B(E2) Transition Strengths of Neutron-rich Carbon Isotopes in a Seniority Scheme

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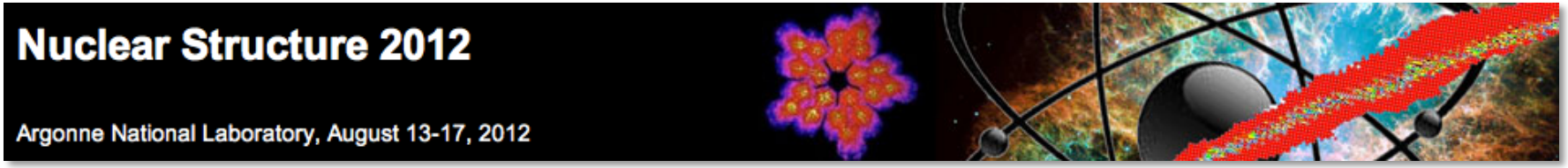

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How is nuclear physics affected by neutron excess and weak binding?

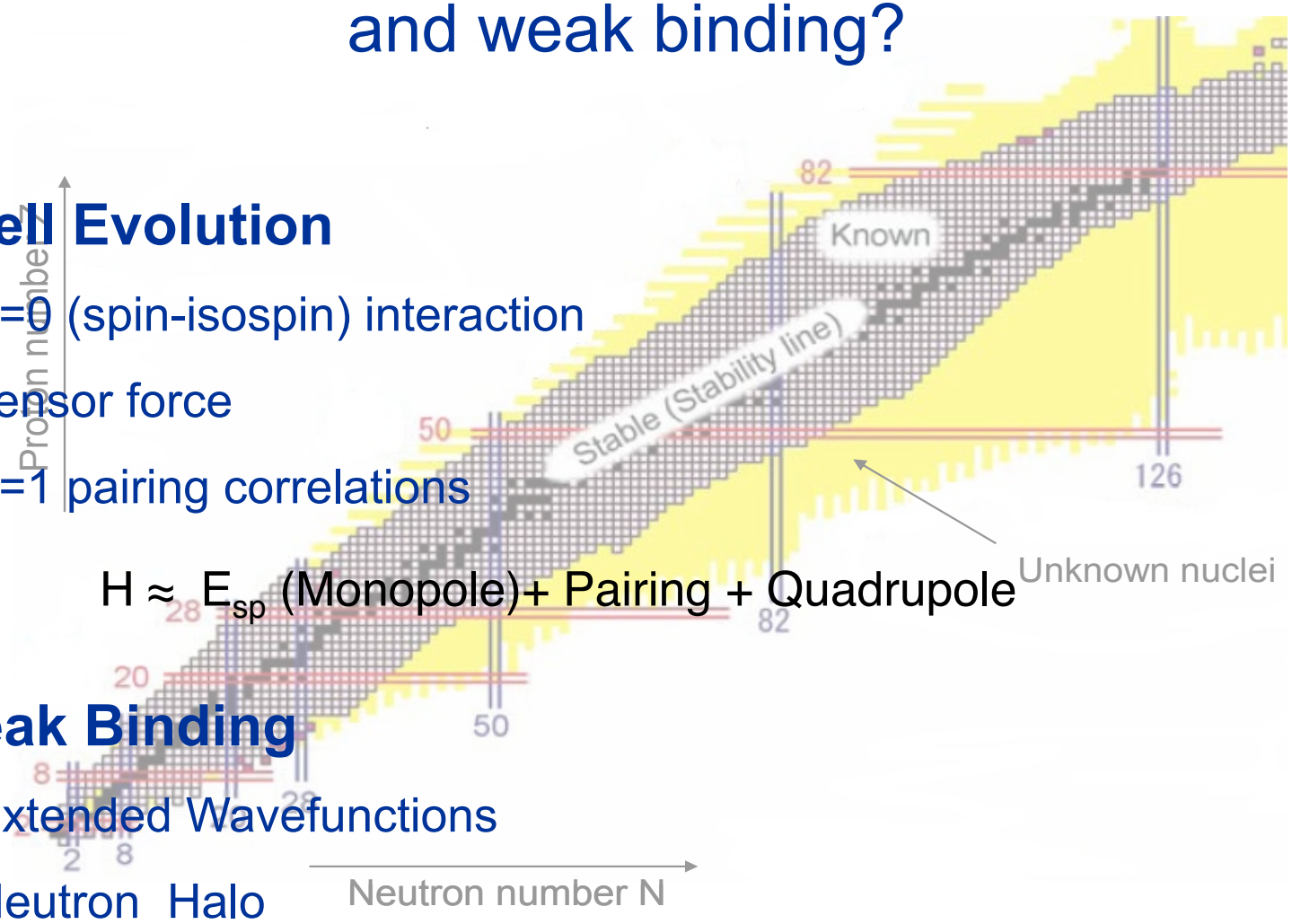
Shell Evolution

- T=0 (spin-isospin) interaction
- Tensor force
- T=1 pairing correlations

$$H \approx E_{sp}\ (\text{Monopole}) + \text{Pairing} + \text{Quadrupole}$$

Weak Binding

- Extended Wavefunctions
- Neutron Halo

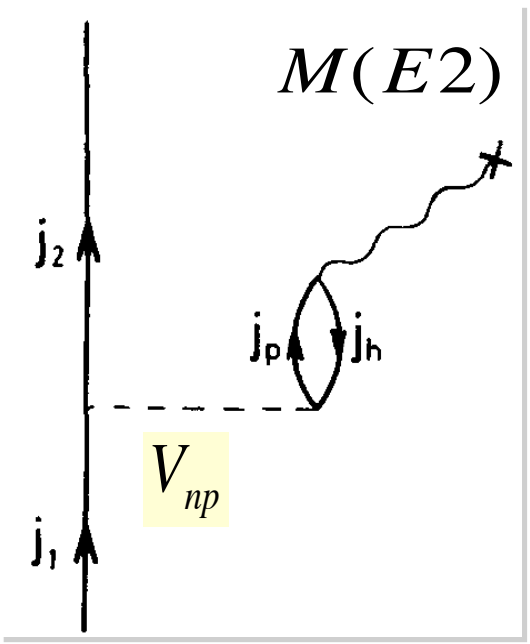


Neutron-rich Carbons provide unique cases to study

Experimentally accessible up to the drip line, systematically examine spectroscopic information

Opportunity to understand how the proton and neutron degrees of freedom are coupled near the drip line

$$B(E2; J_i \rightarrow J_f) = \frac{1}{2J_i + 1} |e < J_f \| M(E2) \| J_f >|^2 \propto \frac{1}{E_\gamma^5 \tau}$$



$$M(E2) = \sum_p r_p^2 Y^2(\theta, \phi)$$

$$\delta M(E2)_n \approx \frac{V_{np}}{\Delta E} M(E2)_n Z$$

$$e_n^{eff} \approx \frac{V_{np}}{\Delta E} Z \qquad e_p^{eff} \approx 1 + \frac{V_{pp}}{\Delta E} Z \approx 1 + e_n^{eff}$$

Spatially extended valence particles have less influence on the core.

Reduced *polarization* may manifest itself in B(E2)'s

Anomalous effective charge

Campaign of experiments at NSCL to measure the lifetimes of the 2^+ states in $^{16,18,20}C$.

Recoil Distance Method with fast beams ($\beta \sim 0.4$)

2^+ states populated in knockout reactions

PRL 107, 102501 (2011) PHYSICAL REVIEW LETTERS week ending 2 SEPTEMBER 2011

Lifetime Measurement of the 2_1^+ State in ^{20}C

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PHYSICAL REVIEW C **86**, 011303(R) (2012)

Excited-state transition-rate measurements in ^{18}C

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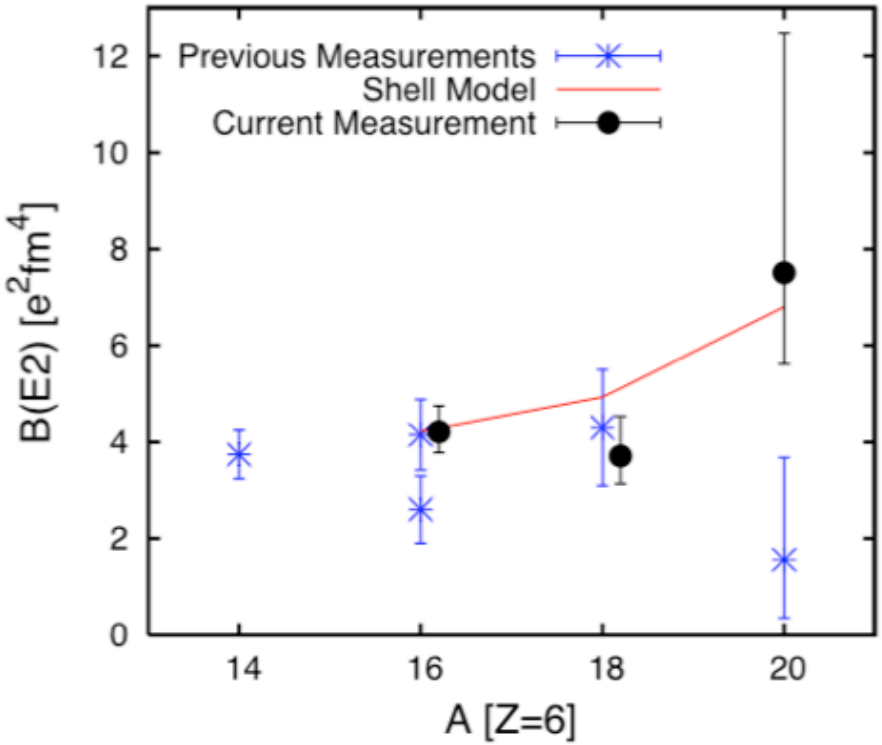


S. Raman et al., ADNDT 36, 1 (1987)
N. Imai et al., PRL 92, 062501 (2004)
M. Wiedeking et al., PRL 100, 152501 (2008)
H. J. Ong et al., PRC 78, 014308 (2008)
Z. Elekes et al. PRC 79, 011302(R) (2009)

M.Petri et al. **^{20}C: PRL 107, 102501 (2011)**
^{16}C: Submitted to PRC

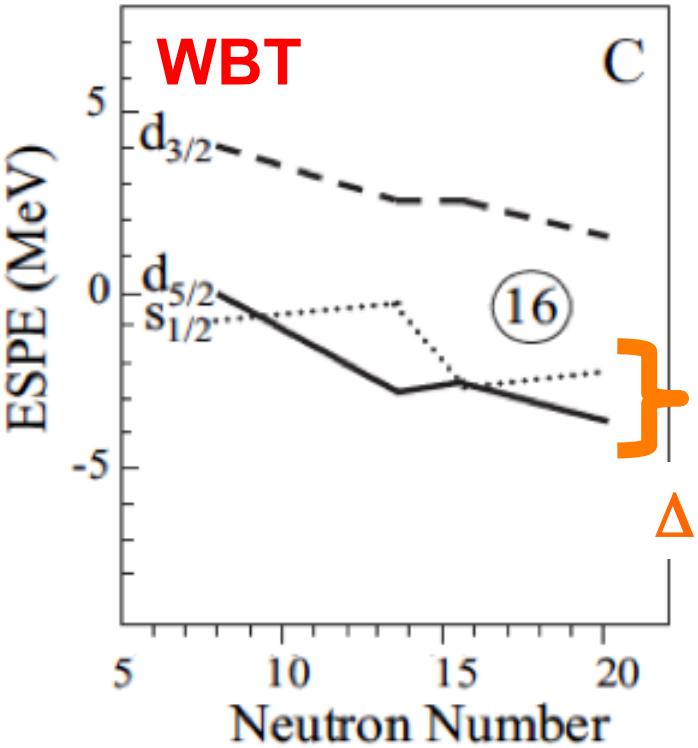
P.Voss et al. **^{18}C: PRC 86, 011303(R) (2012)**

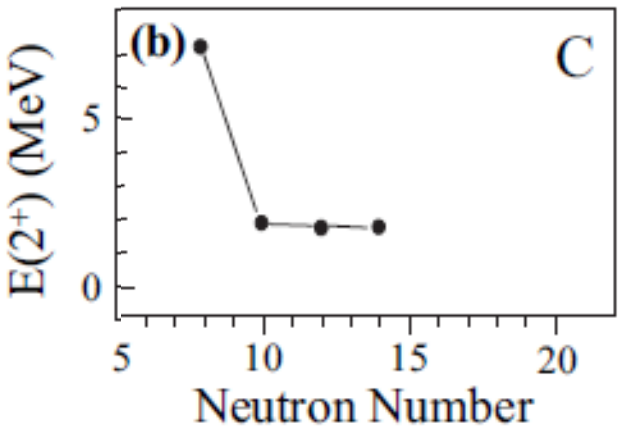
Shell Model: WBT interaction (B.A.Brown)

Effective charges: Sagawa *et al.,* PRC 70, 054316 (2004)

Can we consider a description in terms of a *seniority inspired scheme ?*

I. Talmi, Simple Models of Complex Nuclei.
I. Morales, P. Van Isacker and I. Talmi PLB **703** (2011) 606
M.Caprio et al. PRC **85** 0343324 (2012)



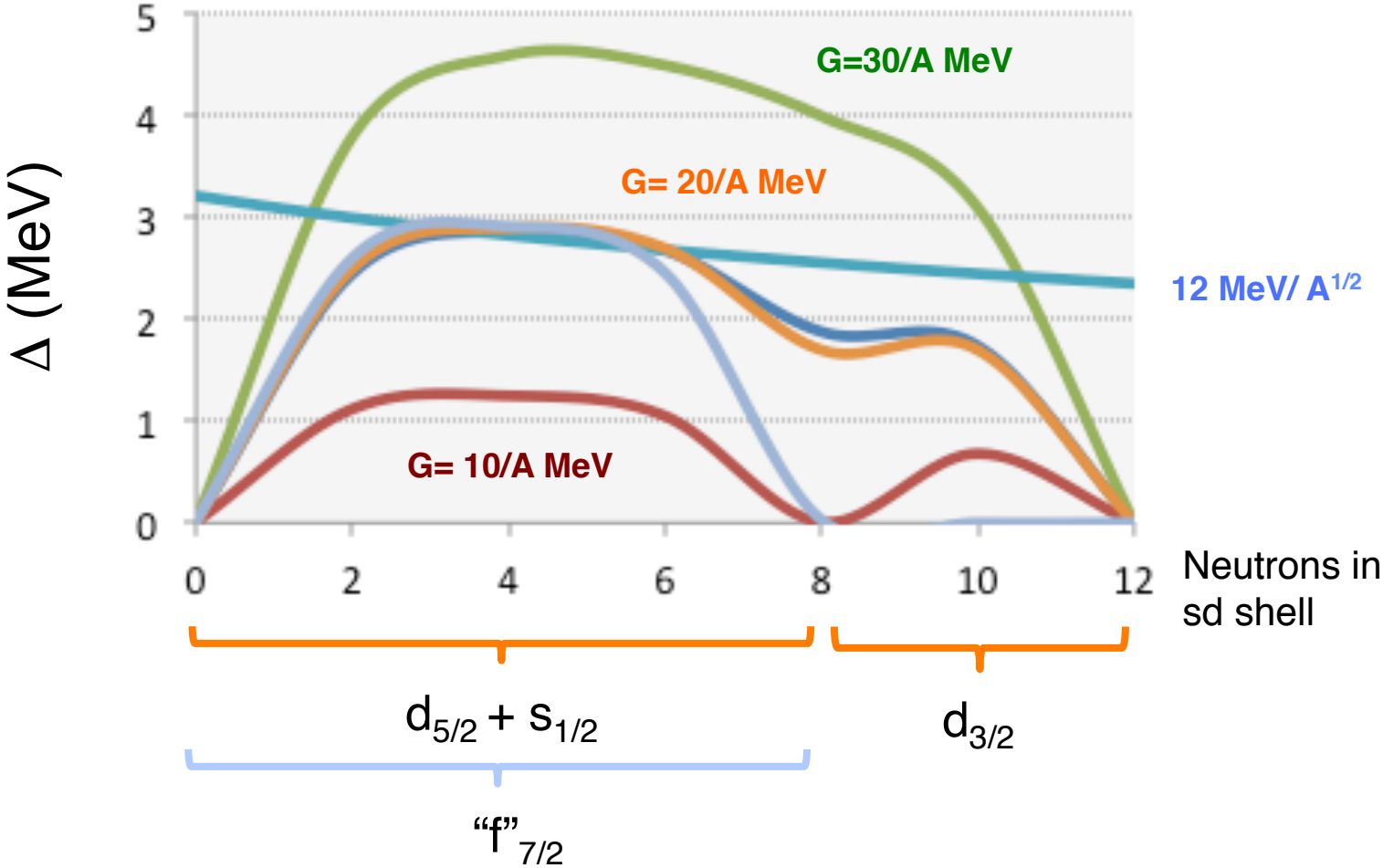


Δ ~ 3MeV

M. Stanoiu *et al.*, PRC 78, 034315 (2008)

Pairing dominates over the single particle spacing ($E_s_{1/2} - E_d_{5/2}$) :

→ **One effective shell 2j+1=8 ($\nu s_{1/2} + \nu d_{5/2}$)**



Neutron shell closed at ^{14}C (N=8) and ^{22}C (N=16)

PRL **105,** 132501 (2010) PHYSICAL REVIEW LETTERS week ending 24 SEPTEMBER 2010

$^{15}C(d, p)^{16}C$ Reaction and Exotic Behavior in ^{16}C

A. H. Wuosmaa,[1] B. B. Back,[2] S. Baker,[2] B. A. Brown,[3] C. M. Deibel,[2,4] P. Fallon,[5] C. R. Hoffman,[2] B. P. Kay,[2] H. Y. Lee,[6] J. C. Lighthall,[1,2] A. O. Macchiavelli,[5] S. T. Marley,[1,2] R. C. Pardo,[2] K. E. Rehm,[2] J. P. Schiffer,[2] D. V. Shetty,[1] and M. Wiedeking[7]

"*In-flight*" production of ^{15}C at ANL from $^{14}C(d,p)^{15}C$ at 8.2 MeV/A

HELIOS

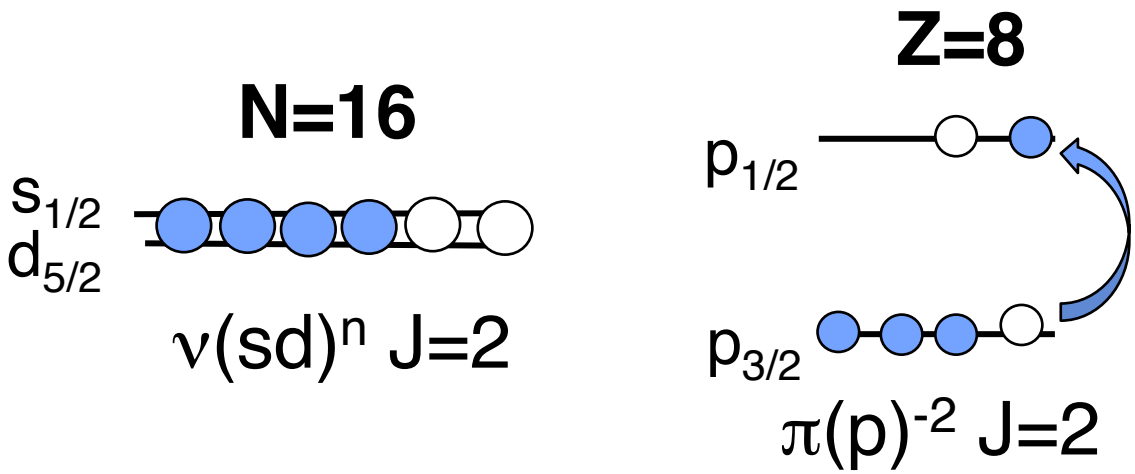
Nucleus	State	E_{exp} (MeV)	S_{exp}
^{16}C	0_1^+	0.000	0.60(.13)
^{16}C	0_2^+	3.027	1.40(.31)

$$|0_1^+>_n \approx 0.55\,|s_{1/2}^2> + 0.84\,|d_{5/2}^2>$$

$$|0_1^+>_n \approx 0.73\,|s_{1/2}^2> + 0.68\,|d_{5/2}^2>$$

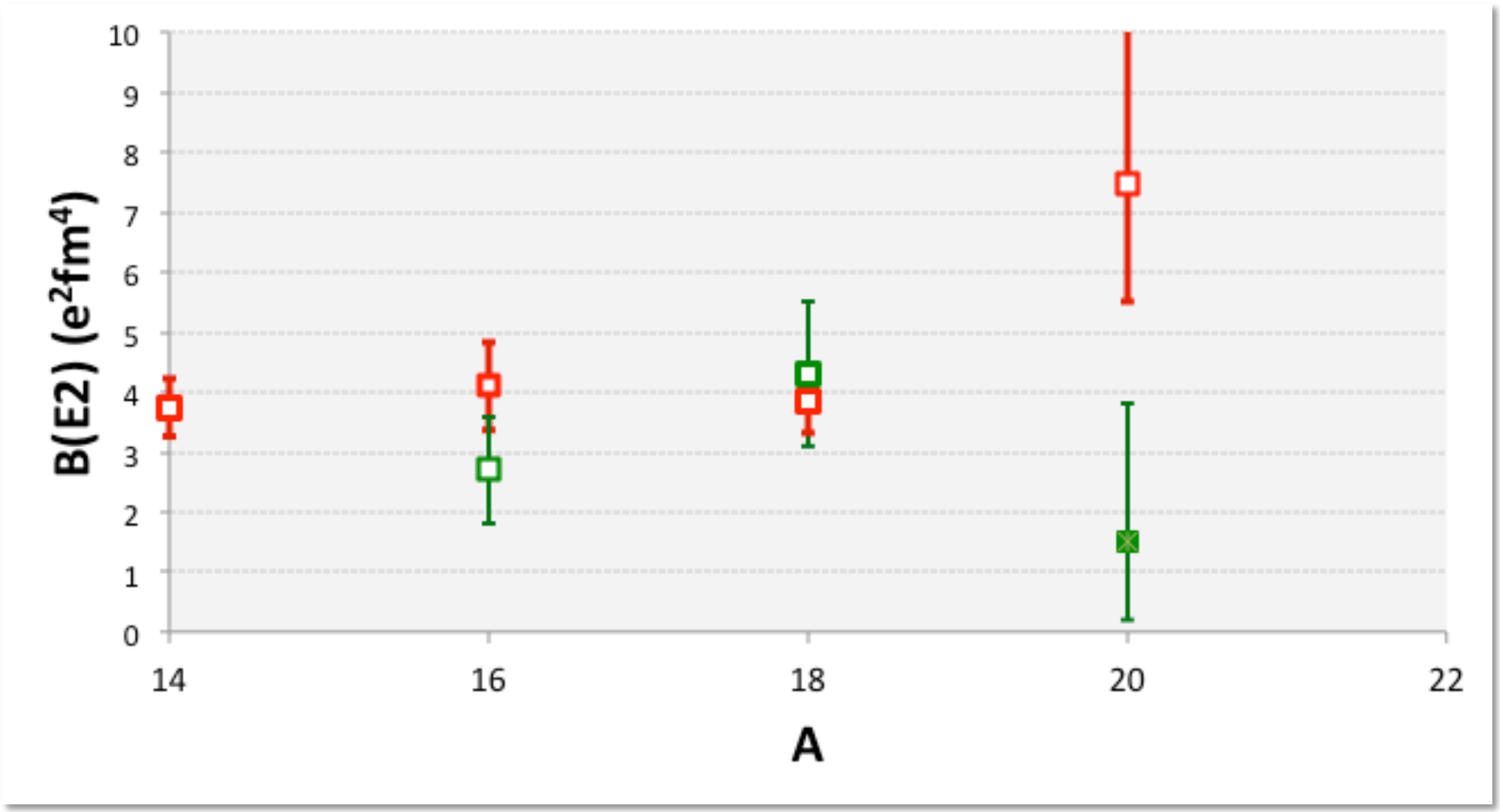
R.D. Lawson et al. PRC**14** 1245(1976)

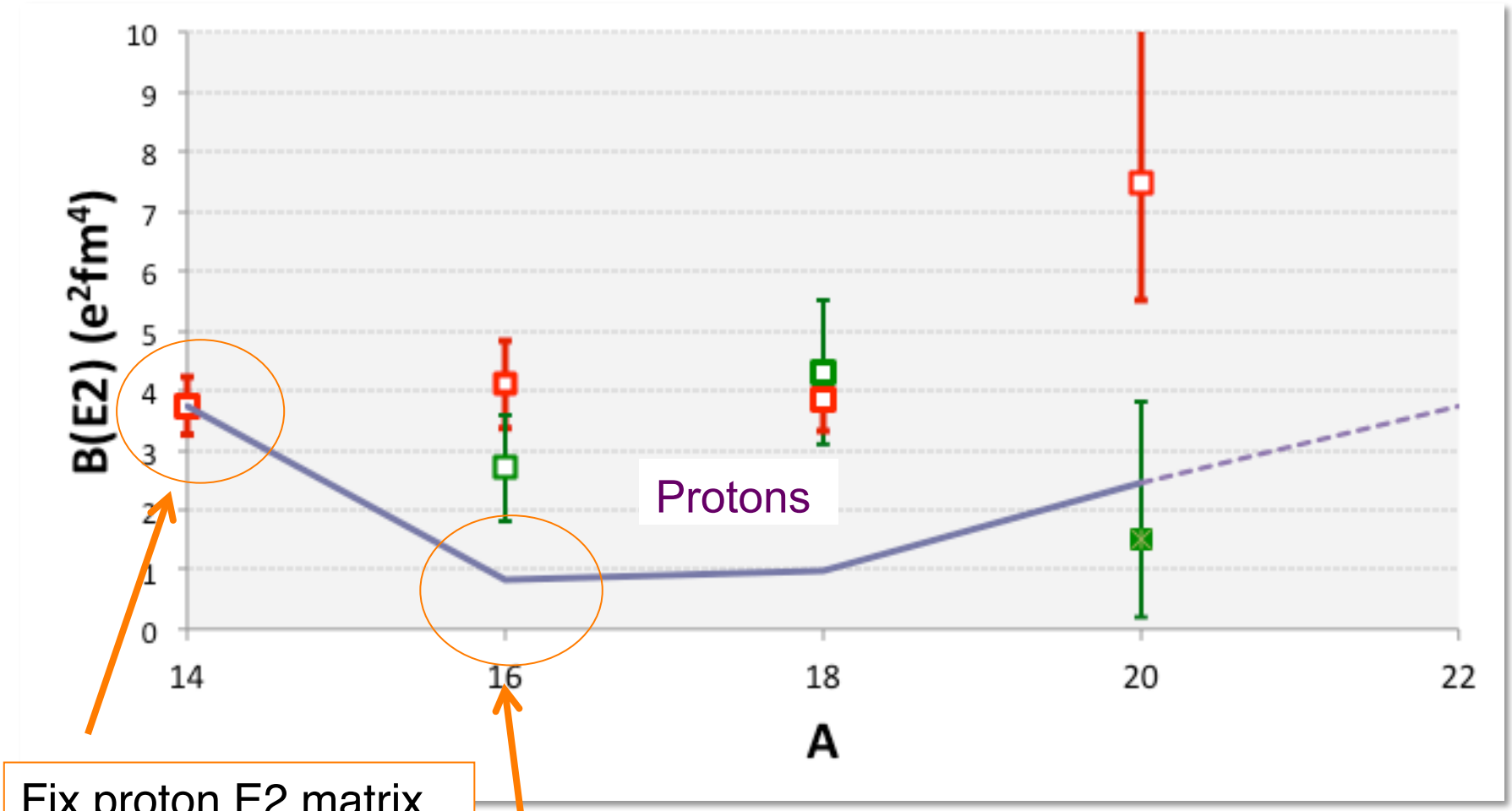
- Rather constant energy of the 2^+
- Large proton-gap, p-h excitation



$$\left|2_1^+\right\rangle = \alpha\left|\nu\left(ds\right)^n\right\rangle + \beta\left|\pi\left(p\right)^{-2}\right\rangle$$

$$B(E2)_n = \frac{n(2j+1-n)}{2(2j-1)} B(E2)_{n=2}$$


B(E2) (e²fm⁴)
10
9
8
7
6
5
4
3
2
1
0
14
16
18
20
22
A



Fix proton E2 matrix element

G.Kasch et al. NPA**178** (1971)

Fix proton amplitude from ^{17}N KO to 2^+ and 0^+

The structure of ^{16}C: Testing shell model and *ab initio* approaches

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Experiment at NSCL - SeGA and S800

^{9}Be (^{17}N, ^{16}C + γ)X at 72MeV/A

$\sigma(2^+)/\sigma(0^+) = 0.28 \pm 0.02$

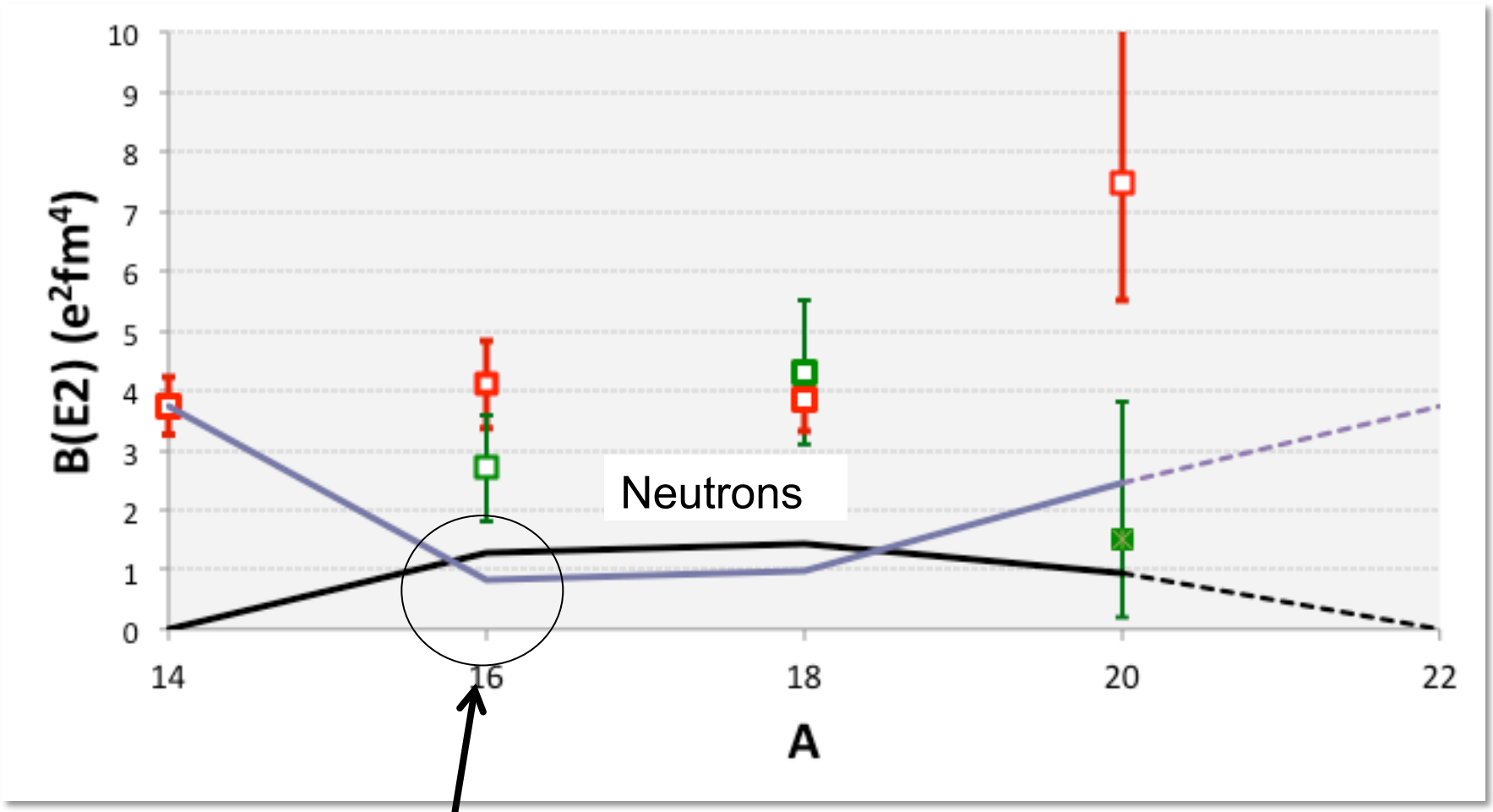
$$|1/2^-; {}^{17}\mathrm{N}\rangle = |\nu(sd)^2; J=0\rangle \otimes |\pi(p)^{-1}; J=1/2\rangle$$

$$|2_1^+; {}^{16}\mathrm{C}\rangle = \alpha|\nu(sd)^2; J=2\rangle \otimes |\pi(p)^{-2}; J=0\rangle + \beta|\nu(sd)^2; J=0\rangle \otimes |\pi(p)^{-2}; J=2\rangle$$

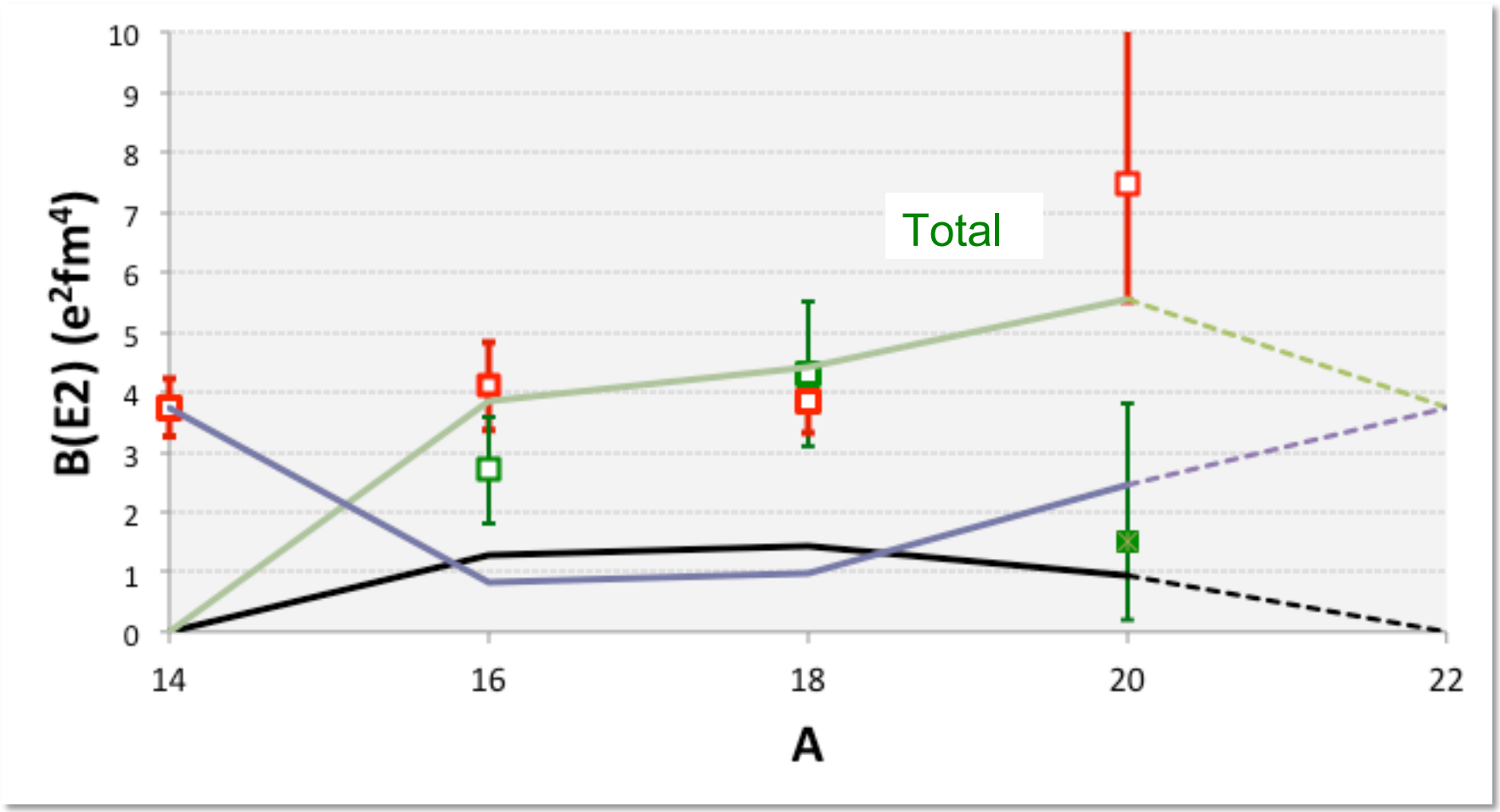
$$|0^+; {}^{16}\mathrm{C}\rangle = |\nu(sd)^2; J=0\rangle \otimes |\pi(p)^{-2}; J=0\rangle$$

$$\sigma(2_1^+)/\sigma(0_1^+) \approx C^2S(2_1^+)/C^2S(0_1^+) \approx \beta^2 \times 5/2$$

$$\Rightarrow \quad \boxed{\beta^{2'} \approx 11(1)\%}$$



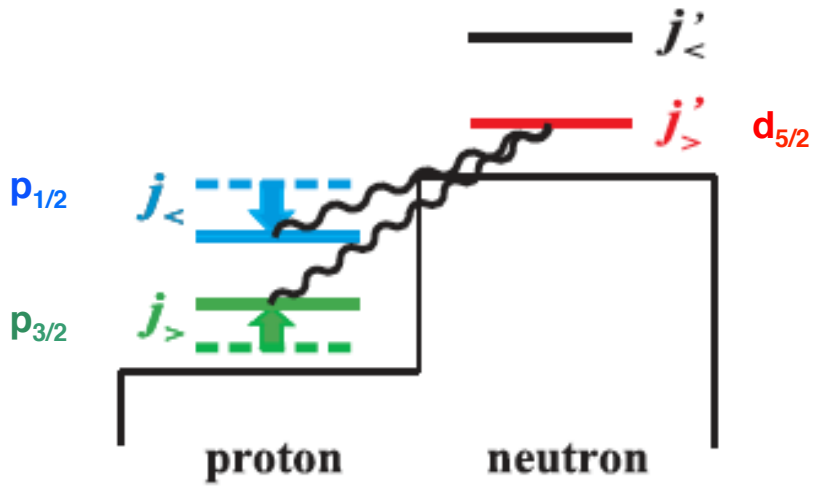
Fix B(E2)n=2



Increased role of the proton component

Increased role of the proton component

Reduced $p_{3/2}$-$p_{1/2}$ spin-orbit splitting



Otsuka et al. PRL **95** 232502 (2005)

Federman et al. Phys. Lett **140B** (1984)

Similar case in the Sr-Zr region

$2p_{3/2}$-$2p_{1/2}$ spin-orbit splitting

$p_{3/2}$ and $p_{1/2}$ similar orbital motion :
small effect from central force, mainly tensor

$$\Delta E_{p(j)} = \frac{1}{2}\{V^{T=0}_{j,j'} + V^{T=1}_{j,j'}\}\, n(j')$$

$$V^{T}_{j,j'} = \frac{\sum_J (2J+1)\langle jj'|V|jj'\rangle_{JT}}{\sum_J (2J+1)}$$

Monopole Average

Schiffer-True interaction

$$\Delta E_{p3/2-p1/2} = \{-.0.35MeV(Tensor) - 0.05MeV(Central)\}n_{d5/2}$$

$$\Delta E_{p3/2-p1/2}(^{20}C - {}^{14}C) \approx -2.4MeV$$

Proton Knockout Spectroscopic Factors $^{A+1}N \rightarrow {}^{A}C$

1-p knockout population of 2^+ proceeds through the proton component

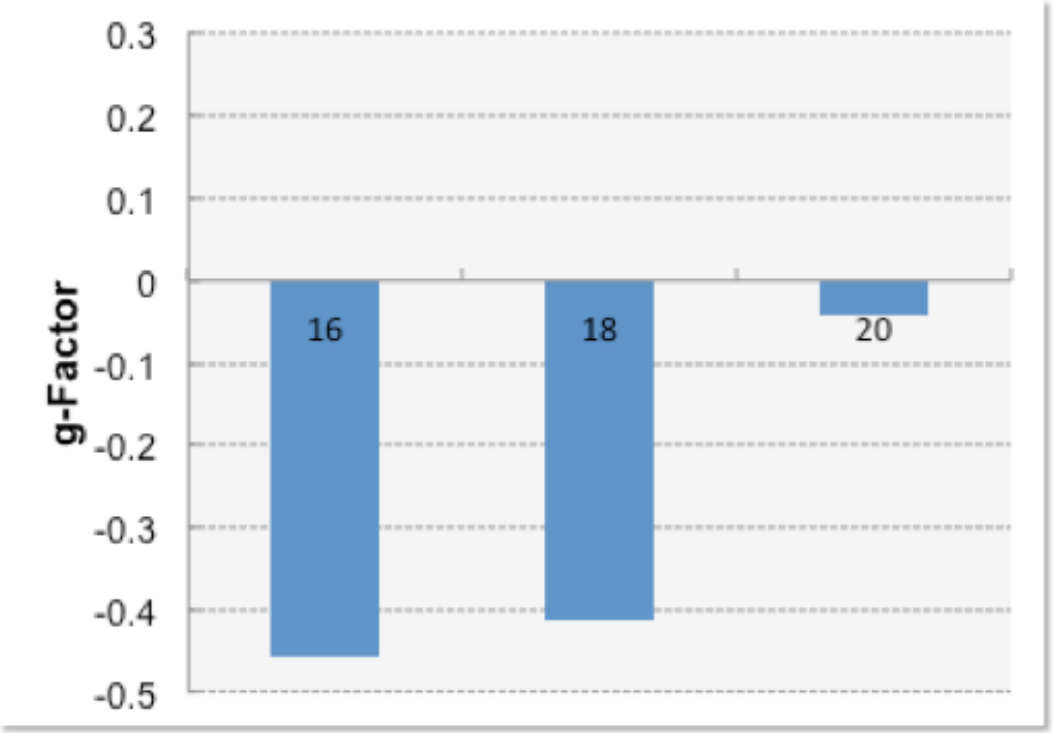
$$\sigma(2_1^+)/\sigma(0_1^+) \approx C^2S(2_1^+)/C^2S(0_1^+) \approx \beta^2 \times 5/2$$

Calculated	^{16}C	^{18}C	^{20}C
WBT	5%	9%	25%
Seniority	11%	13%	> 30%

2^+ Magnetic Moments

Sensitive probe of proton contribution

$$g_{2^+} = \alpha^2 g_\nu + \beta^2 g_\pi$$



$g_\nu = -0.69$ *from* ^{15}C $\qquad$ $g_\pi = 1.45$ *from* ^{13}B *and* ^{15}N

Summary and Conclusions

- **The Carbon isotopes provide an interesting ground to study the evolution of shell structure with isospin and the influence of weak binding.**

- **E2 Transition rates offer a unique probe to isolate these effects.**

Quantitative test of models requiring a consistent descriptio from stability to the dripline.

In particular No-core and ab-initio (3-body), *Navratil, Roth, et al*. .

The increase in the B(E2) can be described in a seniority scheme including the contribution from proton excitations in the p-shell.

A weakening of the proton $p_{3/2}$-$p_{1/2}$ spin-orbit splitting due to the tensor force with the $d_{5/2}$ neutrons increases the proton contribution in the 2^+ .

The proton amplitude can be measured with direct reactions and magnetic moment measurements.