wuosmaa et al., NIMA 580, 1290 (2007)
J. C. Lighthall et al., NIMA 622, 97 (2010)

$^{19}O(d,p)^{20}O$ data

- 8 states identified up to 7 MeV
- Absolute σ from deuteron scattering (20%)
- Angular distributions
  - Distorted wave Born approximation
  - Identified *l = 0* 3^+ level at 5.23 MeV

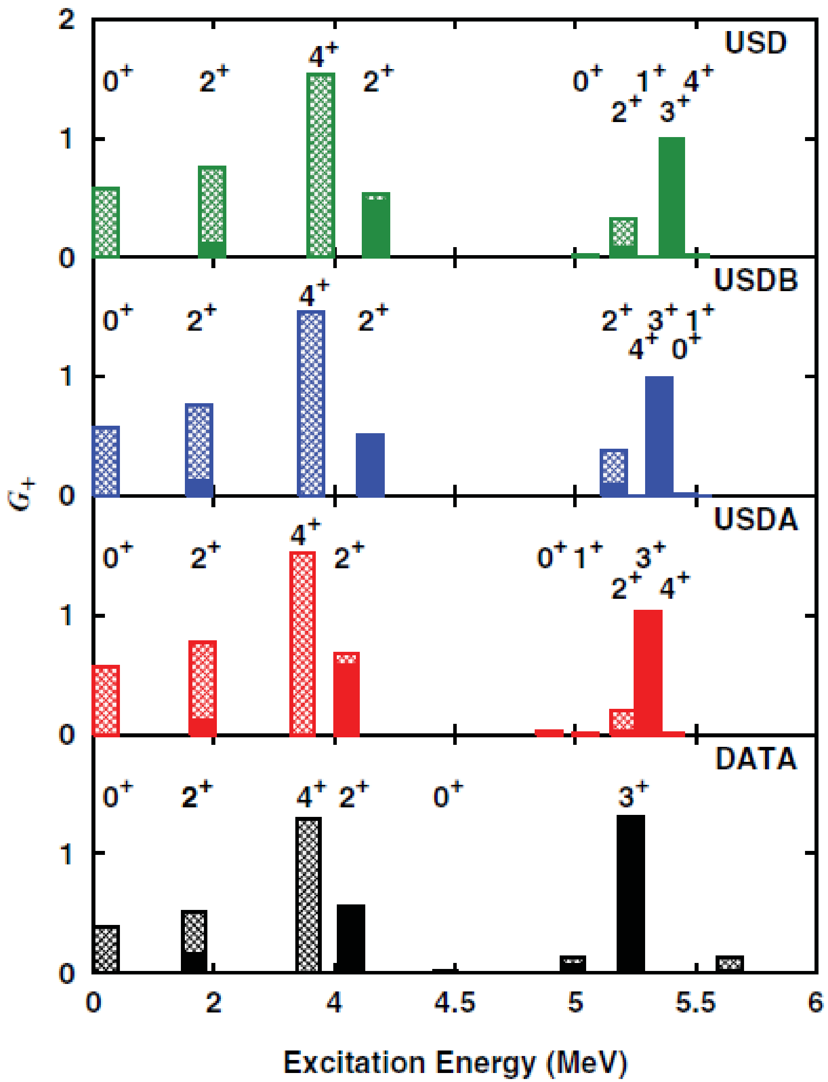






C. M. Perey and F. G. Perey, PR 132, 755 (1963); J. P. Schiffer et al., PR 164, 1274 (1967)

$^{19}O(d,p)^{20}O$ results



C. R. Hoffman et al., PRC 85, 054318 (2012)

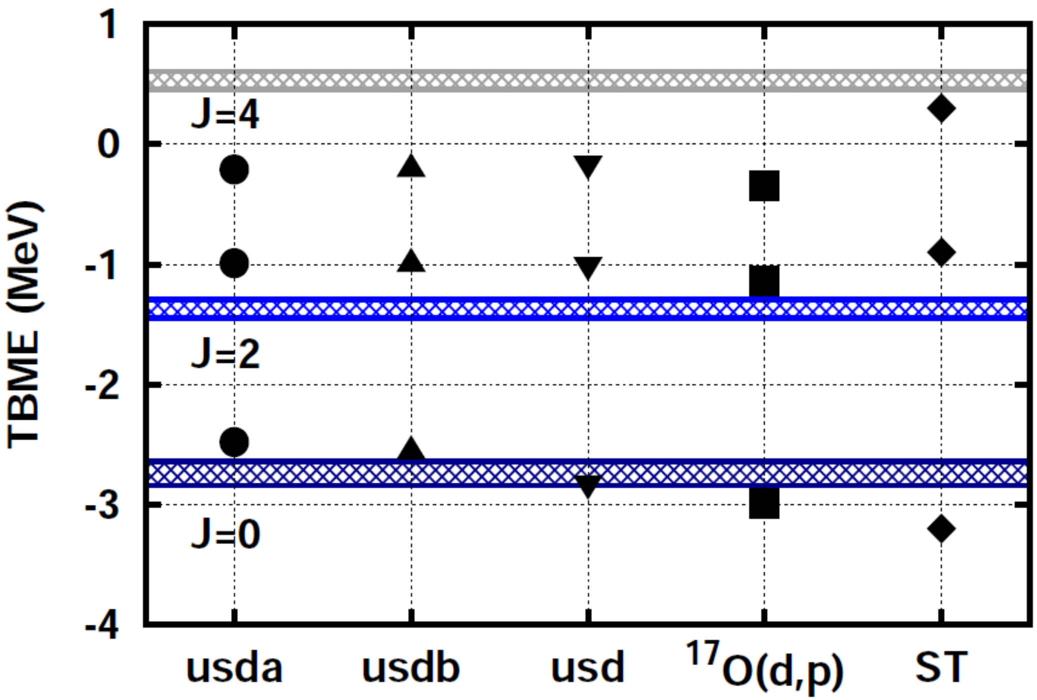
- Distorted wave analysis to extract spectroscopic factors
  - Normalized to $^{16}O(d,p)^{17}O$ data
  - 30% uncertainty in total
  - 15% relative to one-another
- Checks w/ sum rules & $^{18}O(d,p)^{19}O$ data
- Superb reproduction of strength by sd shell interactions
- Some strength to 2p-2h (1p-1h) dominated states
  - 0^+ @ 4.46 MeV
  - 4.99 or 5.64 MeV states
- SOLID → $l = 0$ HATCHED → $l = 2$

$$G_+ = \frac{2J_f + 1}{2J_i + 1} C^2 S,$$

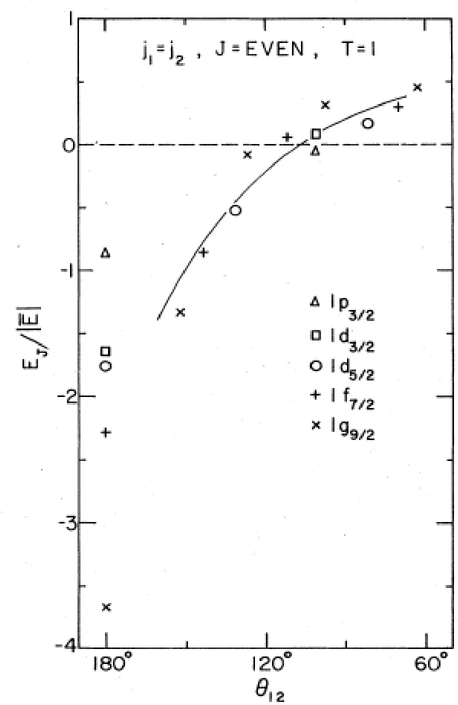
Diagonal T = 1 TBME of the empirical *NN* interaction

- Consider ^{20}O as two-neutron holes inside ^{22}O (N = 14 $0d_{5/2}$) neutron shell
  - ^{22}O is a good closed core
  - Most (>97%) measured strength belongs to $0d_{5/2}$

$$E_0 = 2B[^{21}\mathrm{O}] - B[^{20}\mathrm{O}] - B[^{22}\mathrm{O}] = -3.04(6)\ \mathrm{MeV}, \qquad \langle (d_{5/2})^2 J|V|(d_{5/2})^2 J\rangle = E_0 + \frac{\sum(2J+1)C^2S\cdot E^*}{\sum(2J+1)C^2S}.$$



J. P. Schiffer and W. W. True, Rev. Mod. Phys. 48, 191 (1976)
T. K. Li et al., PRC 13, 55 (1976)



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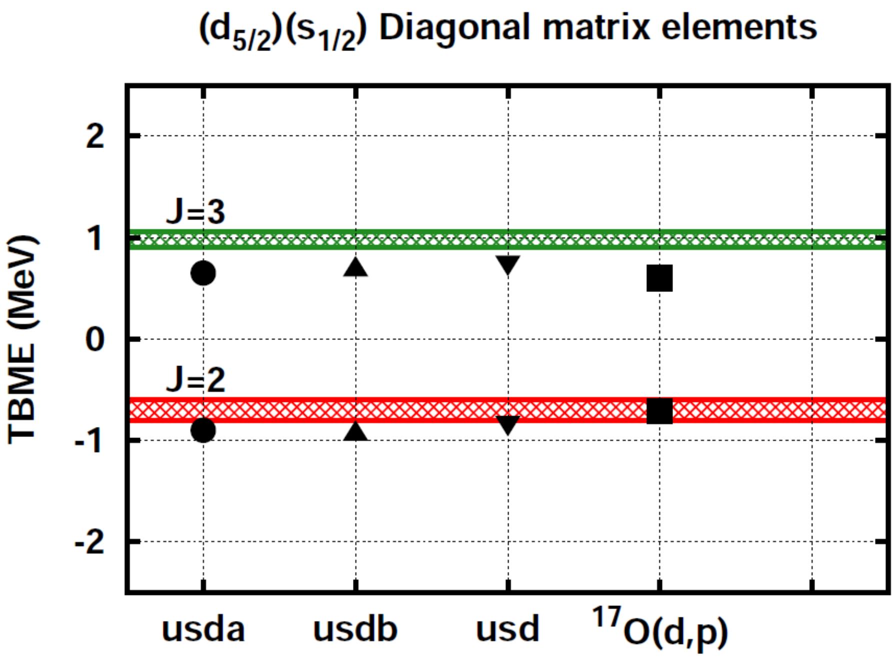
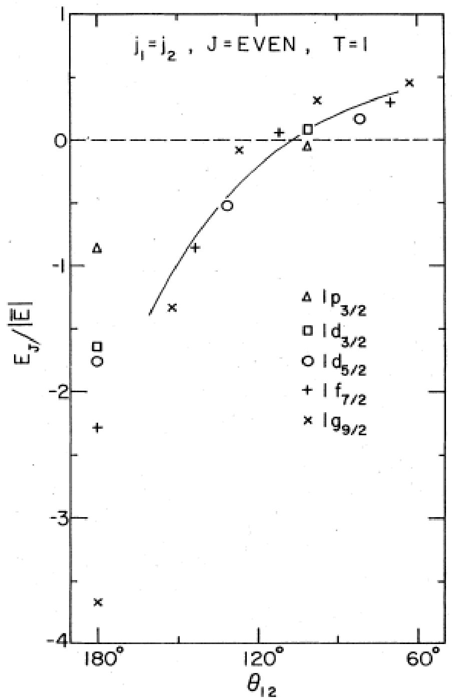
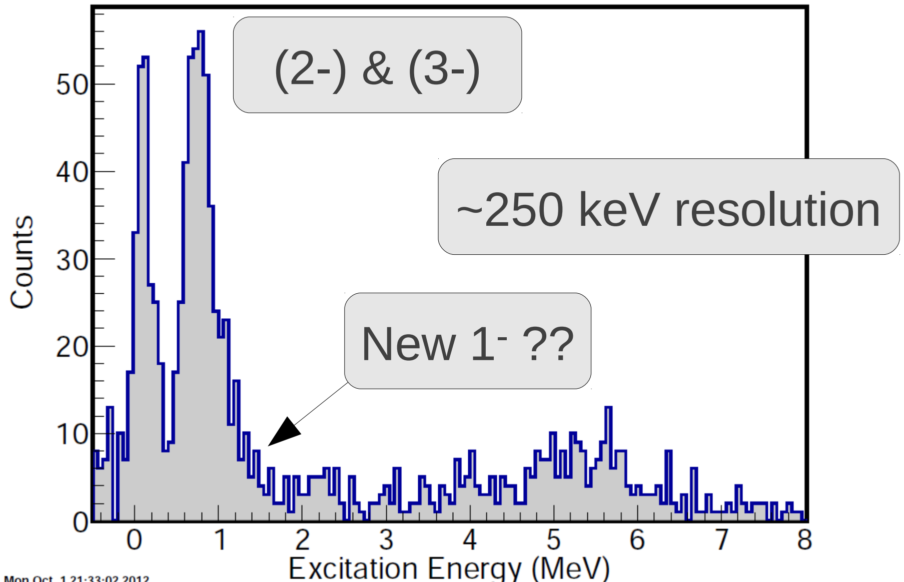
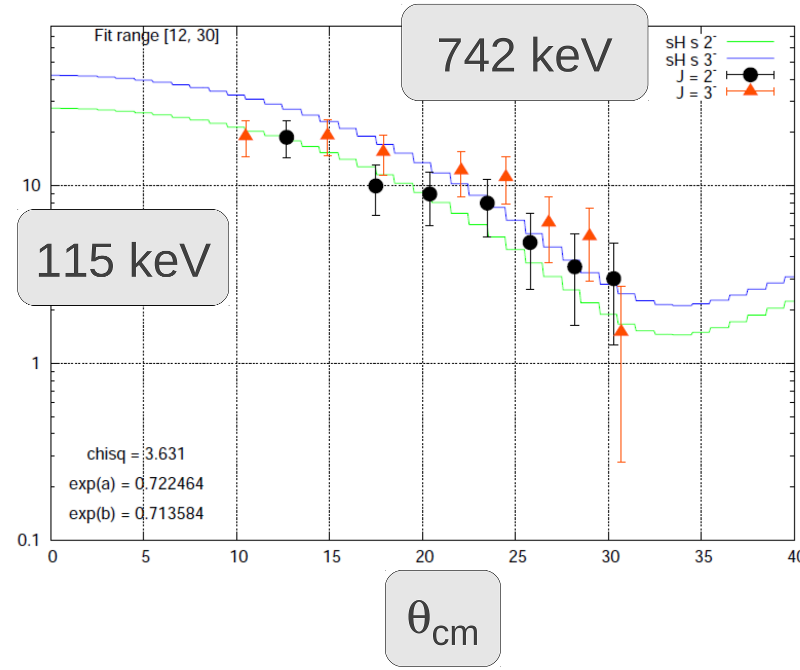


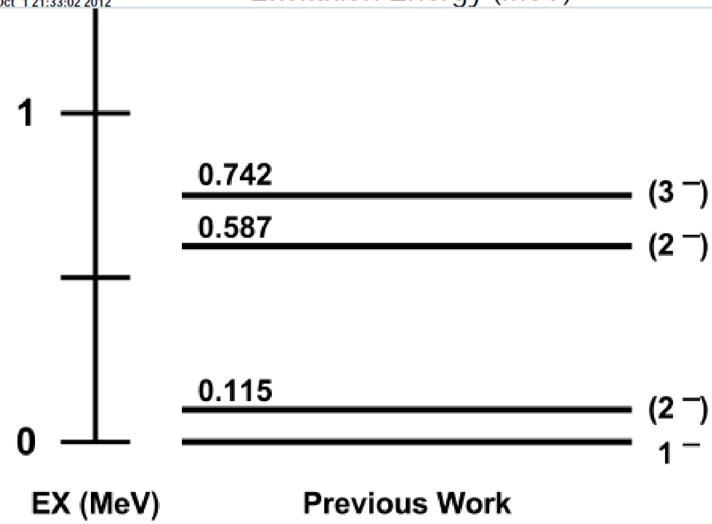


J. P. Schiffer and W. W. True, Rev. Mod. Phys. 48, 191 (1976)
T. K. Li et al., PRC 13, 55 (1976)

Preliminary $^{17}N(d,p)^{18}N$ results

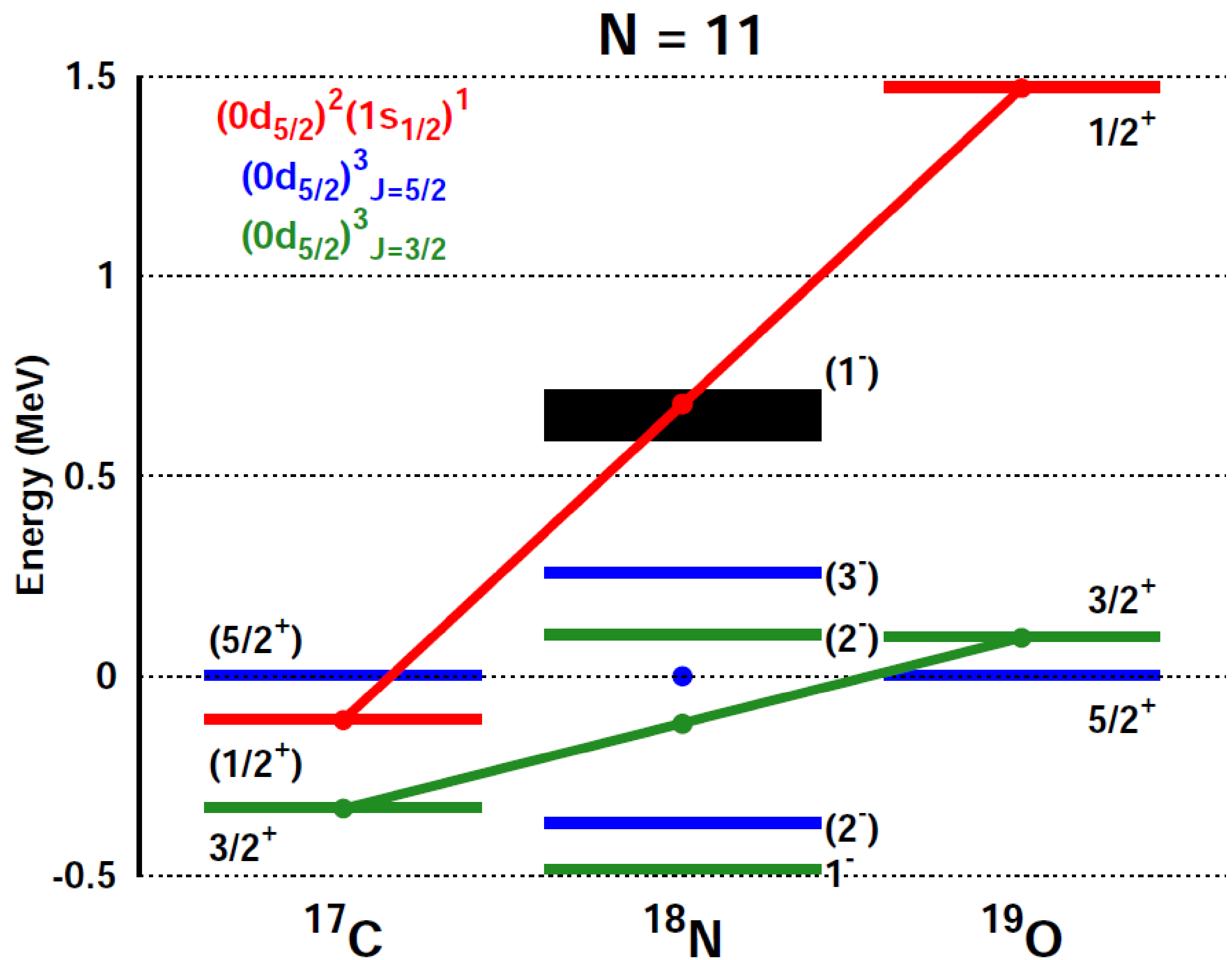




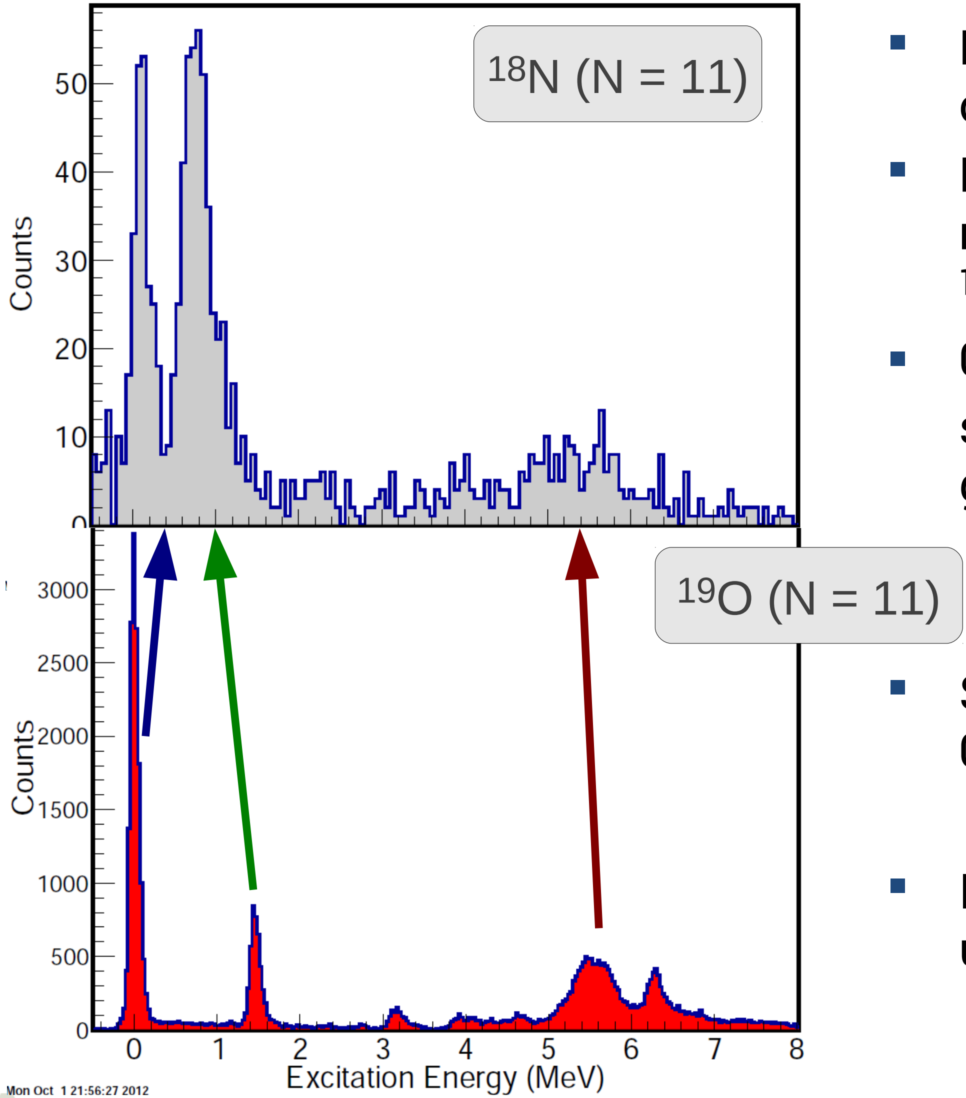


- Strength observed for states at 115 keV and 742 keV
- Consistant with *l = 2* states ($0d_{5/2}$)
- Tentative 2^-, 3^- states likely
- Preliminary relative C^2S are approximately equal

Preliminary $^{17}N(d,p)^{18}N$ results



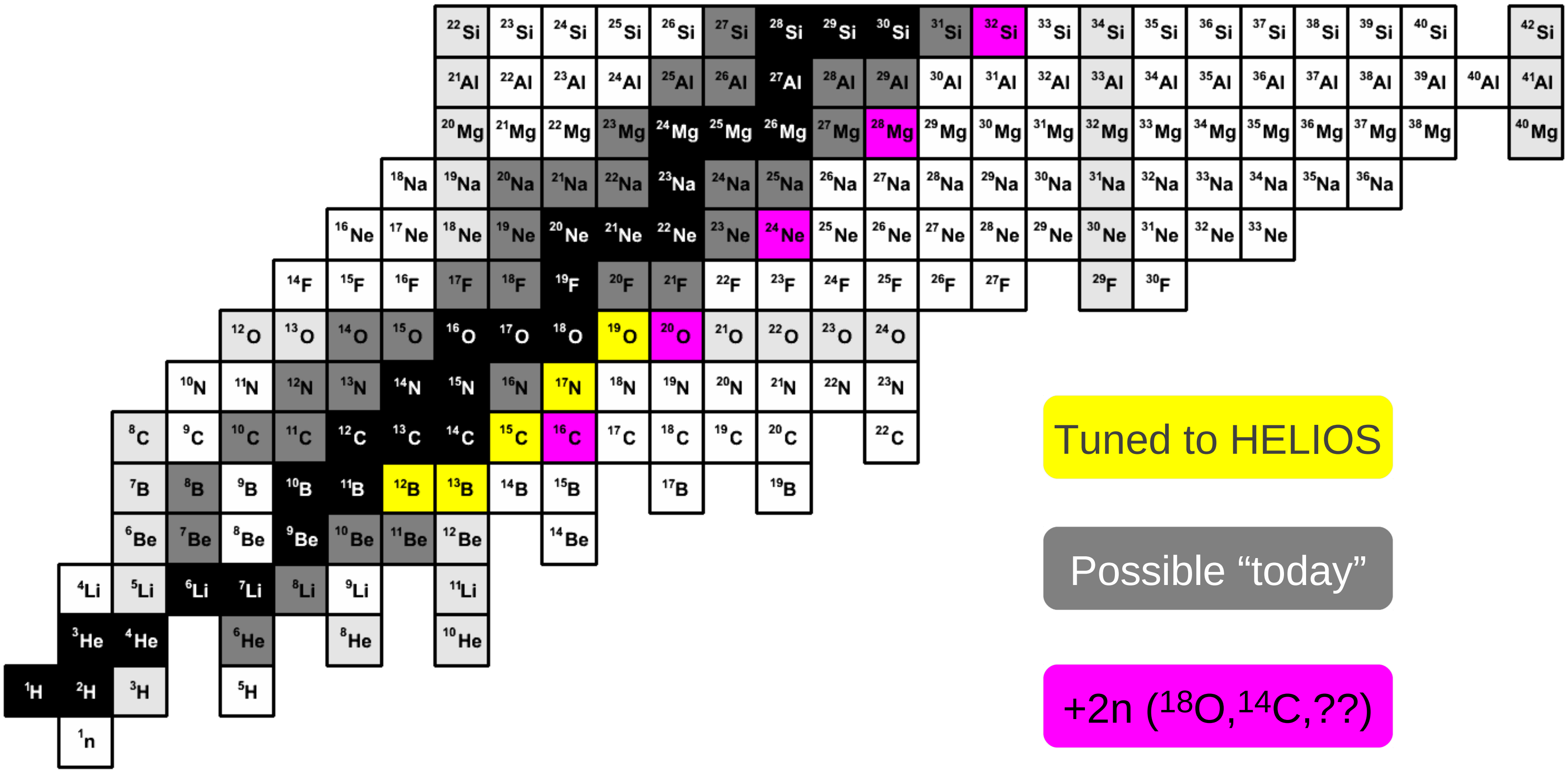
Preliminary $^{17}N(d,p)^{18}N$ results



- Rough locations of single-particle centroids
- Noticeable strength in the (d,p) reactions at ~5 – 6 MeV in ^{18}N and ^{19}O
- $0d_{3/2}$ location and evolution near stability extending out to the ground state in $^{25,26}O$

- Spin-orbit splitting between the $0d_{5/2}$ – $0d_{3/2}$ neutron orbitals
  – Test of >2N forces?
- Is detailed information like this useful??

Future works



Summary and conclusions

- Understanding shell evolution in nuclei is a leading area of research
- The oxygen isotopes provide a rich environment to approach single-particle evolution
- Large influx of data & theoretical investments has lead to leaps and bounds of understanding
  - Increasing the $0d_{3/2}$ single-particle energy is not the answer
  - 3-body forces are crucial to binding in Z = 8 nuclei
    - Do they consistently explain Z = 9 as well??
  - Calculations including the continuum show promise for unbound excited states
    - Combine w/ 3-body?
- Characterize the $0d_{3/2}$ orbital from stability to the drip line
- Used direct reactions with HELIOS to characterize the neutron sd orbitals
  - ^{17}N(d,p)^{18}N – track evolution as a function of proton occupancy
  - ^{19}O(d,p)^{20}O – track evolution as a function of neutron occupancy
- ^{17}N(d,p)^{18}N preliminary results
  - Consistant with single-particle level assignments, candidate for *l = 0* level
  - See high-lying strength (neutron unbound)
- ^{19}O(d,p)^{20}O results
  - $0d_{5/2}$ and $1s_{1/2}$ neutron strengths well described by sd shell model calculations
  - Extracted diagonal two-body matrix elements are in agreement with ^{17}O(d,p)^{18}O results as well as global survey

Acknowledgments

The HELIOS Collaboration

B.B. Back, B.P. Kay, J.P. Schiffer, M. Albers, M. Alcorta, S. Almaraz-Calderon, S.I. Baker, S. Bedoor, P.F. Bertone, J.A. Clark, C.M. Deibel, B. DiGiovine, S.J. Freeman, J.P. Greene, J.C. Lighthall, S.T. Marley, T. Palchan-Hazan, R.C. Pardo, G. Perdikakis, K.E. Rehm, A.M. Rogers, A. Rojas, D. Santiago-Gonzalez, D.K. Sharp, D.V. Shetty, J.S. Thomas, I. Wiedenhover, and A.H. Wuosmaa

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University of Tokyo – T. Otsuka & K. Tsukiyama