A study of neutron-rich carbon isotopes

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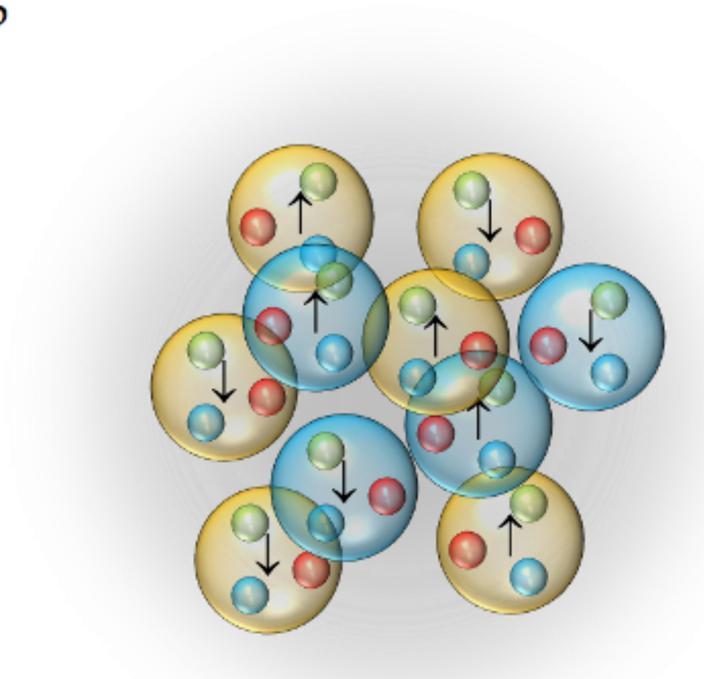
STRUCTURE OF LIGHT NUCLEI

Institute for Nuclear Theory Workshop
Seattle, WA, October 8-12, 2012

Part of the Institute for Nuclear Theory Program
Light Nuclei from First Principles

We have seen the emergence of new and improved theories and computational methods leading to remarkable progress in our understanding of the nuclear force and our ability to describe nuclei from first principles. In this pursuit, the study of light nuclei provides an important challenge and testing ground.

This workshop explores nuclear structure, nuclear forces, and ab initio methods. How do first principles calculations compare with precision experiments? What can we say about underlying structures? What are the remaining challenges and how do we go forward?



Outline

- Introduction
  - physics motivation
  - review carbon properties
  - transition rates
- Data ^{16}C, ^{18}C, ^{20}C
  - A focus on MSU experiments
- Interpretation
  - “standard” shell model (psd space)
  - seniority
  - ab-initio calculations (no-core shell mode)
- ^{40}Mg

Evolution of single particle levels

➢ In a well bound nucleus

- steady evolution of energy levels in a 1 body potential

- modified by 2-body NN interaction (σ.τ, Tensor)

➢ A second distinct effect is due to weakly bound levels

- low *l* levels (*s*, *p*) → extended wavefunctions ("halos")

- Valence nucleons can become decoupled from the core

- Coupling to continuum states

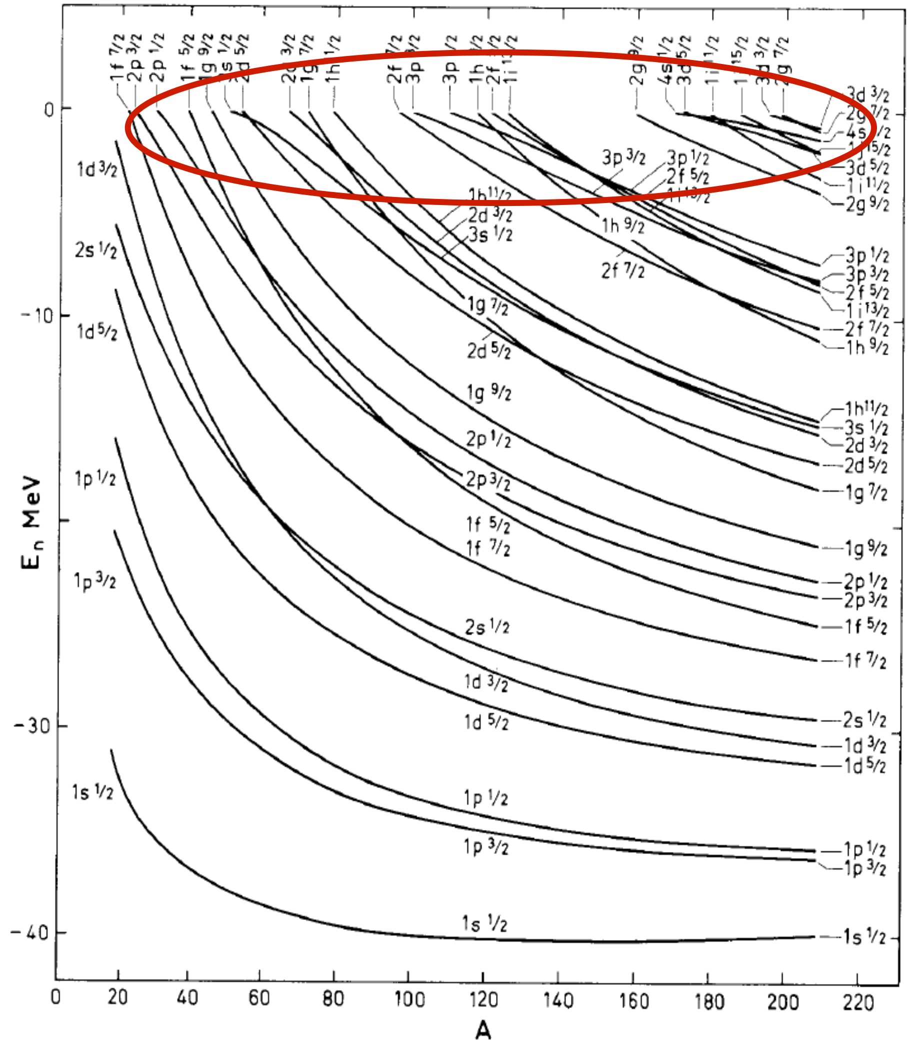


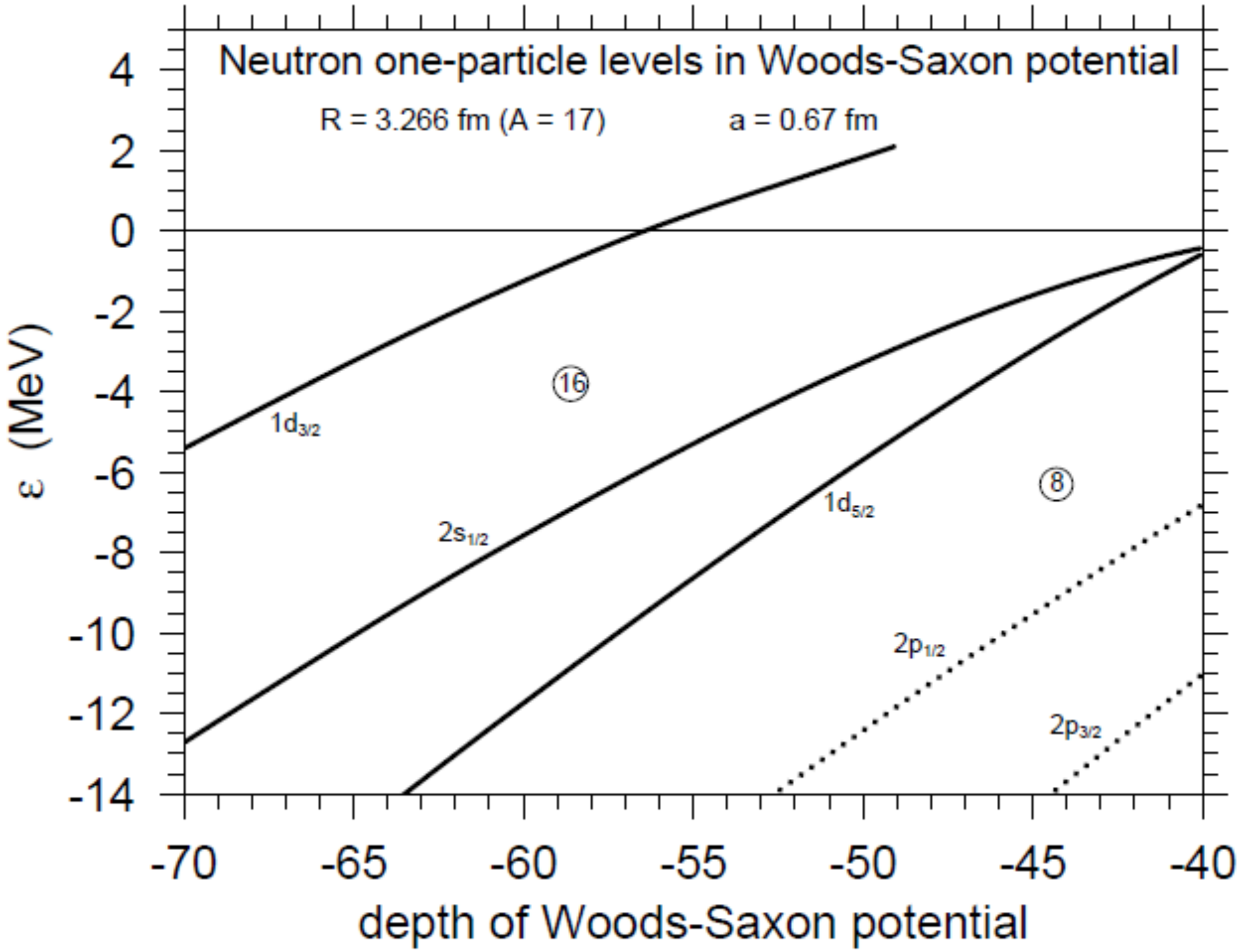
Figure 2-30 Energies of neutron orbits calculated by C. J. Veje (private communication).

A.Bohr and B.R. Mottelson, vol. 1

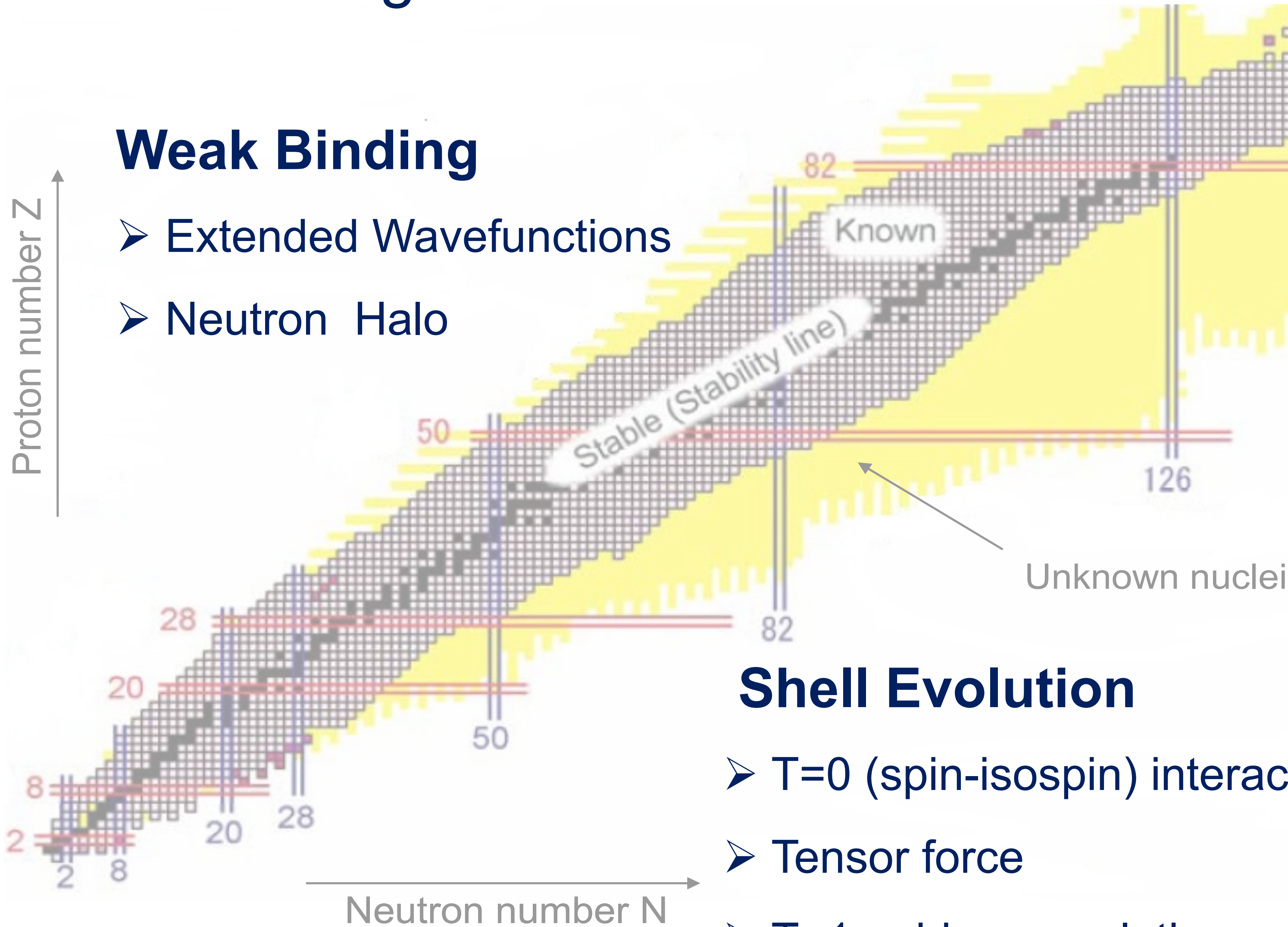
PHYSICAL REVIEW C **76, 054319 (2007)**

Nilsson diagrams for light neutron-rich nuclei with weakly-bound neutrons

Ikuko Hamamoto



How are nuclear properties affected by weak binding and neutron excess?



Weak Binding

- Extended Wavefunctions
- Neutron Halo

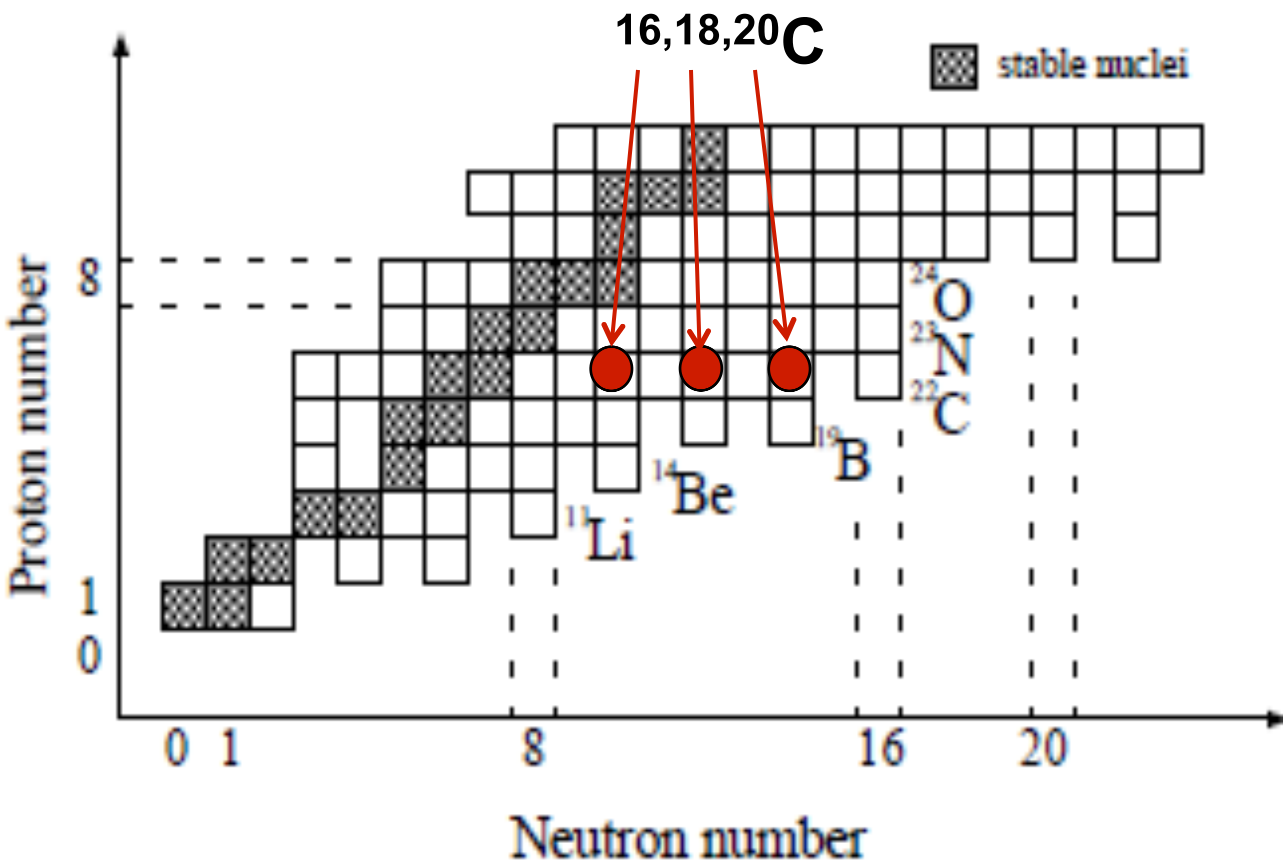
Shell Evolution

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

Some Properties of Carbon Nuclei

Why study neutron-rich Carbons?

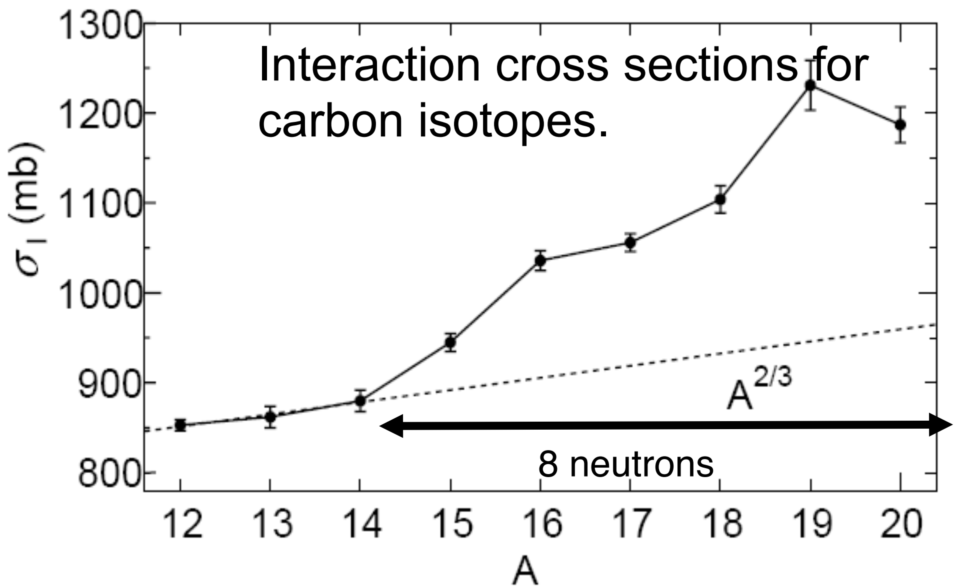
- Experimentally accessible to the drip line
- Provide a quantitative test of theory



Carbon Nuclei

- N=8 closed p-shell (^{14}C)
- N=16 dripline ^{22}C (cf ^{24}O)
- Occupation of $\nu(s_{1/2})$ ($A \geq 15$)
- Weak binding (^{15,17,19}C)
  - ^{22}C di-neutron halo

F.Rintaro. PhD Thesis (U.Tokyo 2002)
Data from A. Ozawa, et al., NPA691, 599 (2001).



N > 8

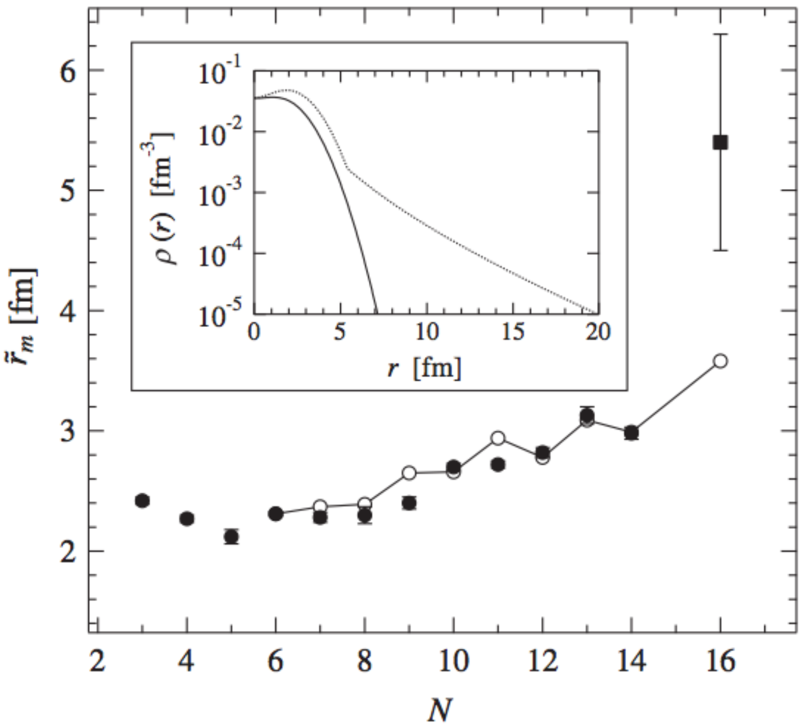
- g.s. large $\nu s_{1/2}$ component
- 2^+ dominant neutron excitation

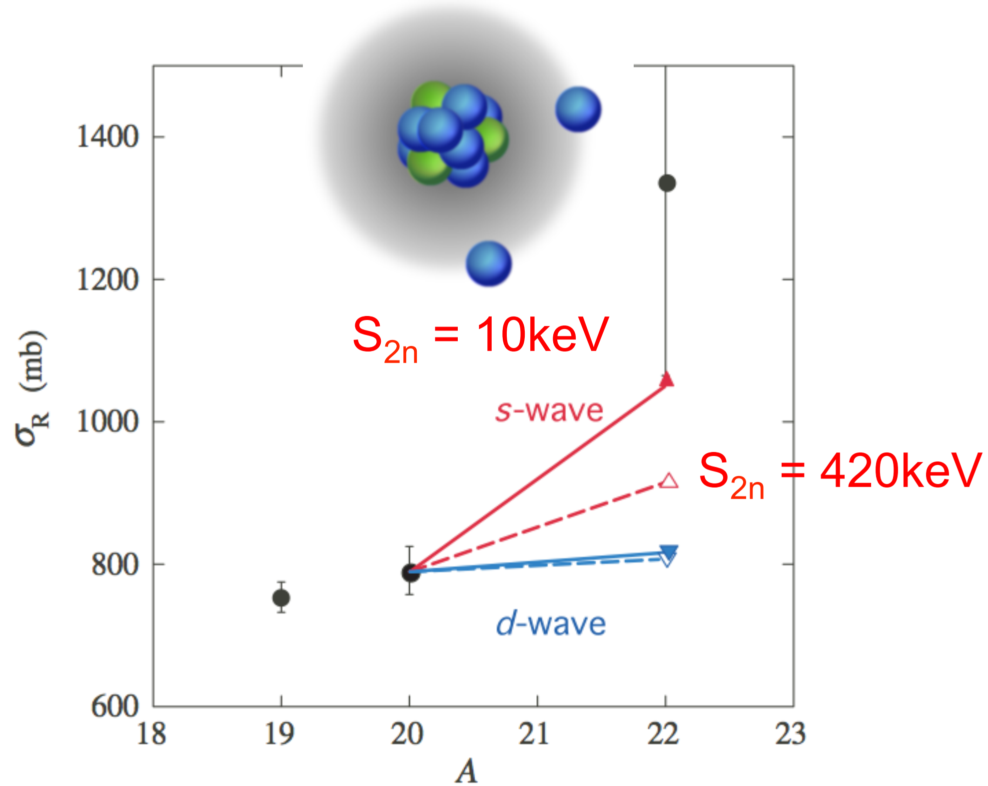
Selected for a Viewpoint in *Physics*
PRL **104,** 062701 (2010) PHYSICAL REVIEW LETTERS week ending 12 FEBRUARY 2010

Observation of a Large Reaction Cross Section in the Drip-Line Nucleus ^{22}C

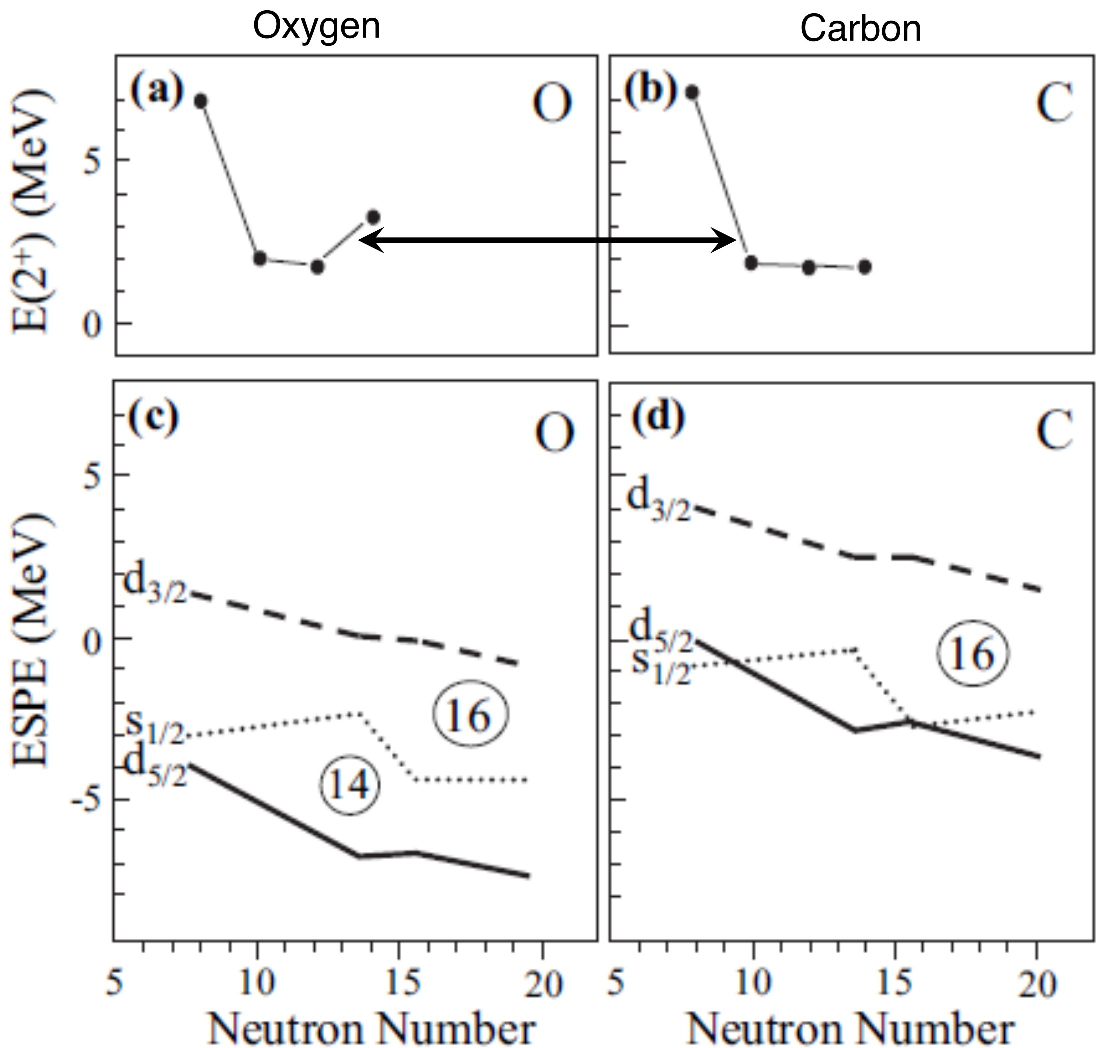
K. Tanaka,[1] T. Yamaguchi,[2] T. Suzuki,[2] T. Ohtsubo,[3] M. Fukuda,[4] D. Nishimura,[4] M. Takechi,[4,1] K. Ogata,[5] A. Ozawa,[6] T. Izumikawa,[7] T. Aiba,[3] N. Aoi,[1] H. Baba,[1] Y. Hashizume,[6] K. Inafuku,[8] N. Iwasa,[8] K. Kobayashi,[2] M. Komuro,[2] Y. Kondo,[9] T. Kubo,[1] M. Kurokawa,[1] T. Matsuyama,[3] S. Michimasa,[1,*] T. Motobayashi,[1] T. Nakabayashi,[9] S. Nakajima,[2] T. Nakamura,[9] H. Sakurai,[1] R. Shinoda,[2] M. Shinohara,[9] H. Suzuki,[10,6] E. Takeshita,[1,†] S. Takeuchi,[1] Y. Togano,[11] K. Yamada,[1] T. Yasuno,[6] and M. Yoshitake[2]

rms radius of 5.4±0.9 fm





Disappearance of the N = 14 shell gap in the carbon isotopic chain



Constant 2^+

TBME V^{pn}

$\pi p_{1/2}$ - $\nu d_{5/2}$ attracts

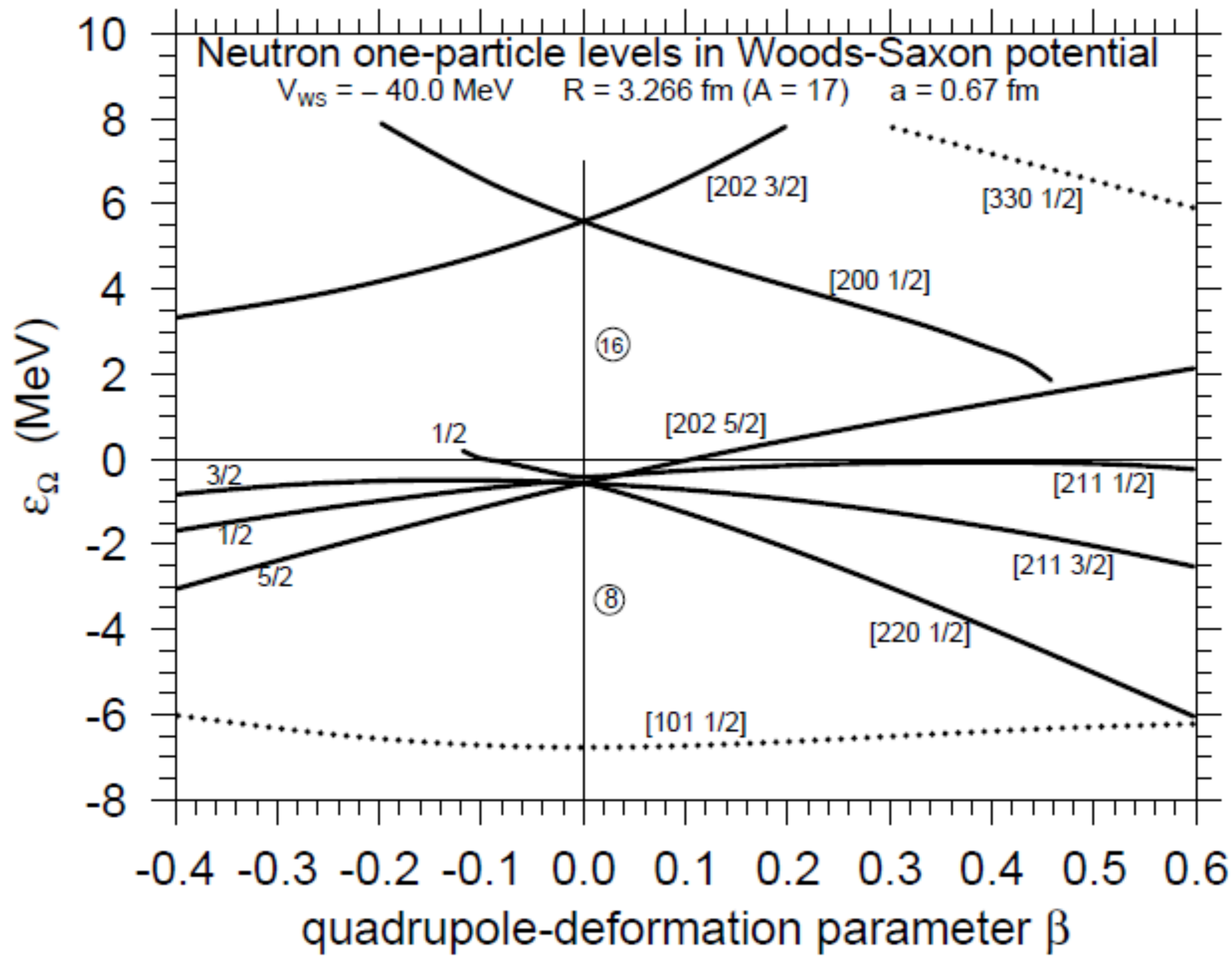
$\pi p_{1/2}$ - $\nu s_{1/2}$ repels

M.Staniou et al., PHYSICAL REVIEW C **78, 034315 (2008)**

PHYSICAL REVIEW C **76, 054319 (2007)**

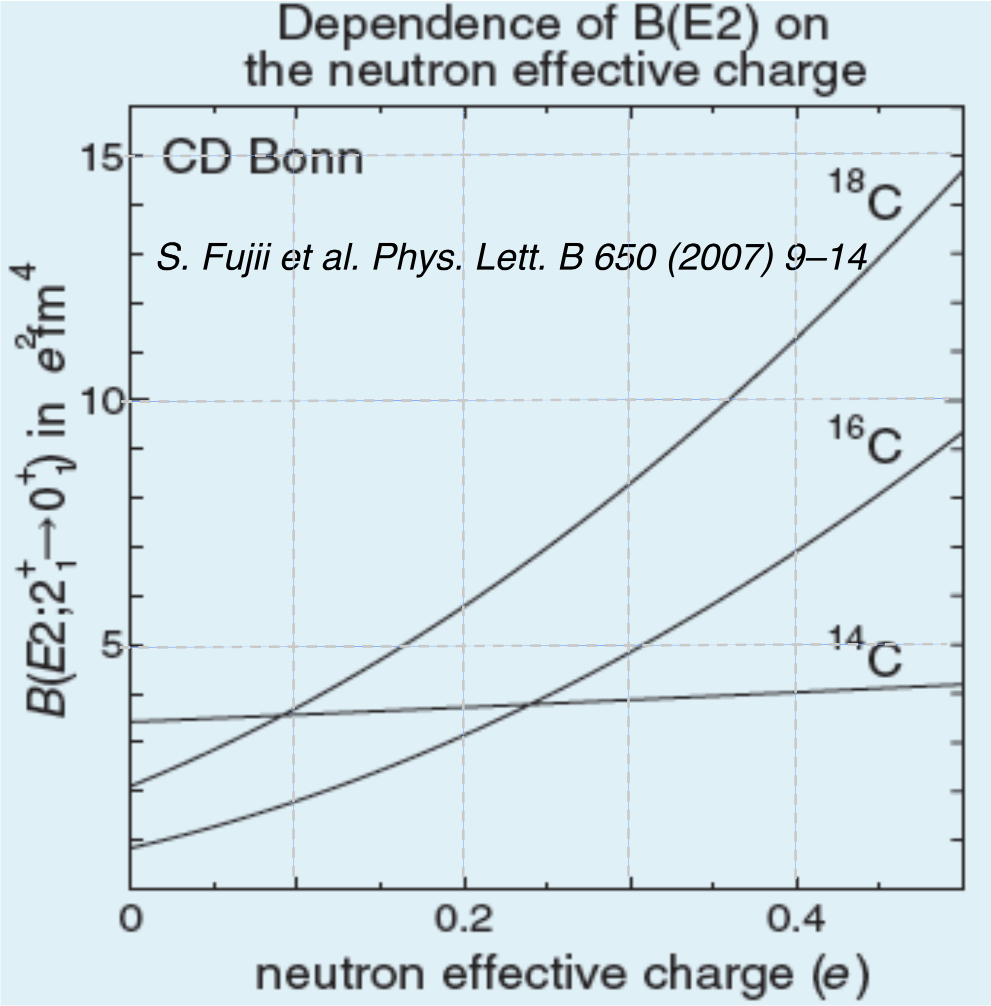
Nilsson diagrams for light neutron-rich nuclei with weakly-bound neutrons

Ikuko Hamamoto



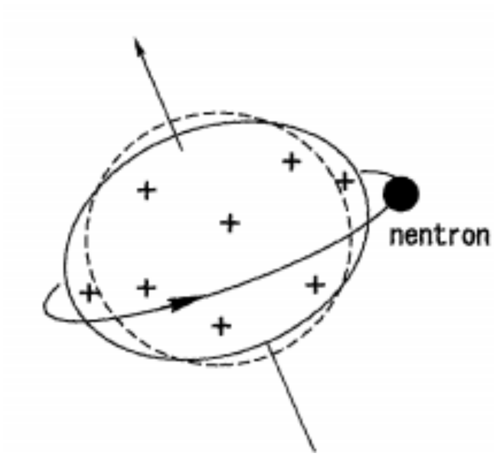
Neutron dominant E2 transitions can exhibit a strong dependence on e_n

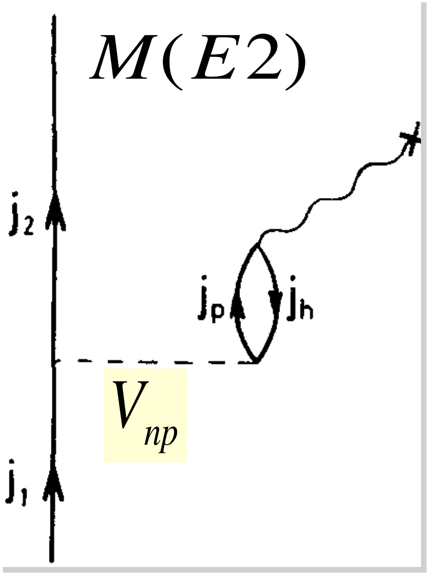
$B(E2) = 1/(2J_i+1) * | Mn*e_n + Mp*e_p |^2$



Binding , B(E2), and Effective Charge

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





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

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

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

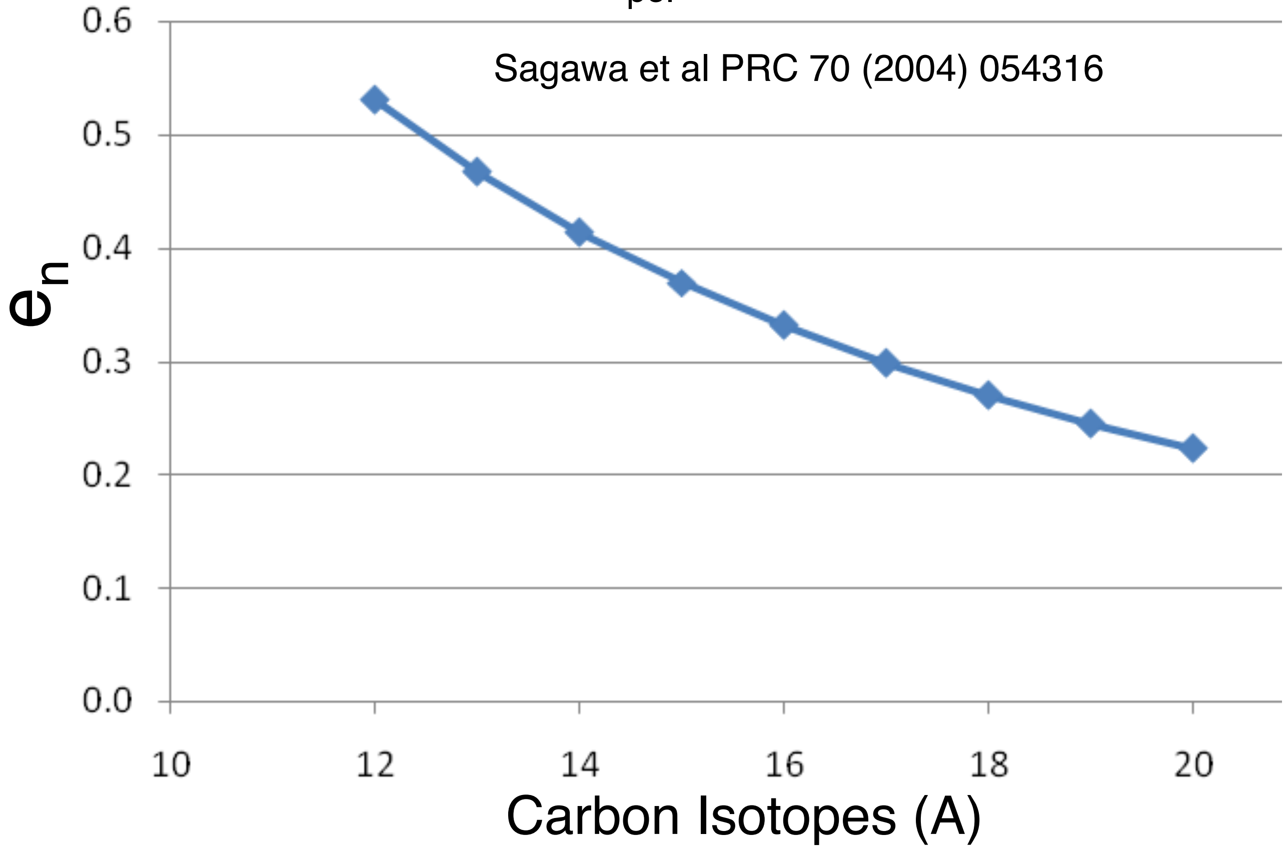
Spatially extended valence particles have less influence on the core.

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

Anomalous effective charge ?

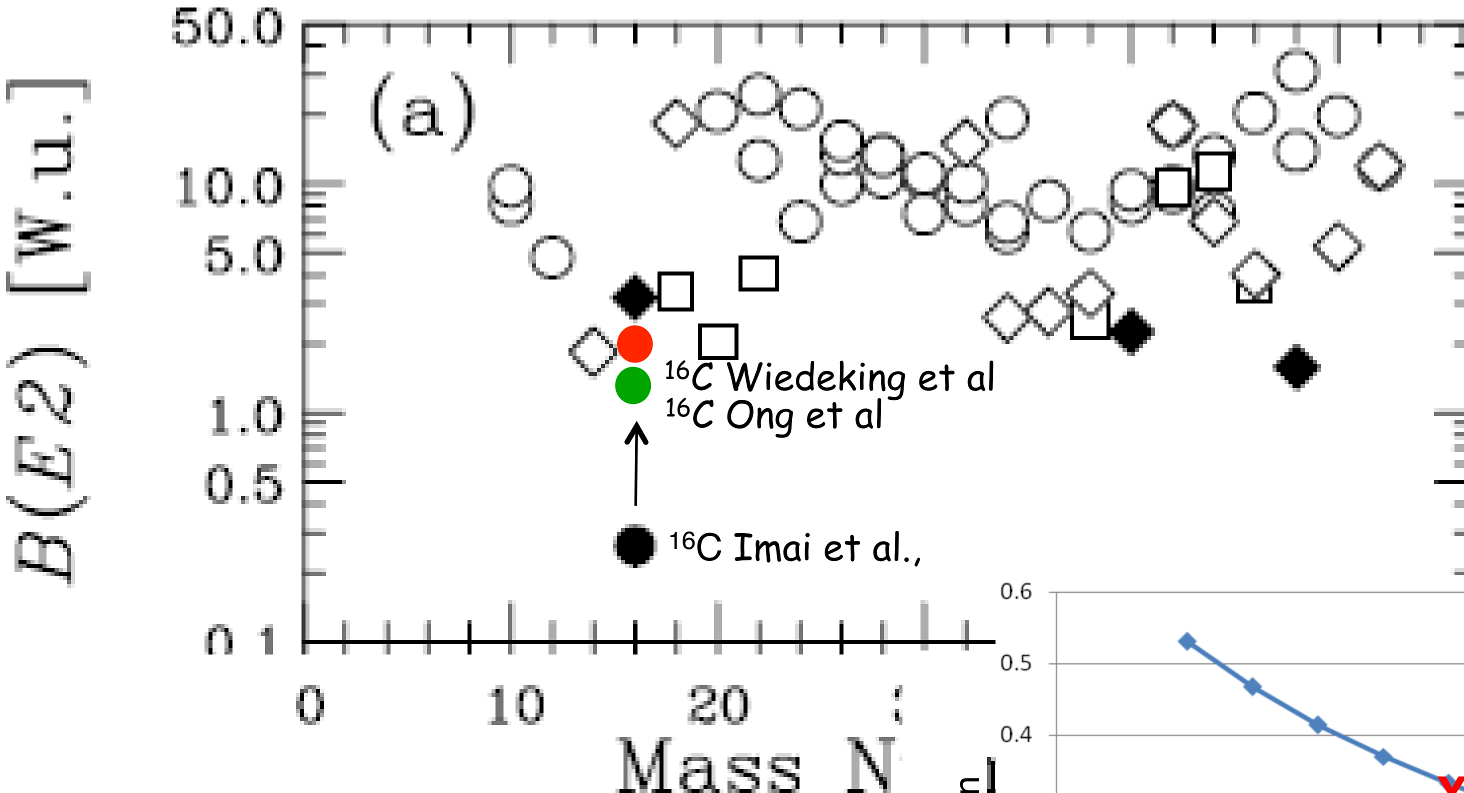
N-Z (~1/A) Dependence of Effective Charges
(Bohr Mottelson Vol 2)

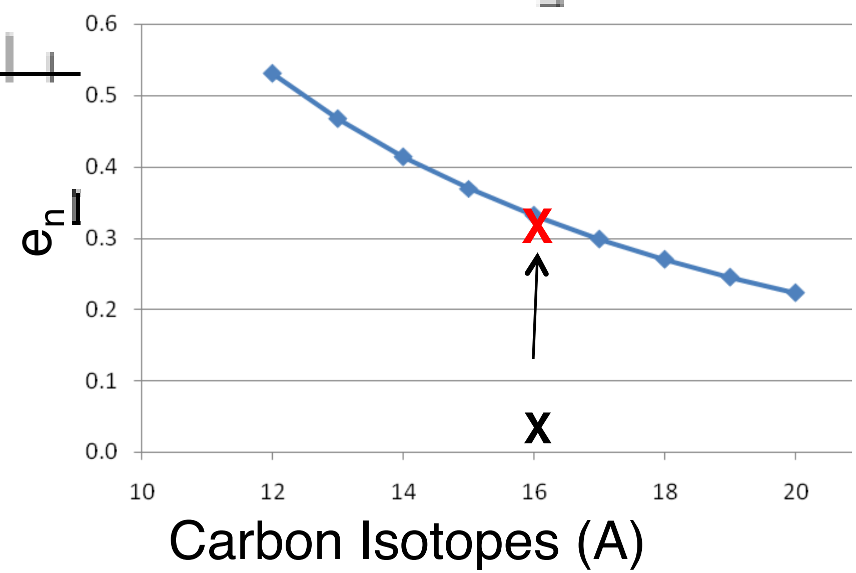
The "appropriate reference" $e_{pol} \sim Z/A$



Effective charge – a measure of coupling between valence particles and core (binding) <u>within a given model-space</u>

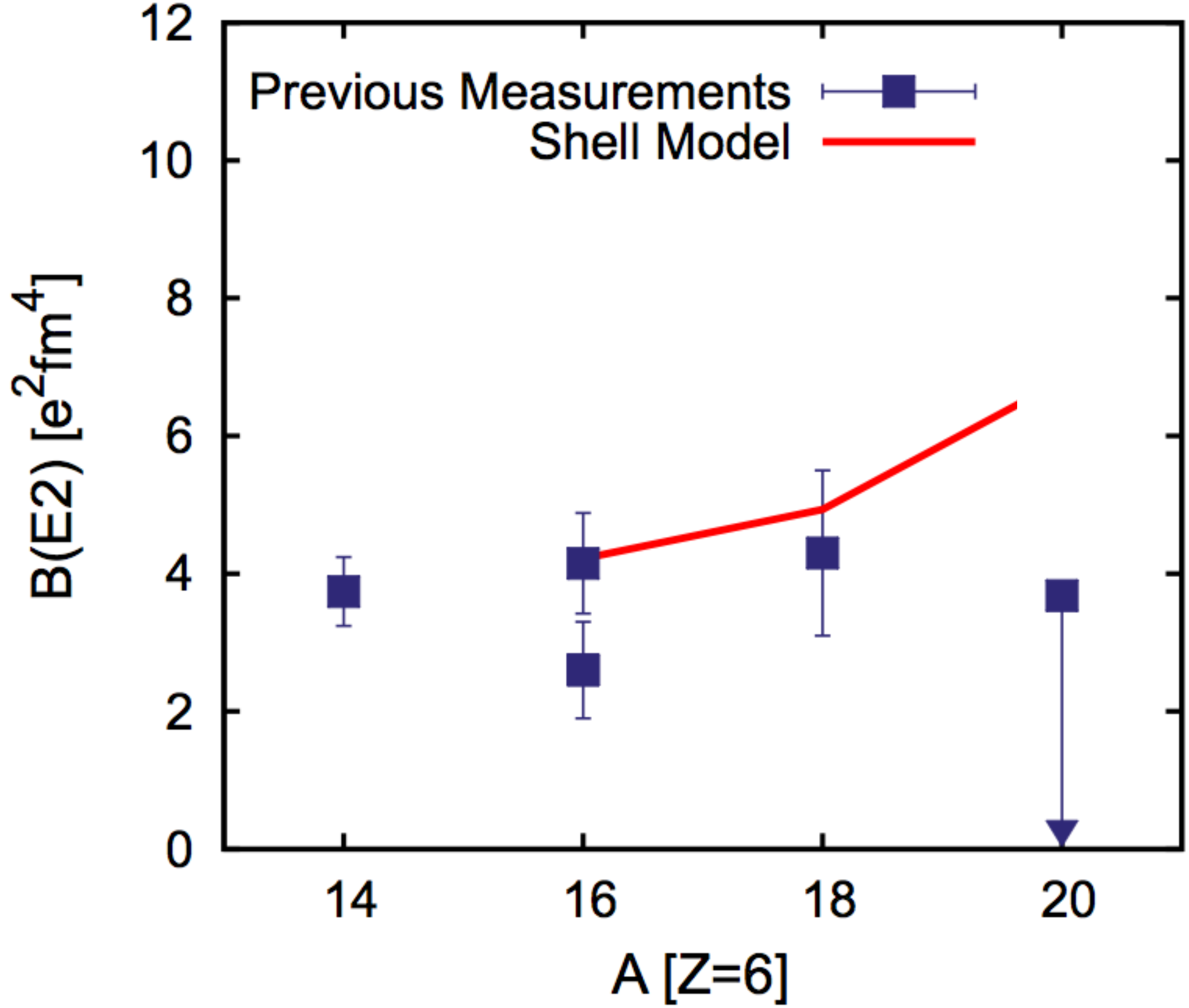
^{16}C: B(E2, $2^+ \rightarrow 0^+$): Review





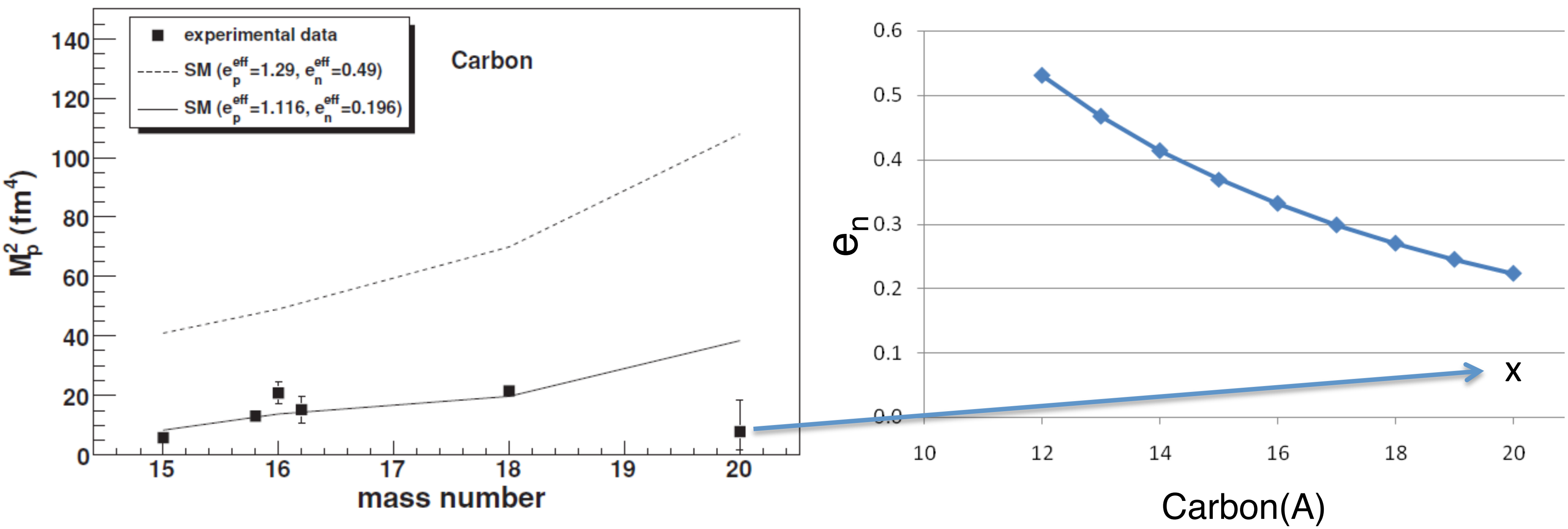
[1] N. Imai et al., PRL 92, 062501 (2004)
[2] M. Wiedeking et al., PRL 100, 152501 (2008)
[3] H. J. Ong et al., PRC 78, 014308 (2008)

Carbon B(E2;2+→0+): Review



Z. Elekes et al. PHYSICAL REVIEW C **79, 011302(R) (2009)**

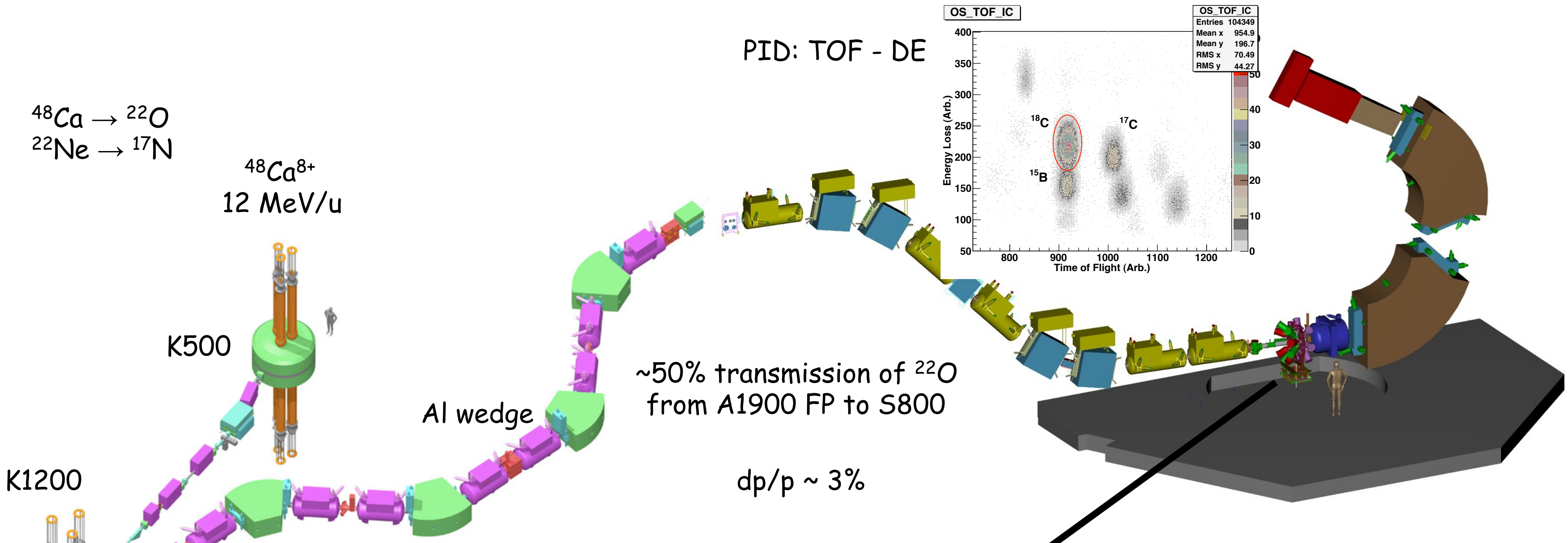
$$B(E2) = 1/(2J_i+1) * | M_n*e_n + M_p*e_p |^2$$



$^{16,18,20}C$ Lifetimes and B(E2) Experiments

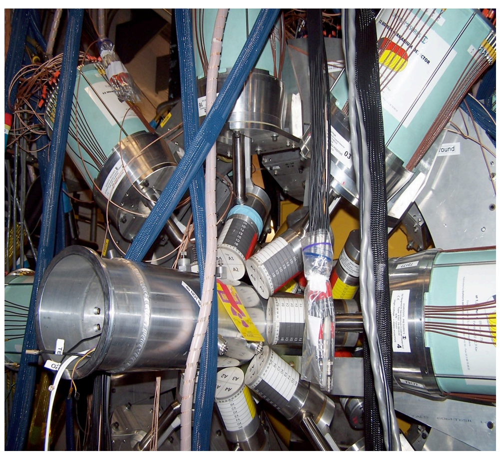
- RIKEN
  - Recoil shadow method (“direct”)
  - Inelastic scattering (“indirect”)
- 88”-Cyclotron LBNL
  - Low velocity Recoil Distance Method (“direct”)
- NSCL/MSU
  - Fast velocity Recoil Distance Method (“direct”)

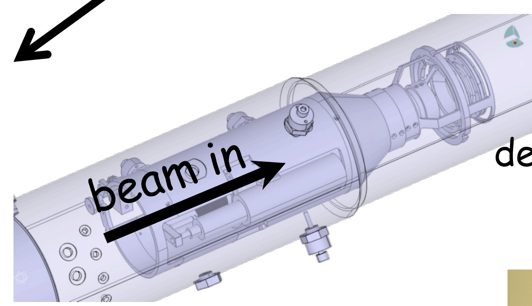
The NSCL $^{16,18,20}C$ Experiments

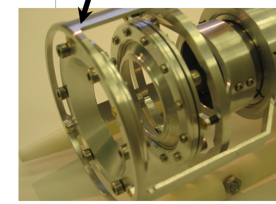


SeGA

7@30 deg
8@140 deg

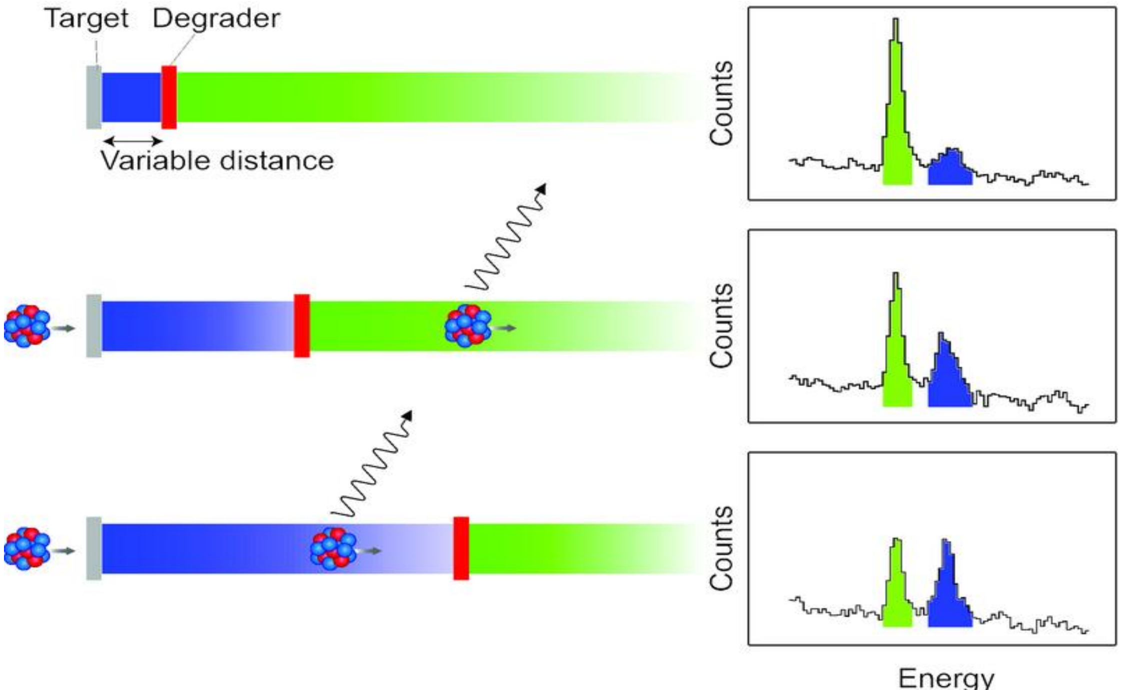




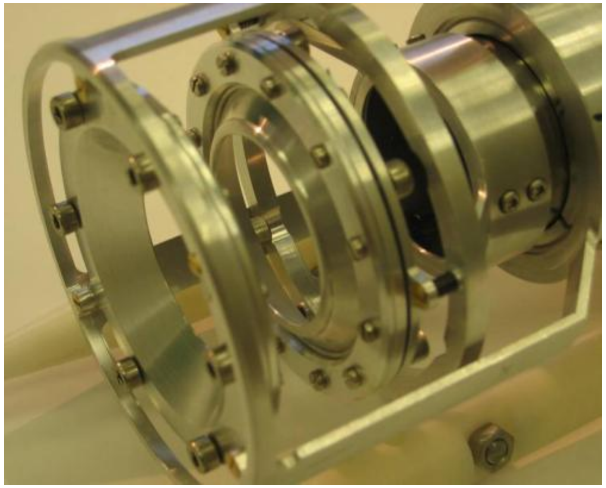


A. Dewald et al., GSI Scientific Report 2005, p. 38 (2006)

Recoil Distance Measurements



Target-Degrader Distance:
0.1 - 10mm (precision 1μm)
Flight time:
0.17 – 17 psec (v/c=0.5)

Koln/NSCL plunger

Extracting Lifetimes

Life is a little more complicated ….

A simulation tool based on GEANT4 and ROOT has been developed for Recoil Distance Method lifetime measurements at the NSCL
[P. Adrich et al., NIM A 598 (2009) 454]

Simulating the experiment (fixing parameters that have an effect on the Doppler shift)

- **Properties of incoming heavy-ion beam (modeled based on experimental data), i.e. the angle and position of the incoming beam on target reconstructed from the measured angle and position at the FP by means of back-tracing in the known magnetic field of S800**
- **Interaction of heavy-ions and γ-rays in matter (GEANT4 models employed, stopping powers can be tested using the data)**
- **SeGA response (modeled based on experimental data)**
- **Reaction kinematics, i.e. possible momentum spread due to the knockout reaction for light projectiles (modeled based on experimental data and/or theory)**

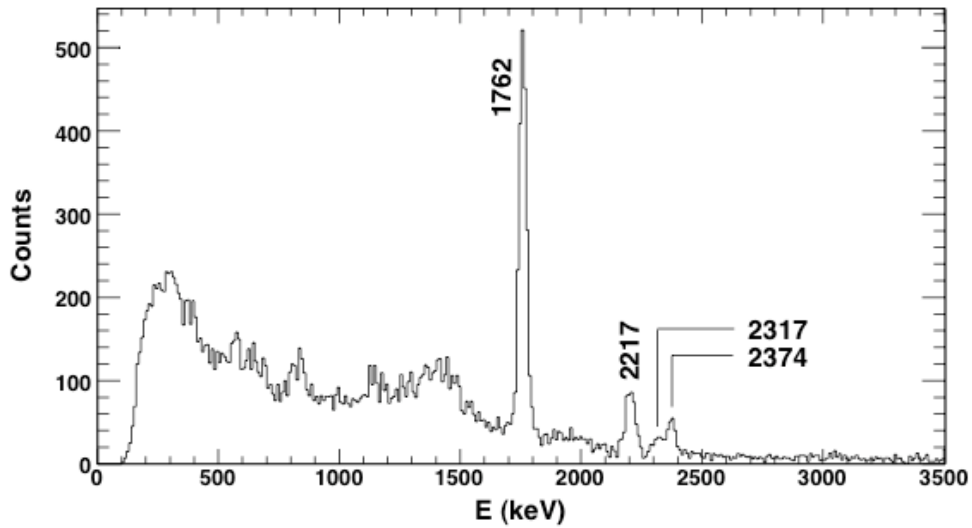
The simulated γ-ray spectrum expected from the plunger-SeGA setup under the given experimental conditions is then compared with the experimental one

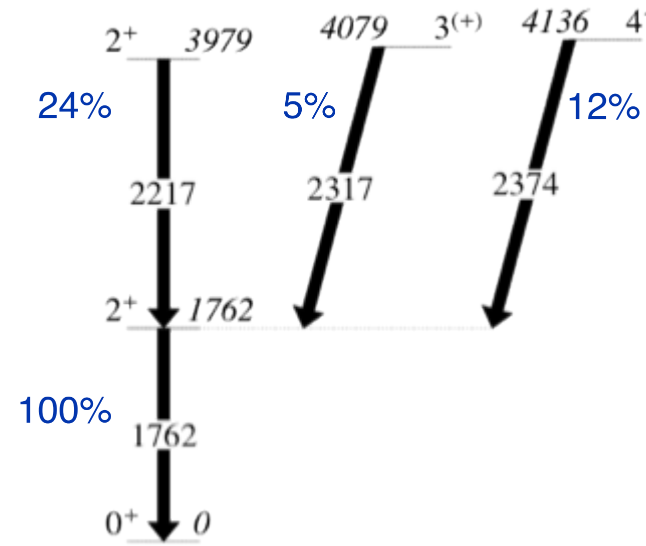
☞ In a plunger experiment with fast beams the beam particles that emerge from the target are energetic enough to **generate reactions in the degrader** (S800 settings, deduce fraction of target/degrader reactions.)

Data

^{16}C data

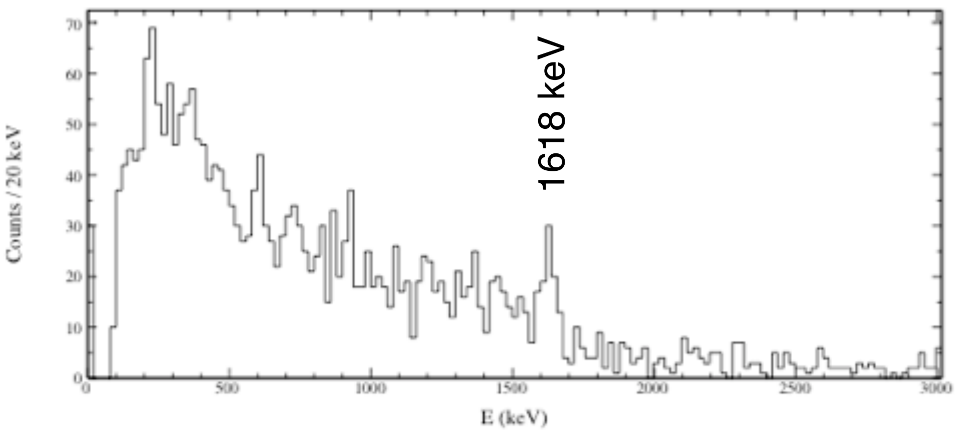
$^{9}Be(^{17}N,^{16}C+\gamma)X$

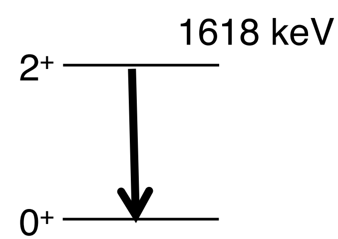


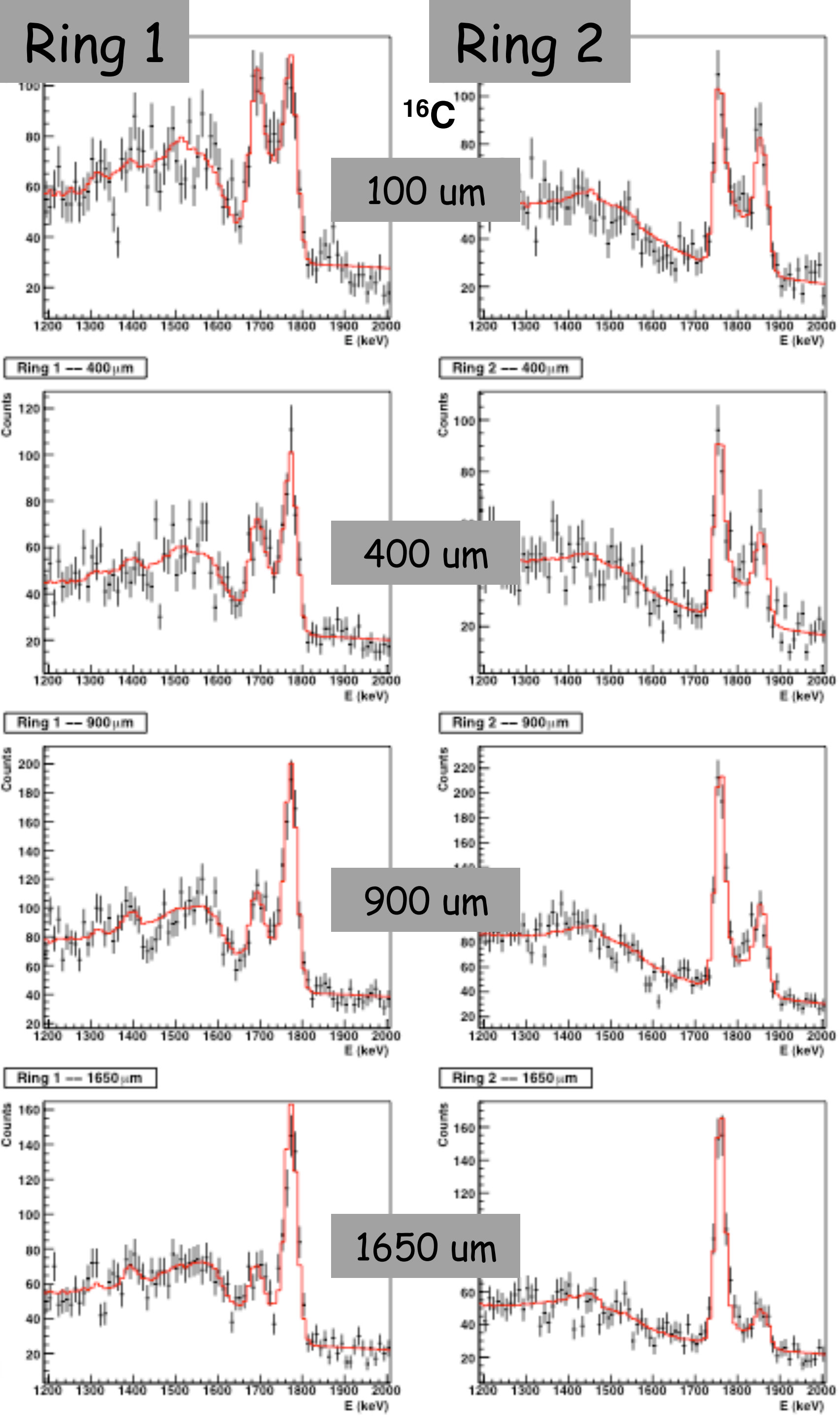


^{20}C data

$^{9}Be(^{22}O,^{20}C+\gamma)X$



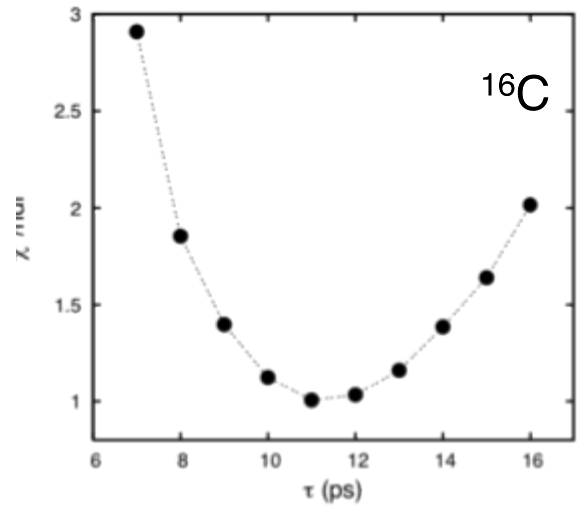




^{16}C Lifetime

M.Petri et al., Phys. Rev. C accepted (2012)

τ = 11.4 ± 0.3 (stat) ± 1.0 (syst) ps



Previous values
11.7(20) ps

Wiedeking et al., PRL 100, 152501 (2008)

^{18}C Lifetime

Philip Voss *et al* Phys. Rev. C 011303(R) (2012)

τ = 22 ± 1 (stat) ± 3 (syst) ps

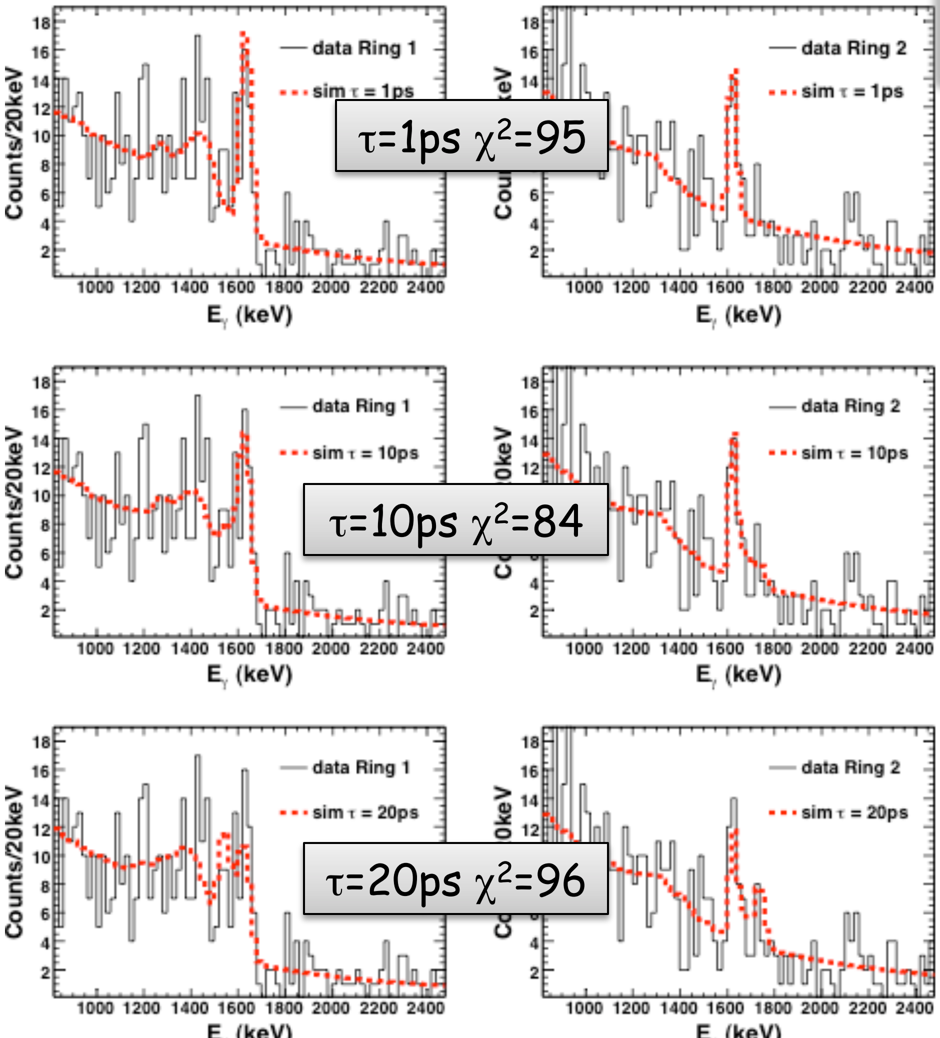
Previous value18.9(9)(44) ps
Ong et al PRC78, 014308 (2008)

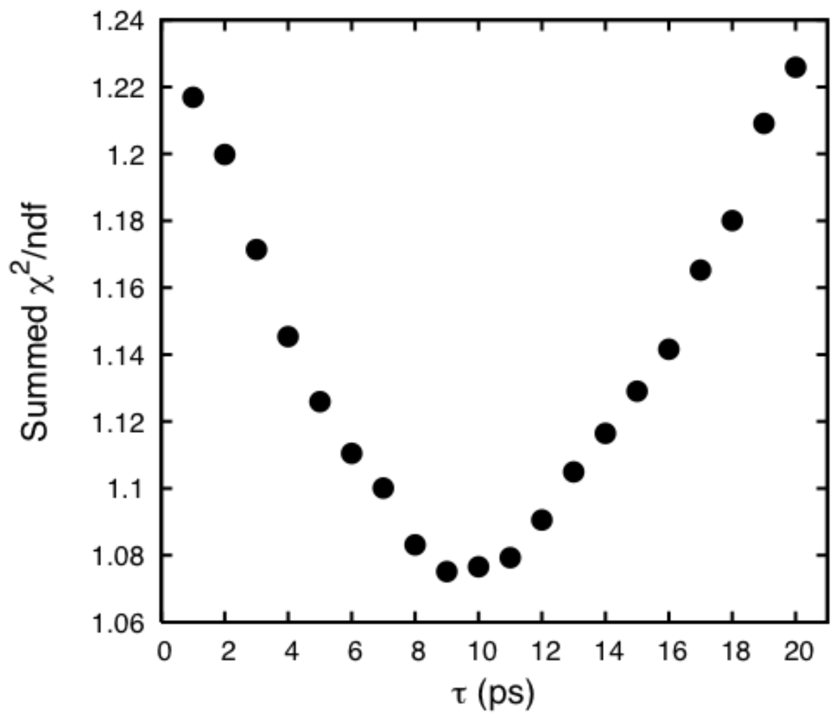
^{20}C Lifetime

M.Petri et al., Phys. Rev. Lett. 107, 102501 (2011)

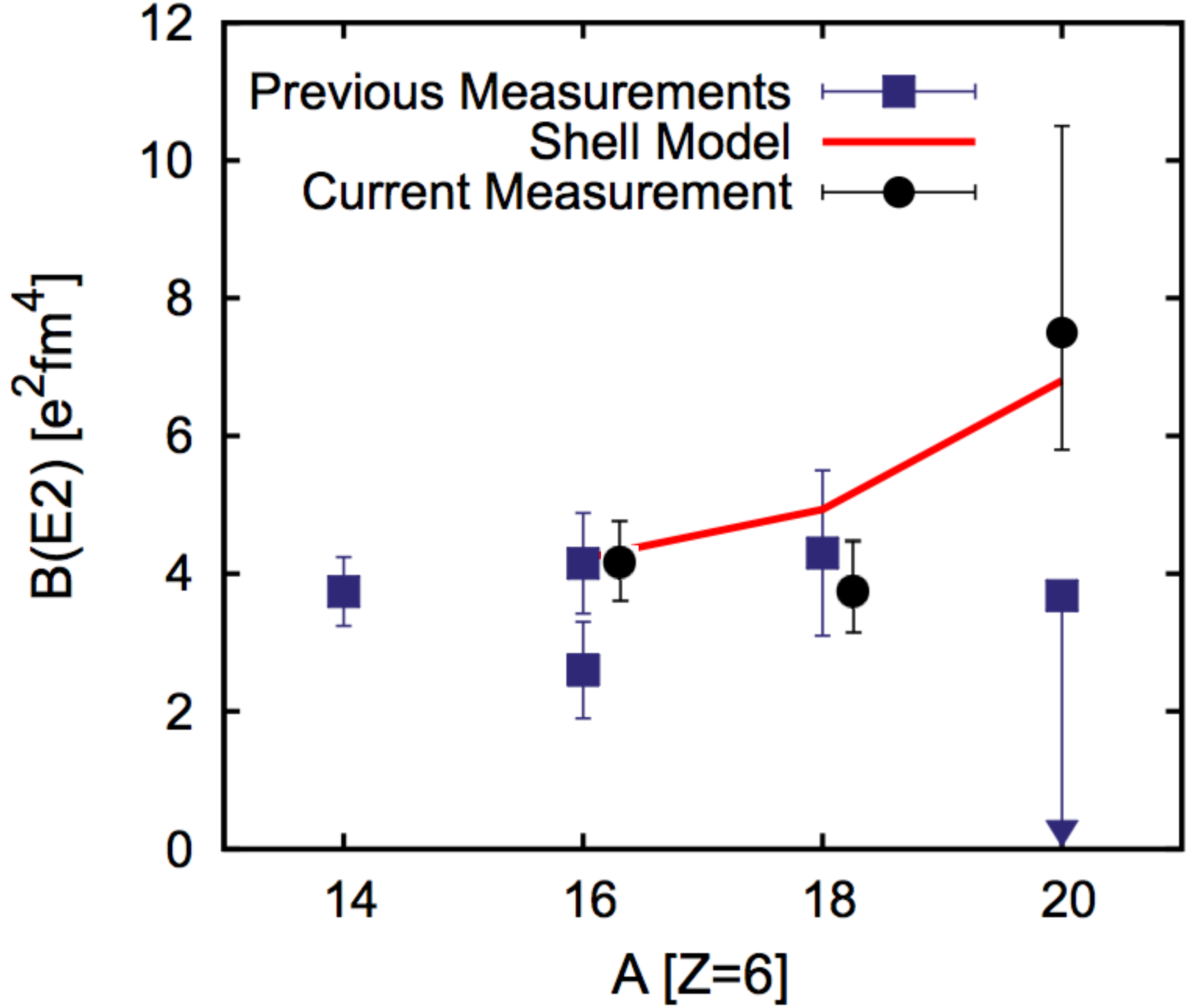
$$\tau = 9.8 \pm 2.8\,(\text{stat})\; {}^{+0.5}_{-1.1}\,(\text{syst})\text{ ps}$$

Ring 1 | Ring 2





Carbon B(E2;2+→0+)



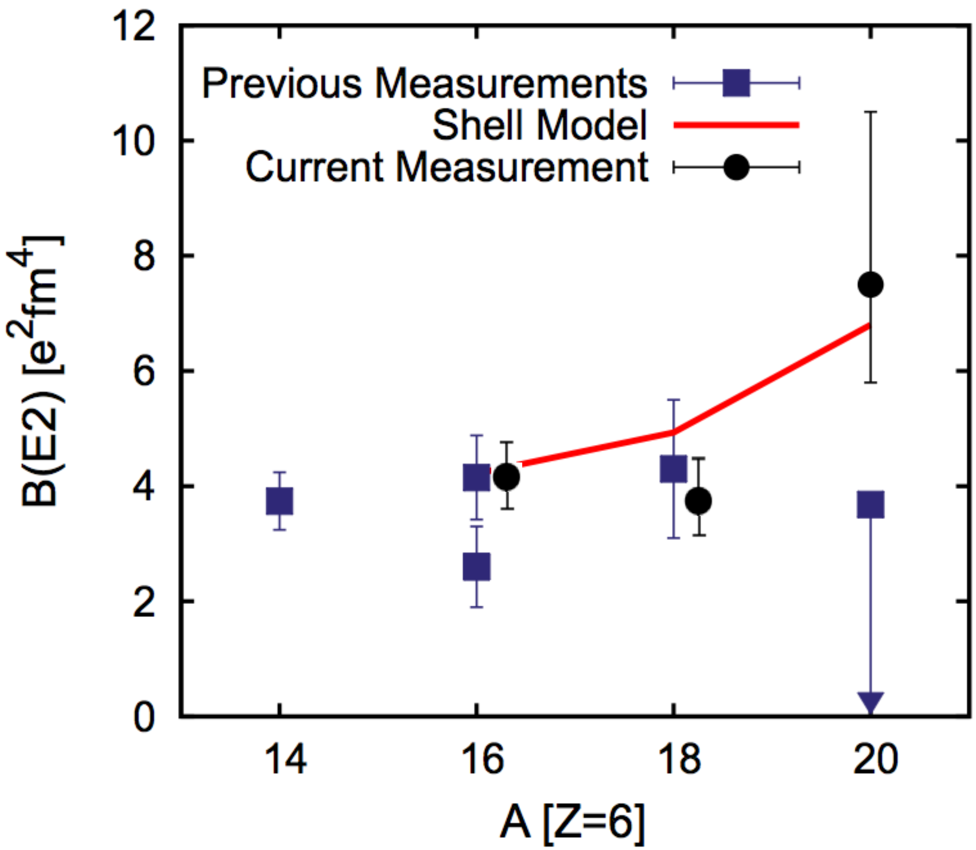
Shell Model Interpretation

Shell Model B(E2) Carbon Isotopes

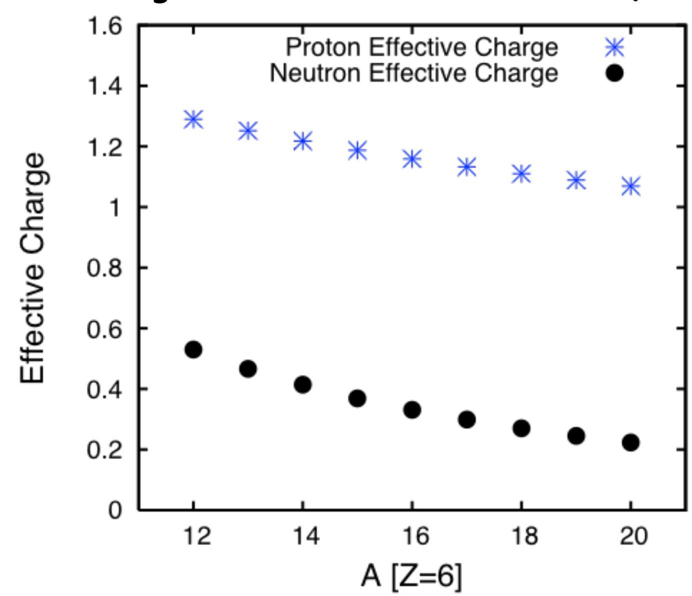
$B(E2)=1/(2J_i+1)\ |M_n e_n^* + M_p e_p^*|^2$

Shell Model WBT interaction (B.A.Brown)

	M_p	M_n
^{16}C	1.28	9.39
^{18}C	1.76	11.16
^{20}C	**3.06**	11.48

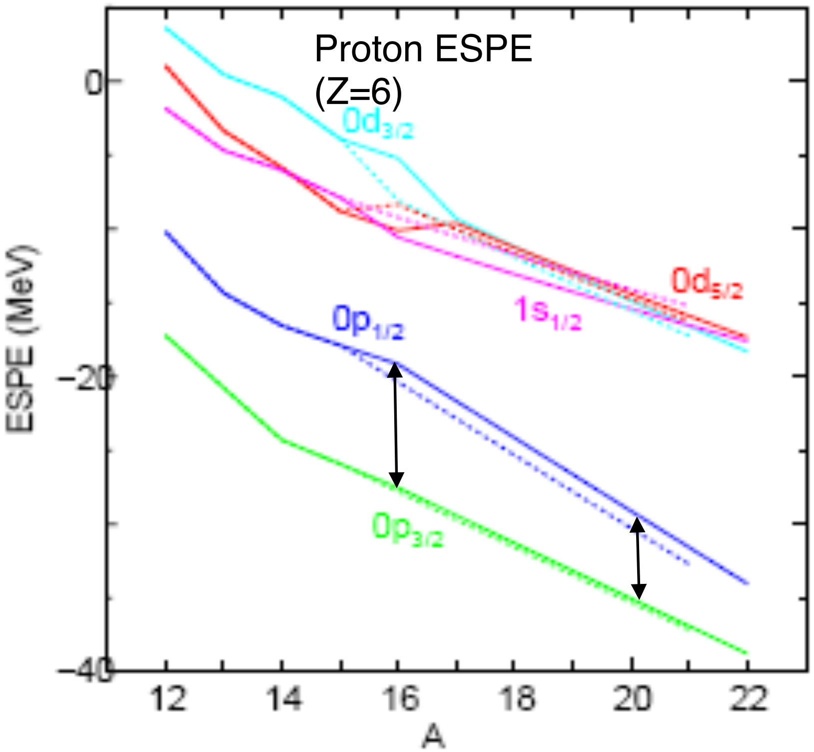


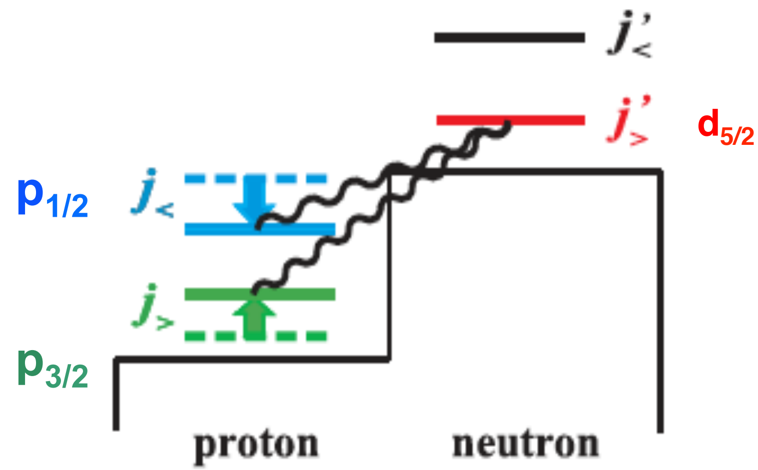
Sagawa et al., PRC 70, 054316 (2004)



Reduced Orbit Splitting: Carbon Isotopes

R.Fujimoto. PhD Thesis (U.Tokyo 2002)





$\pi p_{1/2} - \nu d_{5/2}$ attractive
$\pi p_{3/2} - \nu d_{5/2}$ repulsive

- Reduced $p_{3/2}$-$p_{1/2}$ gap
- Increased proton component
- Increased B(E2)

Schiffer-True interaction

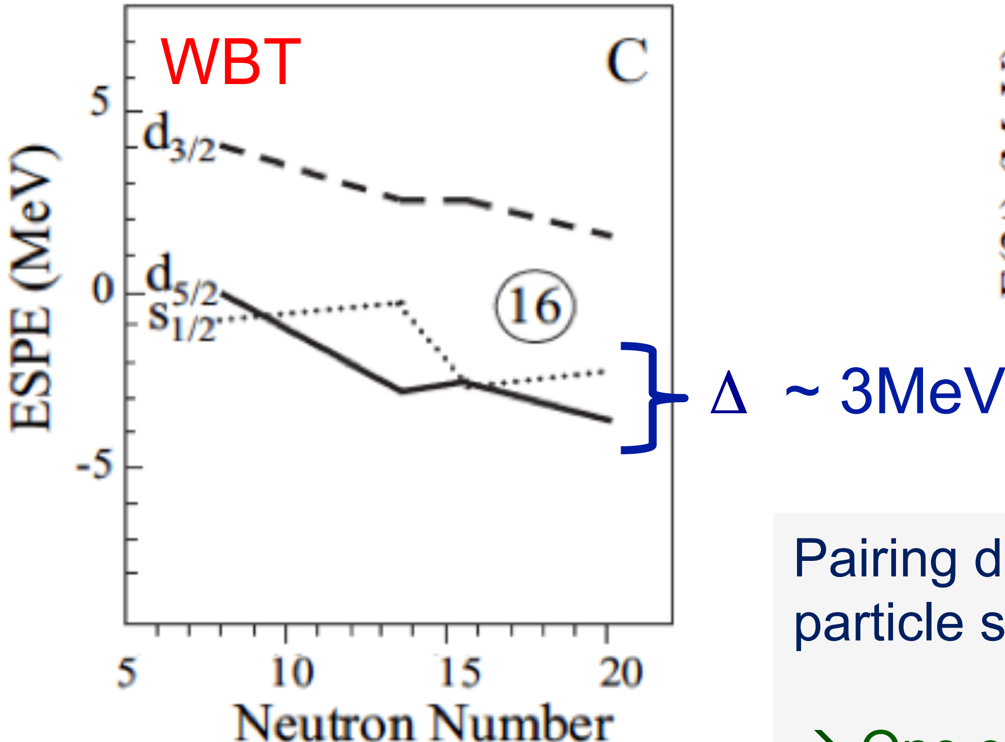
$$\Delta E_{p3/2-p1/2} = n_{d5/2}(-0.35MeV(Tensor) - 0.05MeV(Central))$$

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

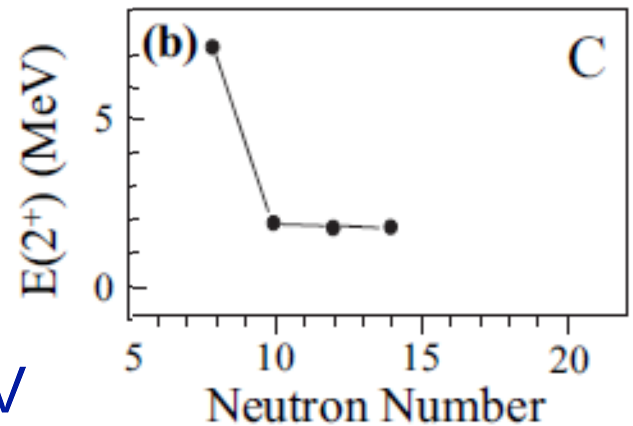
Similar case in the Sr-Zr region
$2p_{3/2}$-$2p_{1/2}$ spin-orbit splitting

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)

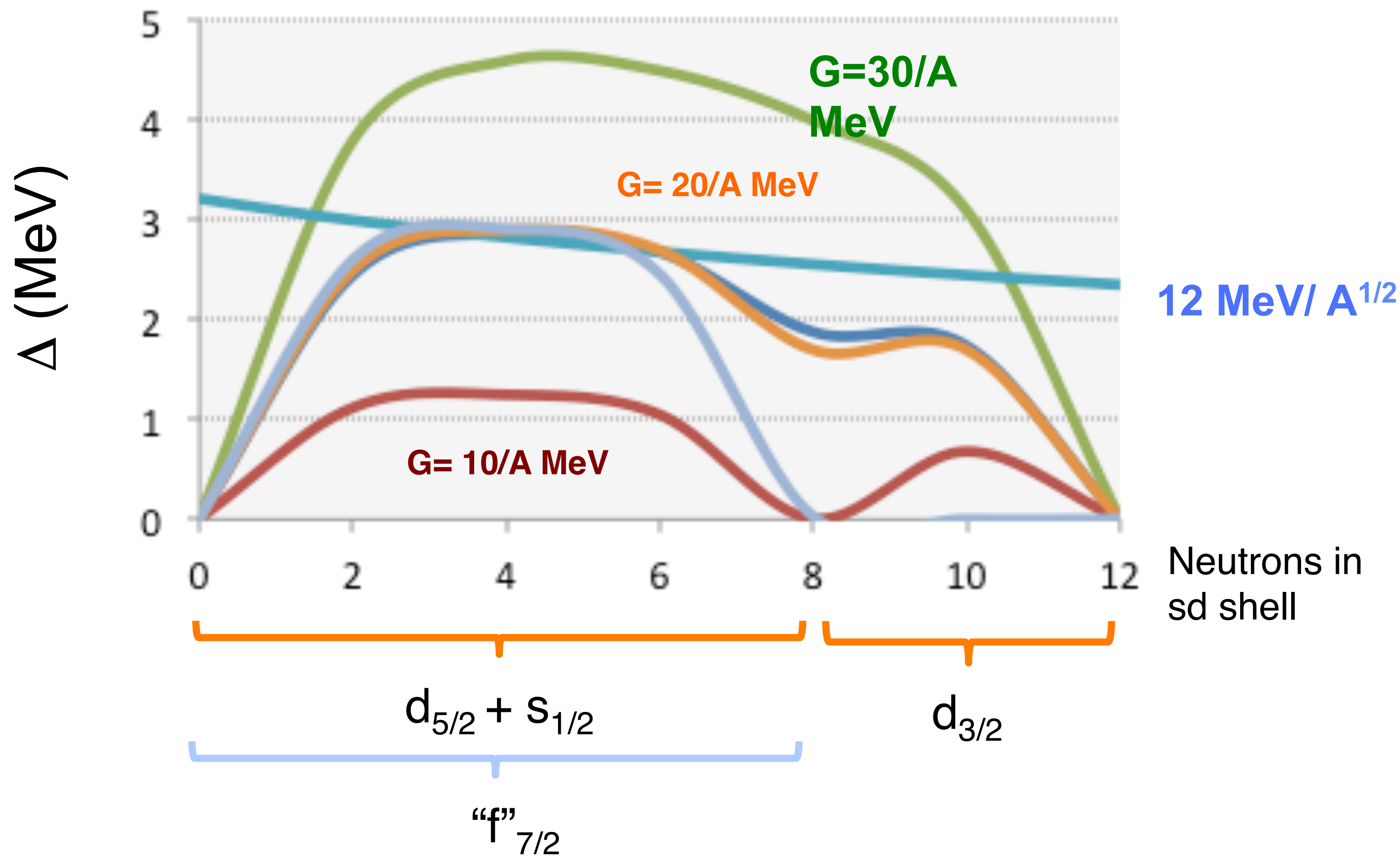


M. Stanoiu *et al.*, PRC 78, 034315 (2008)

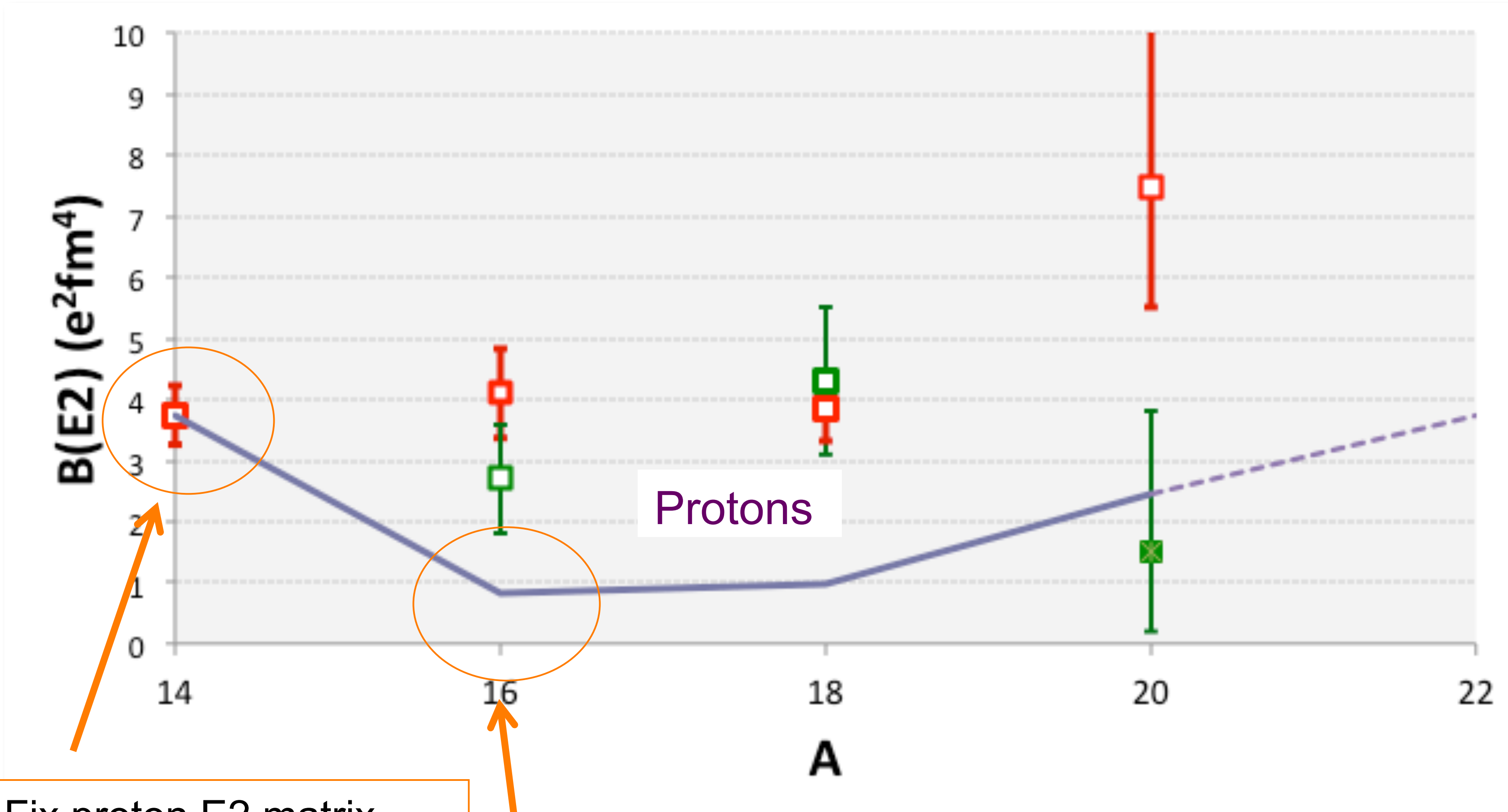


Pairing dominates over the single particle spacing ($E\_s_{1/2} - E\_d_{5/2}$) :

→ 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)

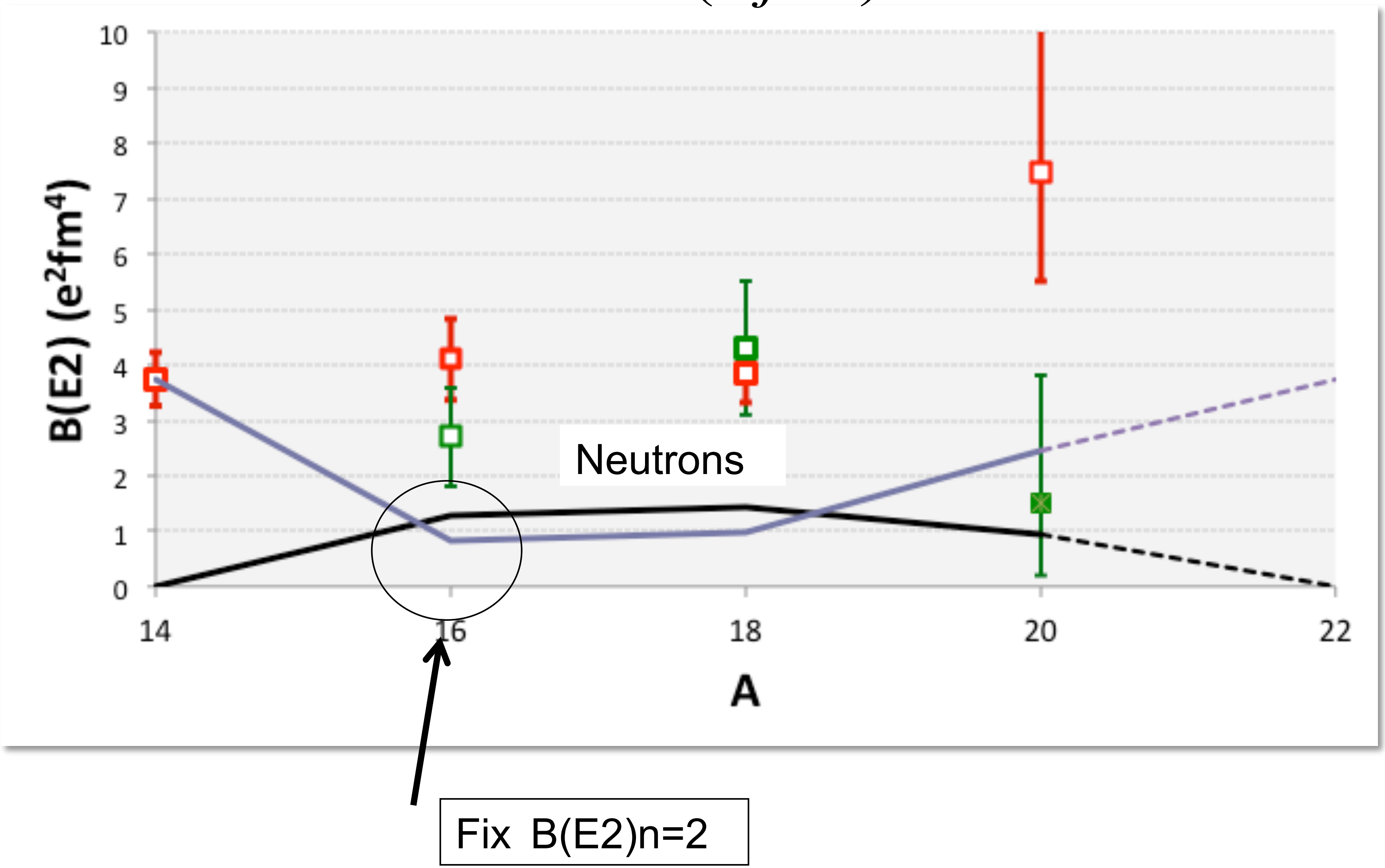


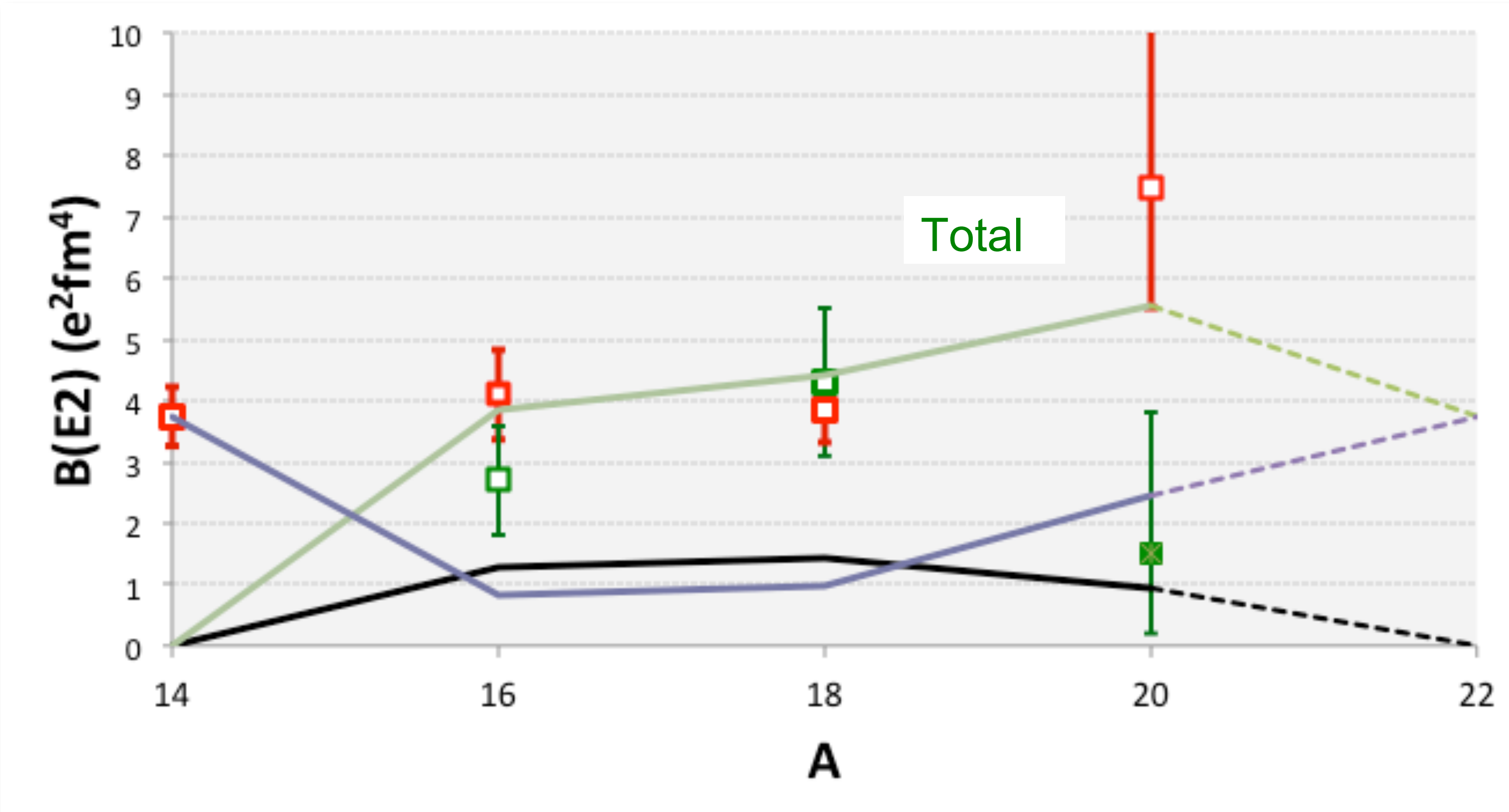
Fix proton E2 matrix element

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

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

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





Increased role of the proton component

Shell Model Components

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

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

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

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

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

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

$\sigma(2+)/\sigma(0+) = 0.28 \pm 0.02$ ⟶ $\beta^2 \approx 11(1)\%$

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

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

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

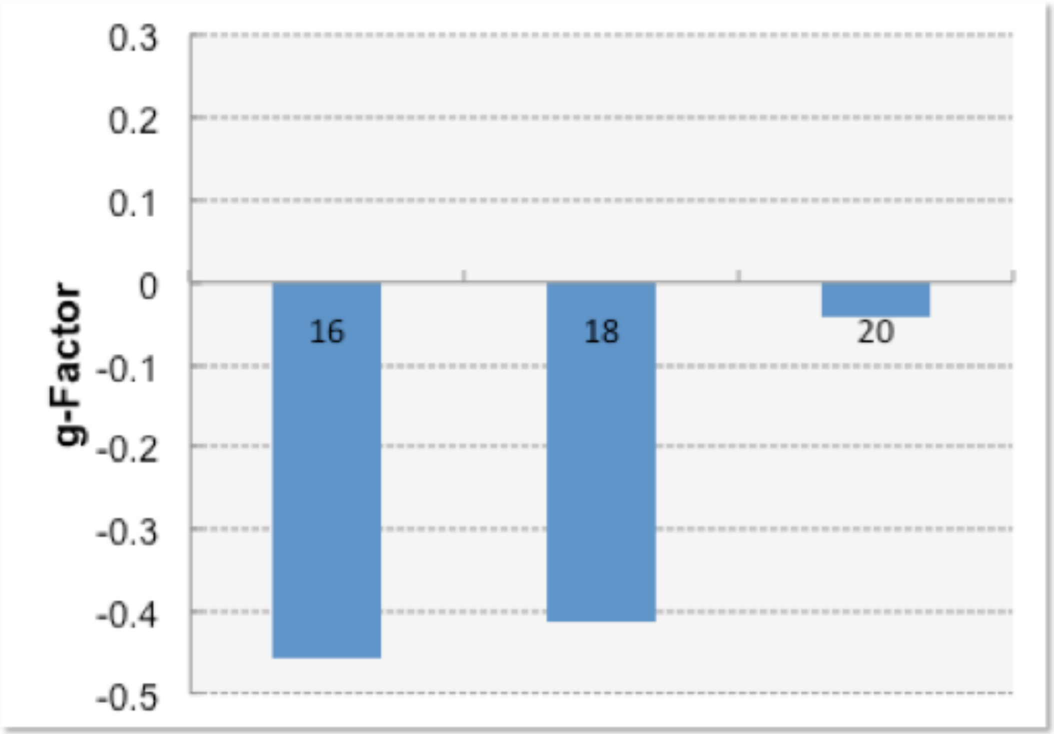
Proton amplitudes (β^2)

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

2^+ Magnetic Moments

Sensitive probe of proton contribution

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



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

Ab Initio

- No Core Shell Model (NCSM)
  - CD Bonn (NN)
  - Chiral NN and NN+3N

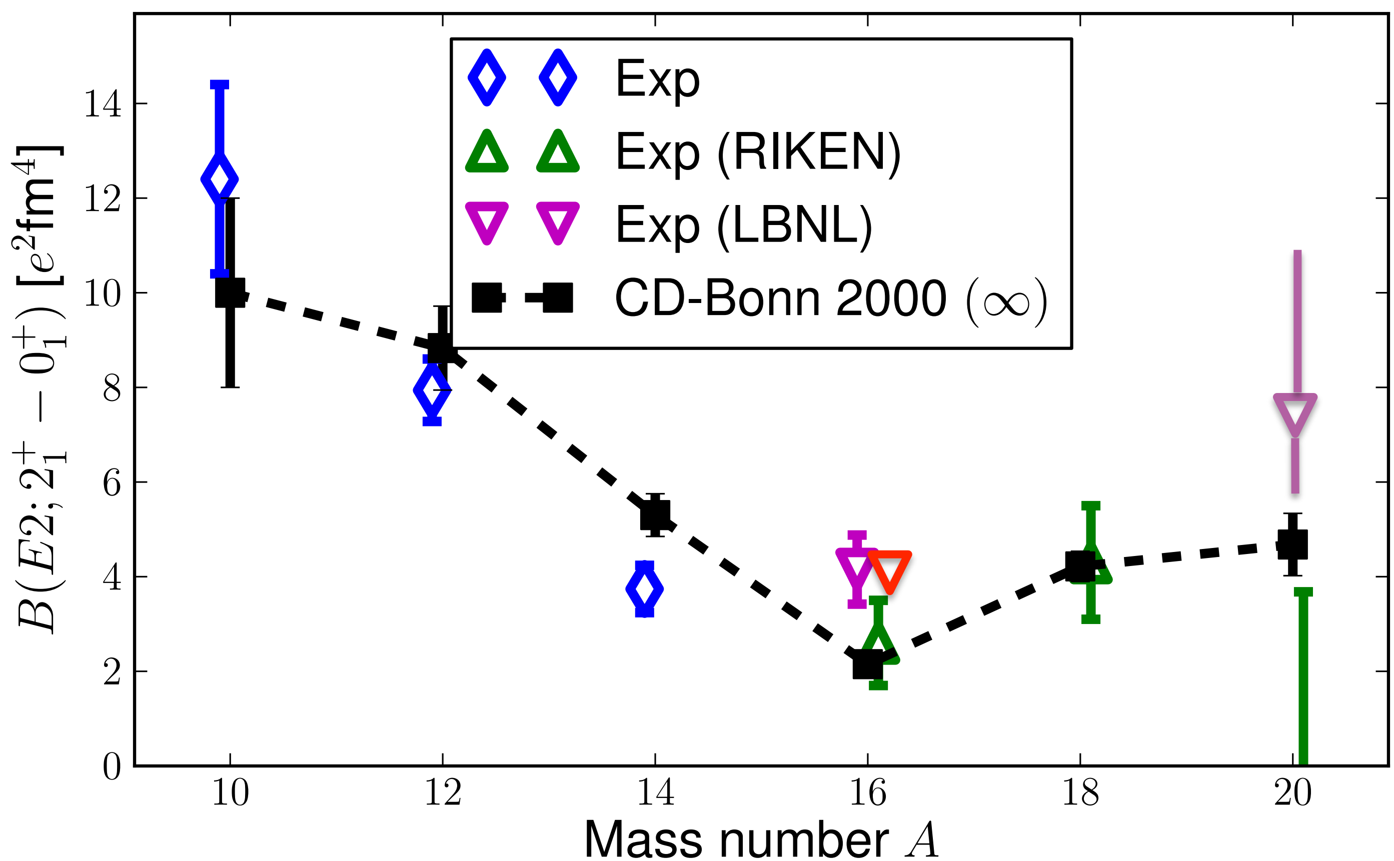
P. Navrátil, J. P. Vary, and B. R. Barrett, Phys. Rev. Lett. **84**(25), 5728 (2000).

P. Navrátil, S. Quaglioni, I. Stetcu, and B. R. Barrett, J Phys G Nucl Partic **36**(8), 083101 (2009).

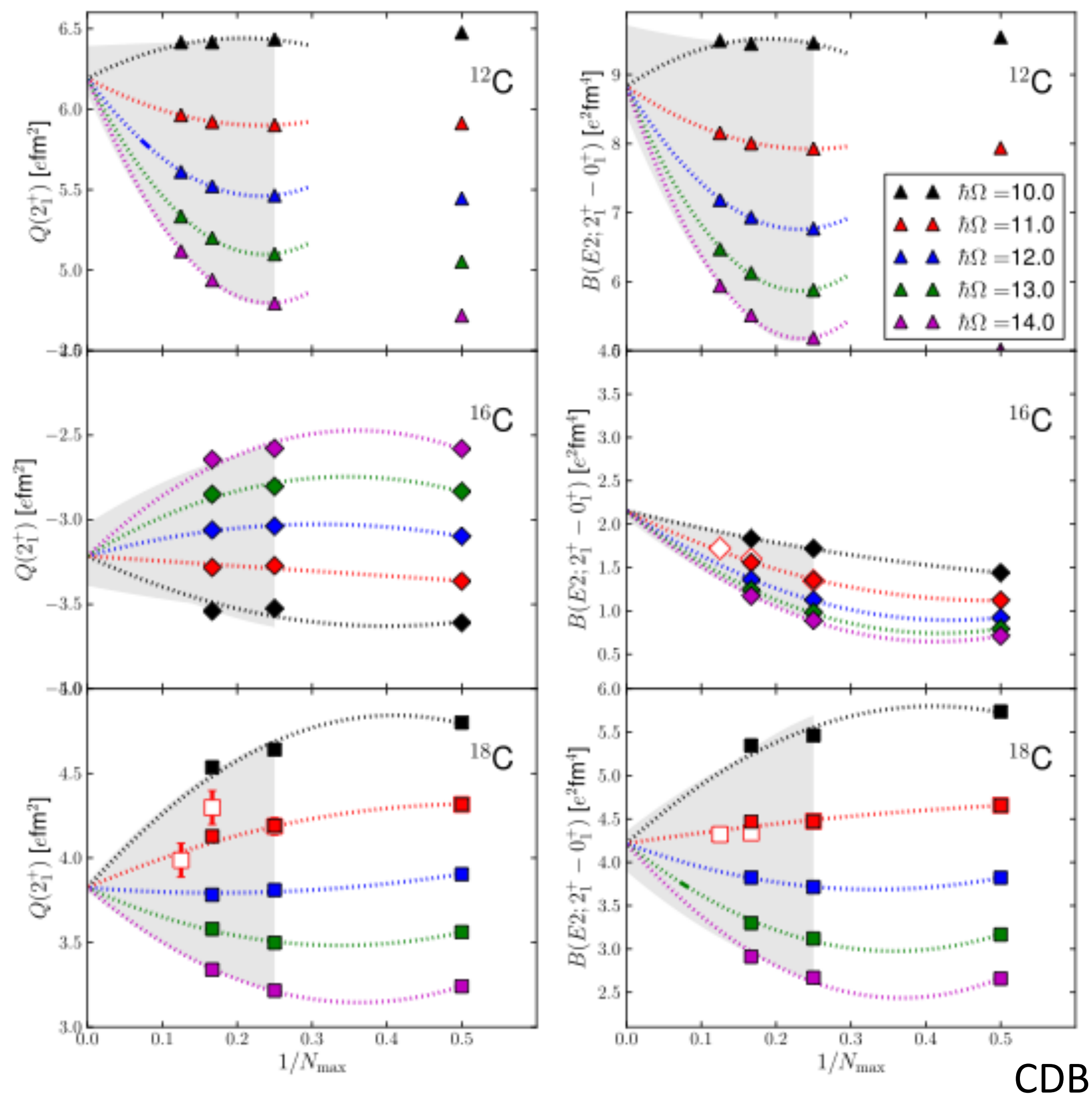
NCSM

C. Forssén,[1,*] R. Roth,[2] and P. Navrátil[3]

arXiv:1110.0634v2 [nucl-th]



Model-space dependence of calculated E2 observables for $^{12,16,18}C$



CDB2k NN potential

^{16}C Higher-Lying Transitions

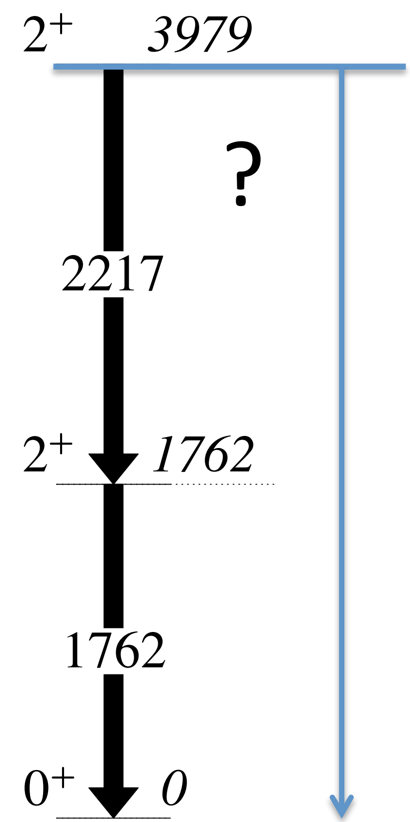
- 2_2 decay sensitive to E2 and M1 transition rates

- Data
  - $2_2 \rightarrow 0^+$ <10%

- CD Bonn NN
  - $2_2 \rightarrow 0^+$ ~70%

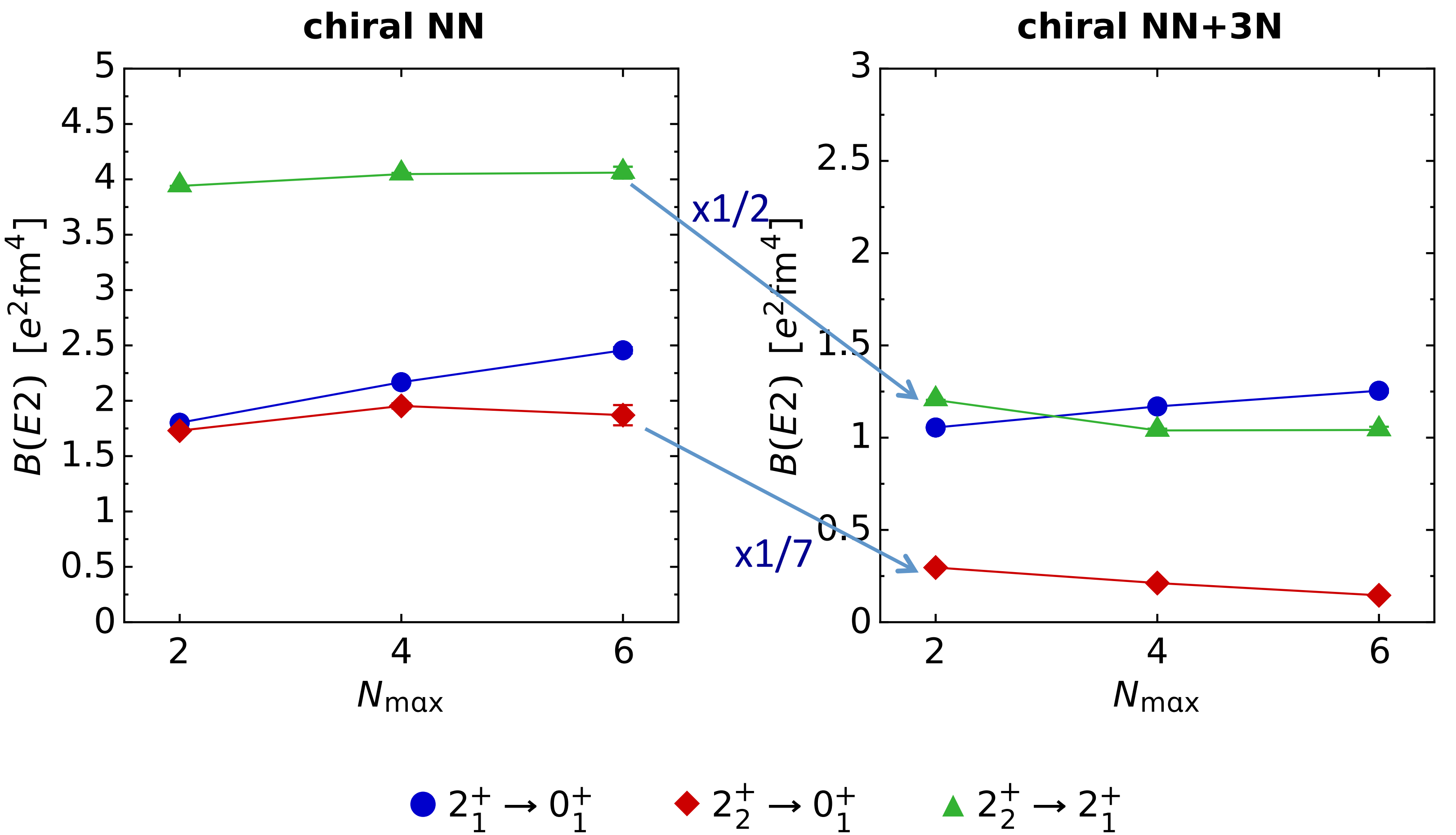
- Chiral NN
  - $2_2 \rightarrow 0^+$ ~75%

These NN-only Calculations fail to describe the decay of 2_2 state in ^{16}C



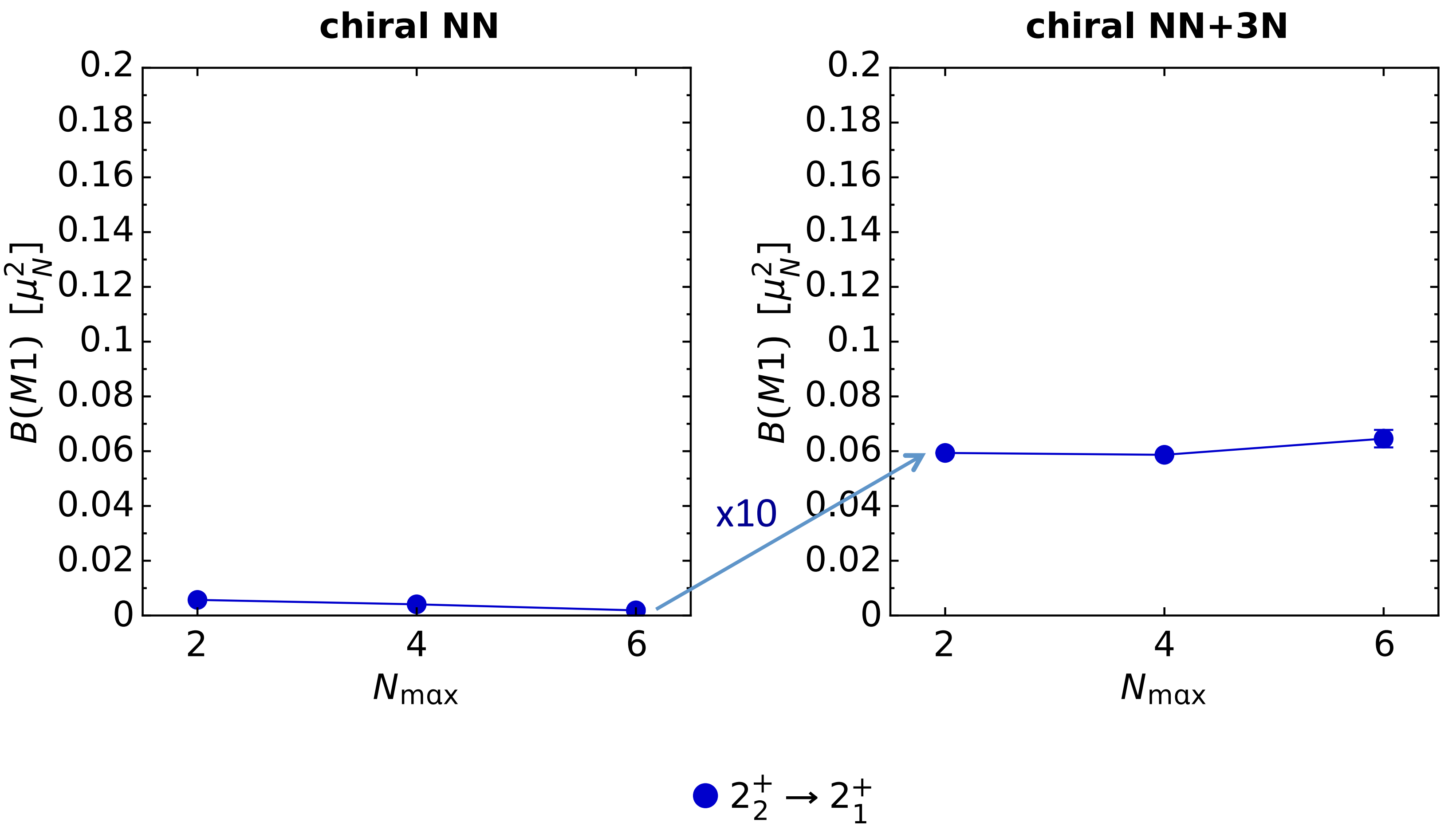
C16 – B(E2) Strength

Slide - Robert Roth



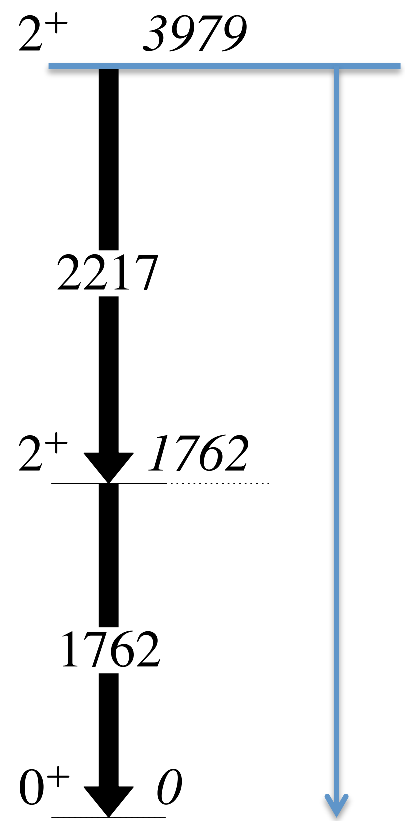
C16 – B(M1) Strength

Slide - Robert Roth

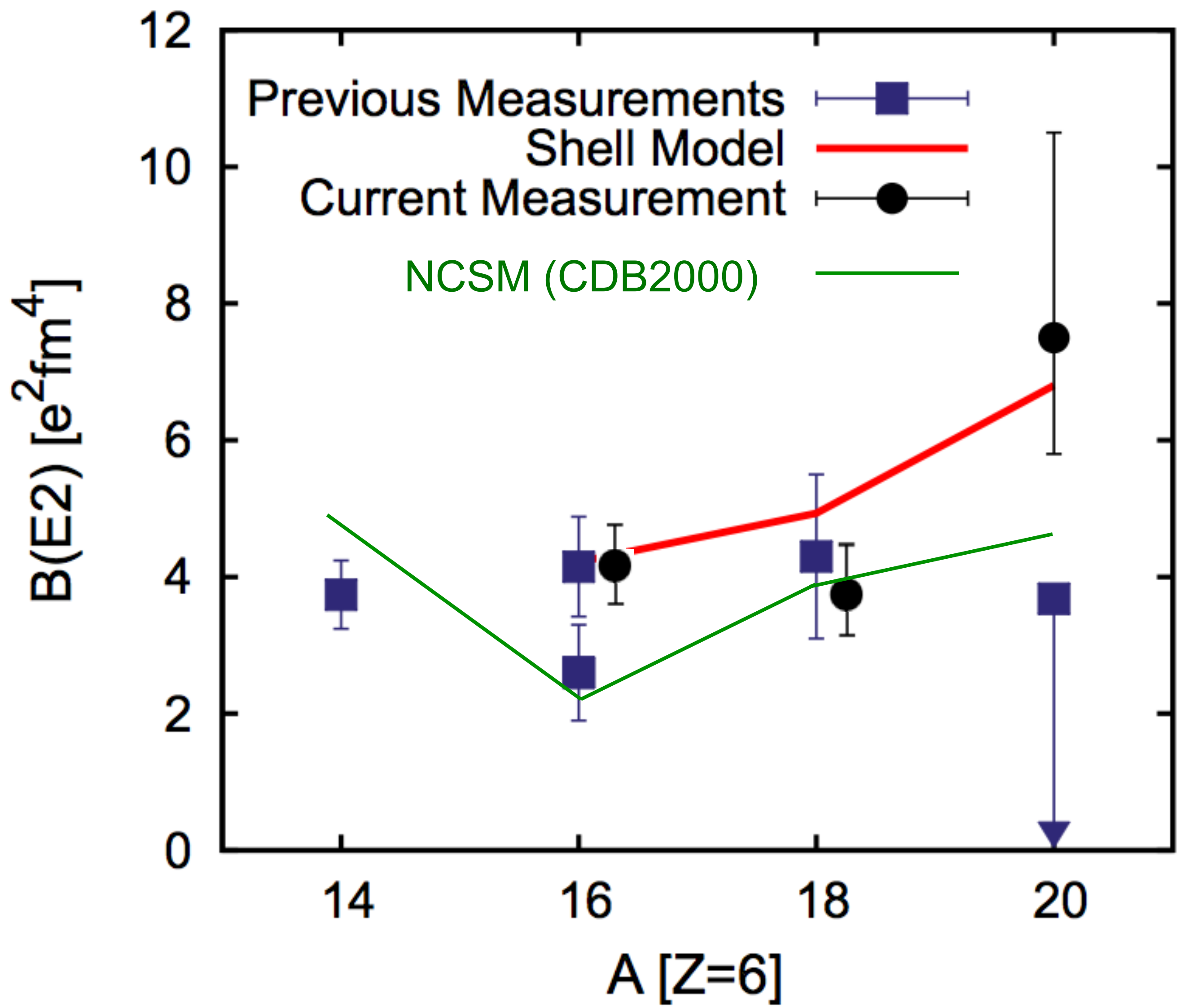


^{16}C Higher-Lying Transitions

- Data
  - $2_2 \rightarrow 0^+$ <10%
- CD Bonn NN
  - $2_2 \rightarrow 0^+$ ~70%
- Chiral NN
- $2_2 \rightarrow 0^+$ ~75%
- Chiral NN + 3N
  - $2_2 \rightarrow 0^+$ ~ 3%
  - *Absolute $B(E2{:}2_1 \rightarrow 0)$ is low*

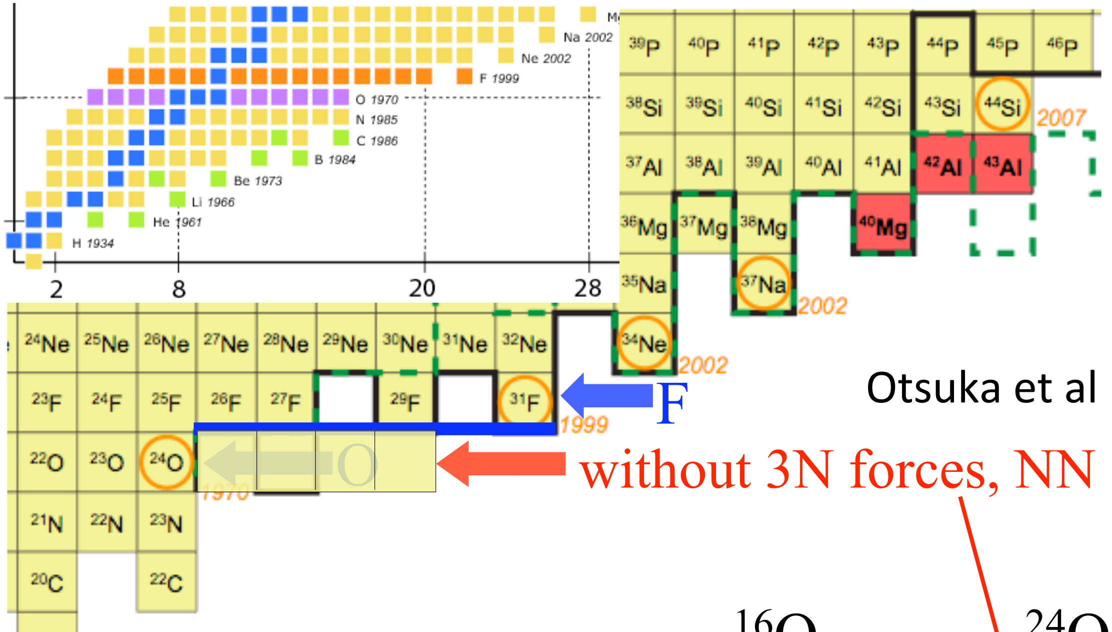


Carbon Isotopes B(E2) Systematics



^{40}Mg
"mapping the drip line"

The oxygen anomaly - not reproduced without 3N forces

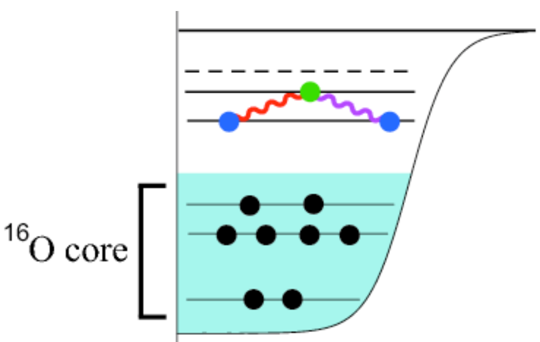


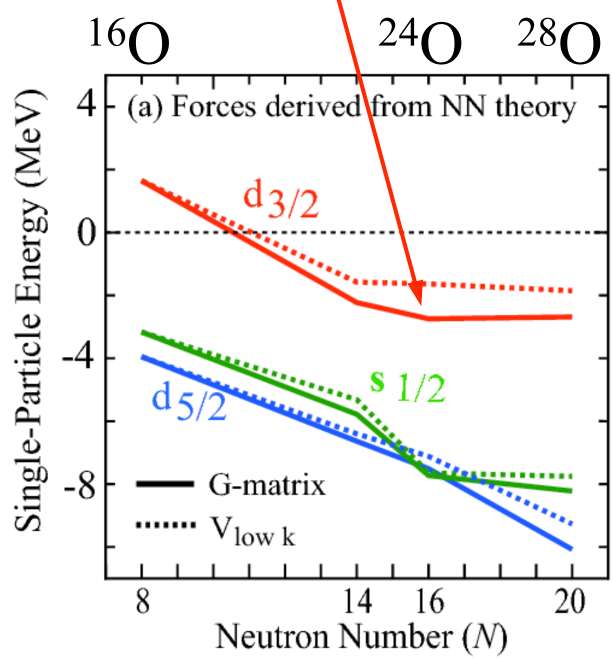
Slide A.Schwenk (ECT* 2011)

Otsuka et al PRL 105,032501 (2010)

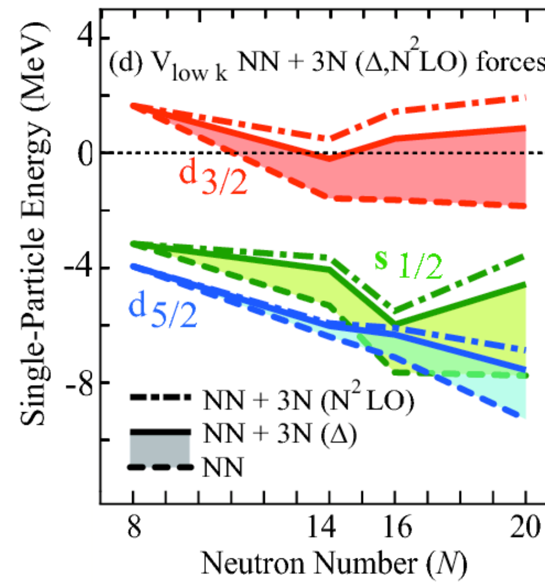
without 3N forces, NN interactions too attractive

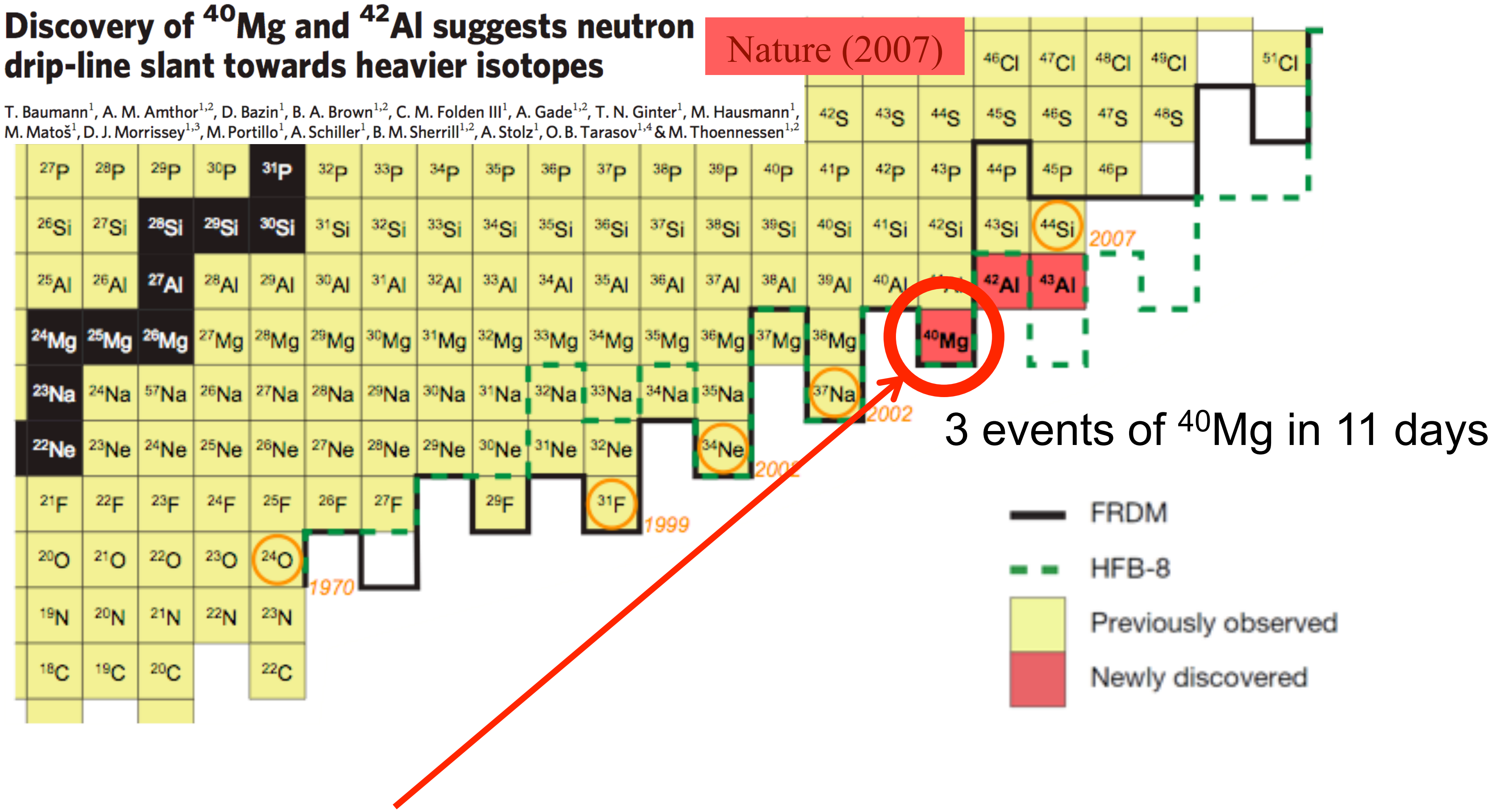
many-body theory based on two-nucleon forces:
drip-line incorrect at ^{28}O





With 3N



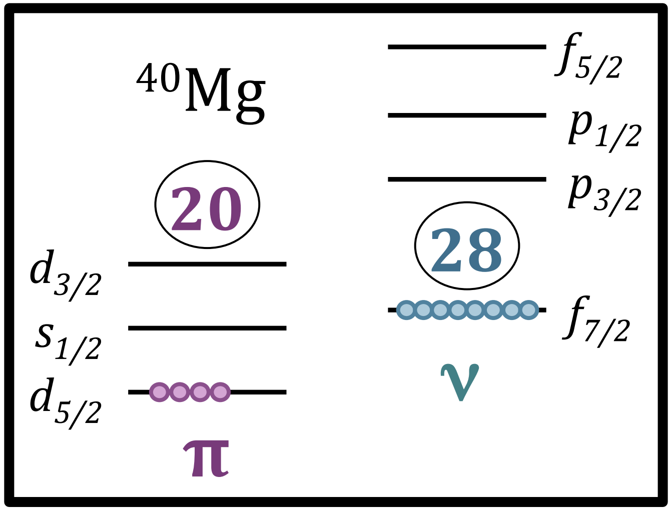


Only 5 years ago, ^{40}Mg was first observed at NSCL, and beam intensities are now approaching those required to perform spectroscopy in this nucleus.

With present-day facilities, ^{40}Mg may be one of the heaviest drip-line(?) nuclei experimentally accessible.

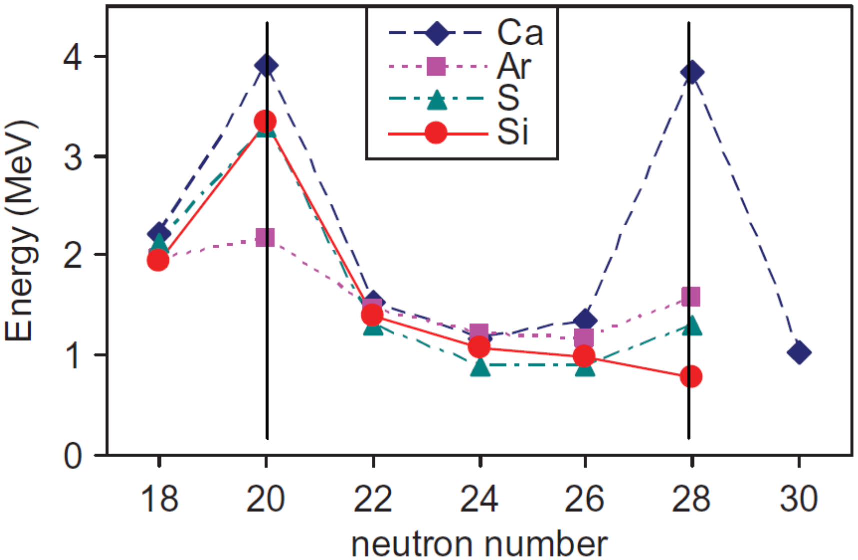
Toward the Dripline at Z=12

^{40}Mg is at the edge of the experimentally-known neutron dripline, and the last bound neutron orbital is expected to be the $2p_{3/2}$ state.



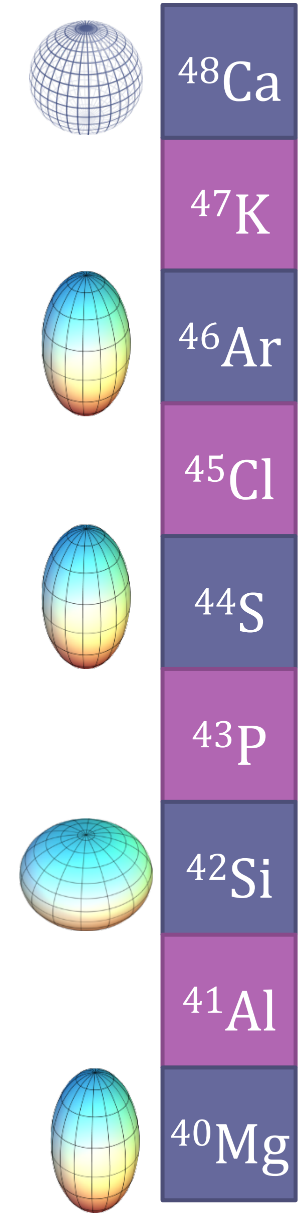
Neutron configuration with *l*=1 occupancy can lead to formation of neutron halo.

N=28 Isotones Below $_{20}$Ca



At Z=20, N=28 is a good shell gap, and ^{48}Ca is a spherical, doubly-magic nucleus

Below Z=20, E(2+) and B(E2) data provided first indications that N=28 was no longer magic.



N=28

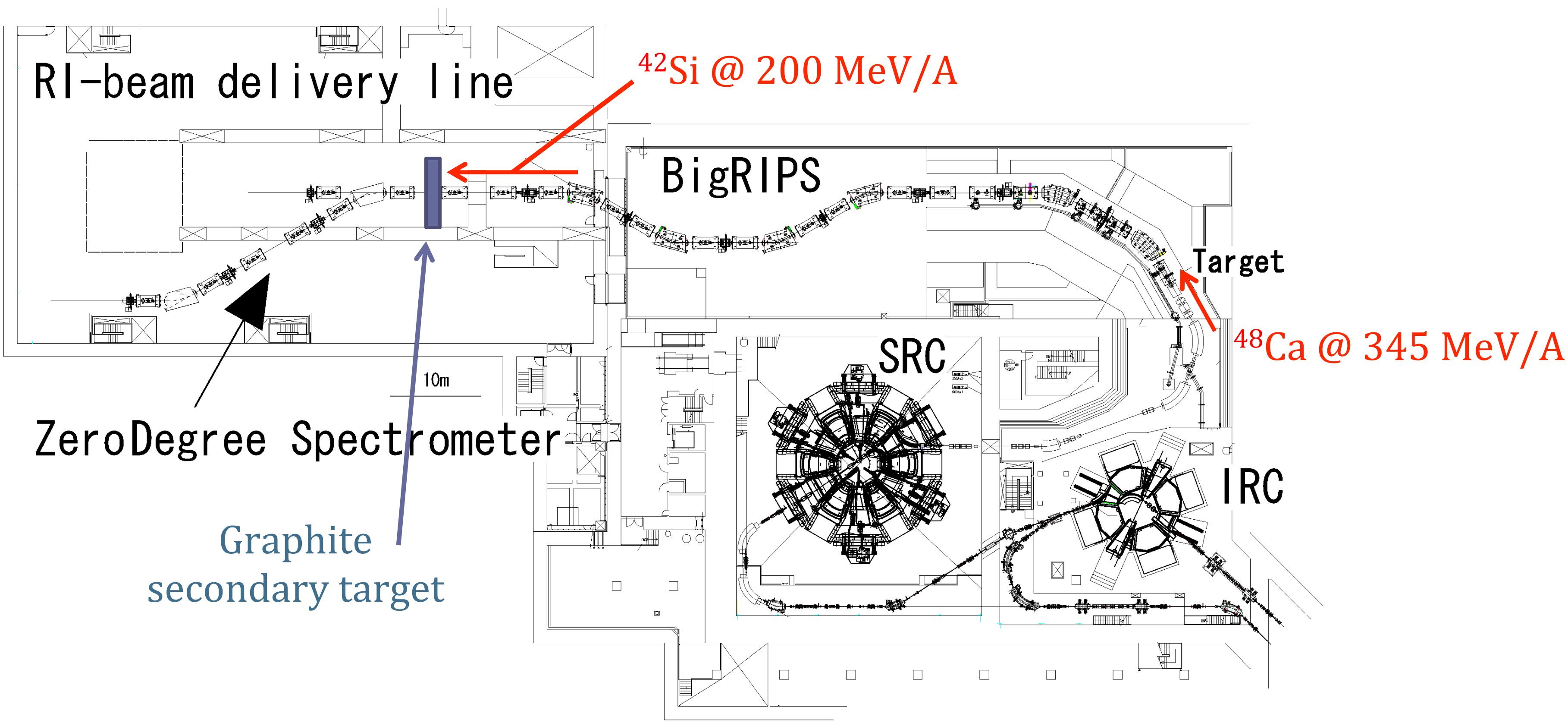
Quenching of the N=28 gap leads to deformation, predicted in both shell-model and relativistic mean-field calculations.

Rapid shape evolution and shape coexistence are also predicted in theoretical approaches.

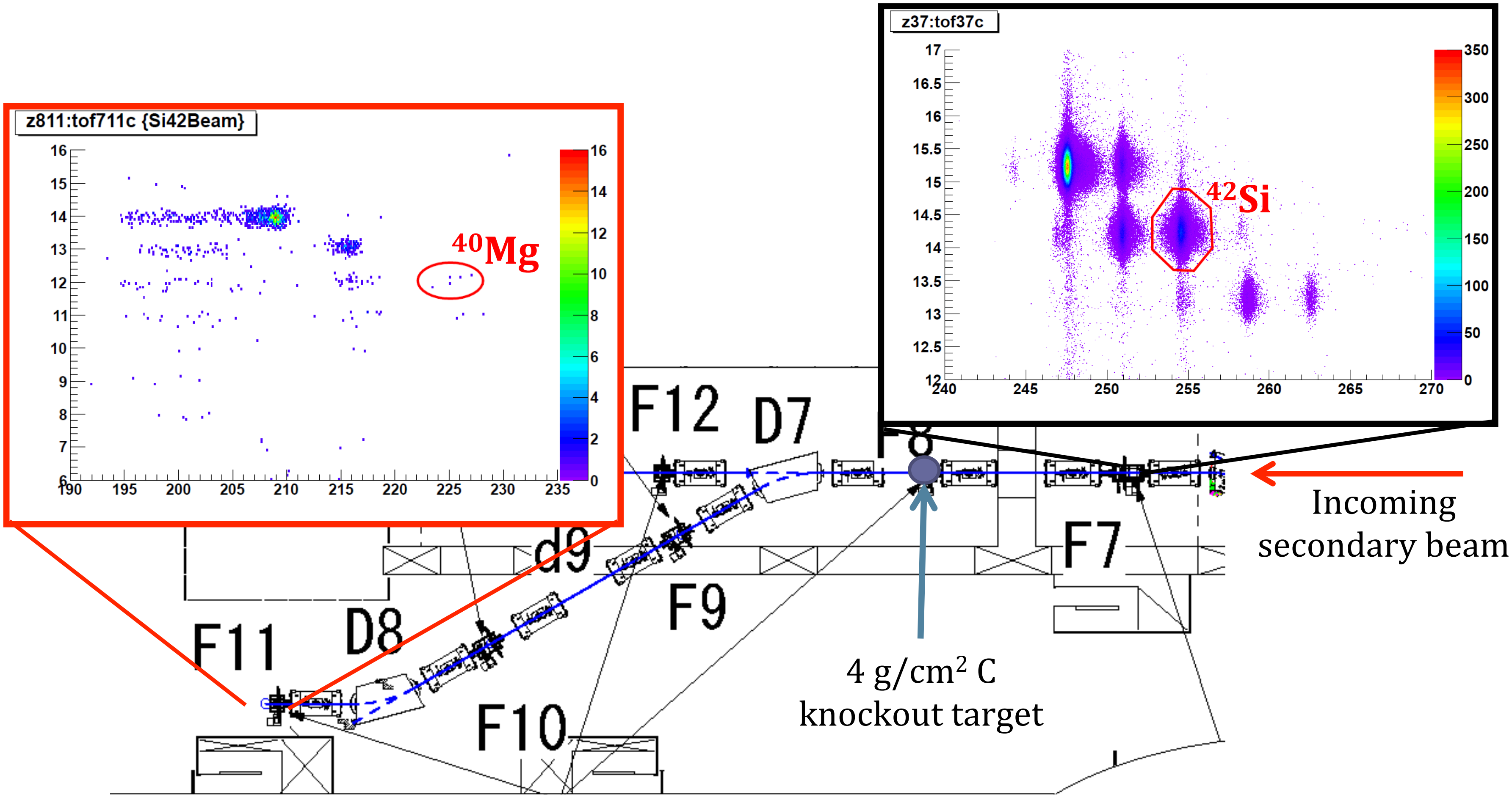
Gaudefroy and Grevy, Nucl. Phys. News **20**, 13 (2010).
Li *et al*., PRC **84**, 054304 (2011). Nowacki and Poves, PRC **79**, 014310 (2009).

Nucleon Knockout at RIBF

- High intensity of ^{48}Ca primary beam at RIBF in RIKEN made possible measurement of ^{42}Si 2p knockout to ^{40}Mg
- ^{42}Si produced at a rate of 25 pps/100 pnA following fragmentation of a ^{48}Ca beam



2p Knockout – ^{42}Si into ^{40}Mg



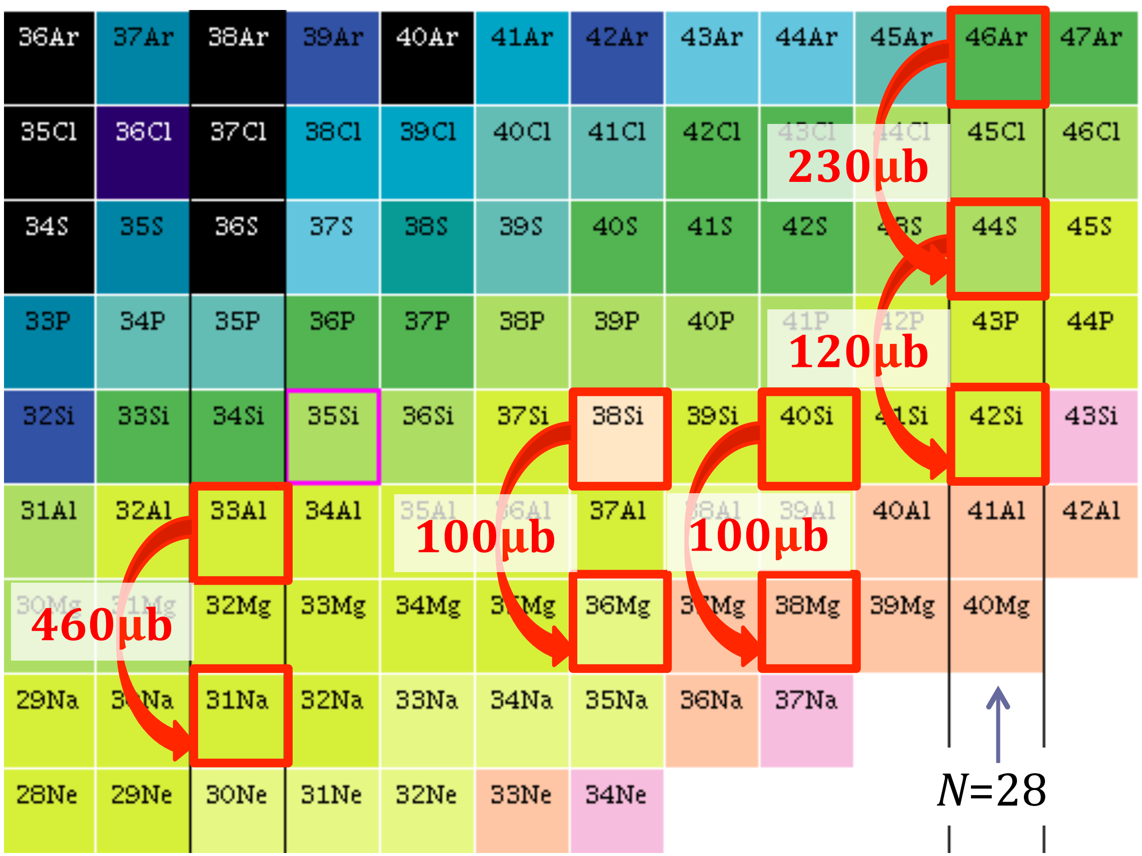
- Knockout from 200MeV/A ^{42}Si on a 4 g/cm^2 target
- Based on 5 observed ^{40}Mg, measured inclusive 2p knockout cross-section of ~40 μb.

What Do We Expect?

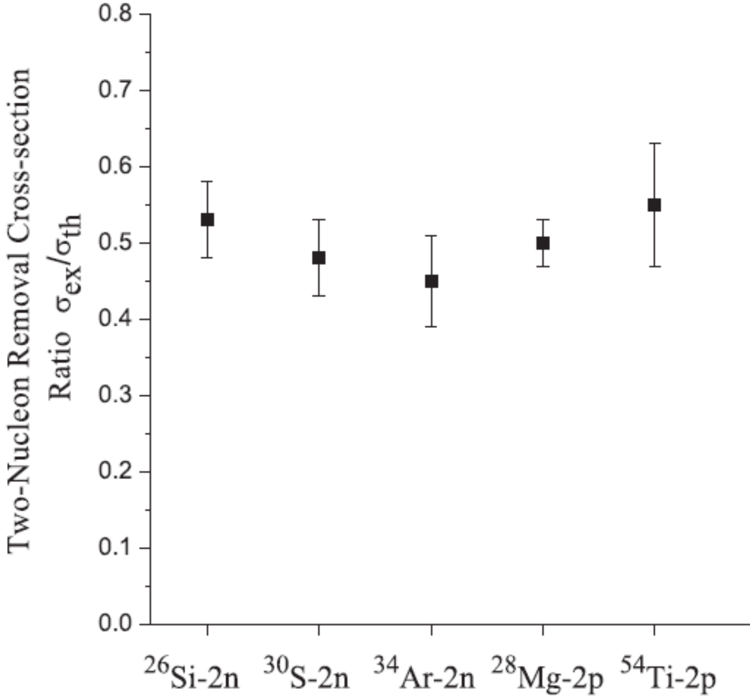
$$\sigma_{-2p\ (inclusive)}\ (^{42}\text{Si} \rightarrow {}^{40}\text{Mg}) = 40\ \mu\text{b}$$

In this region, 2p inclusive removal cross-sections are nominally on order of a few hundred μb

⇒ cross-section into ^{40}Mg appears to be low



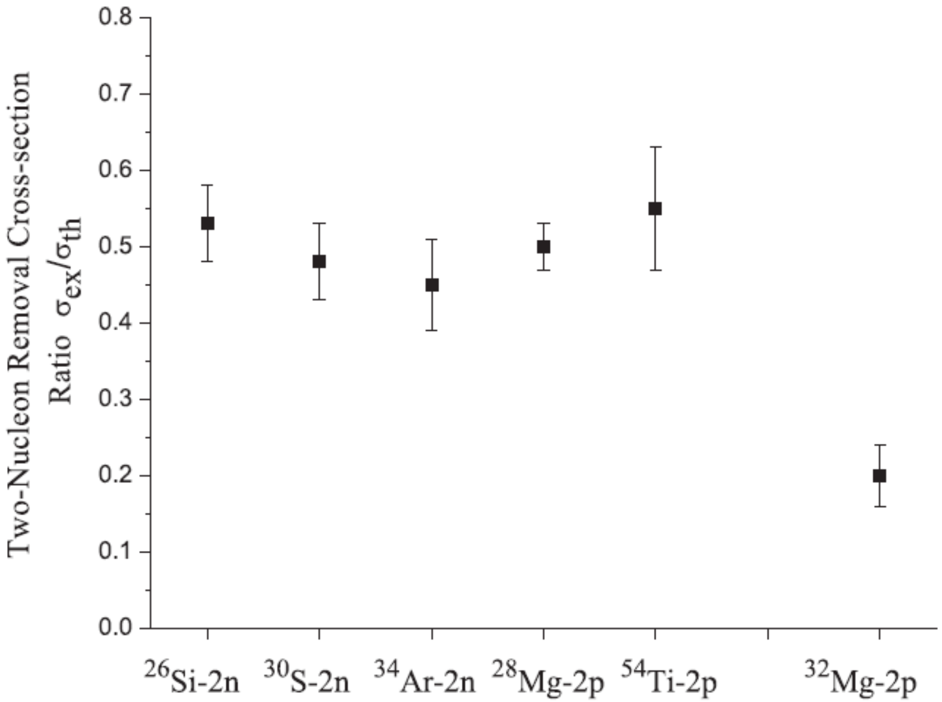
2p Knockout Cross-Section Suppression?



Two nucleon knockout experiments have suggested suppression of experimentally observed inclusive cross-sections by factor of ~2 compared to theoretical values.

Fallon *et al.*, PRC **81**, 041302(R) (2010).

2p Knockout Cross-Section Suppression?



Two nucleon knockout experiments have suggested suppression of experimentally observed inclusive cross-sections by factor of ~2 compared to theoretical values.

Additional suppression has been attributed to nuclear structure effects.

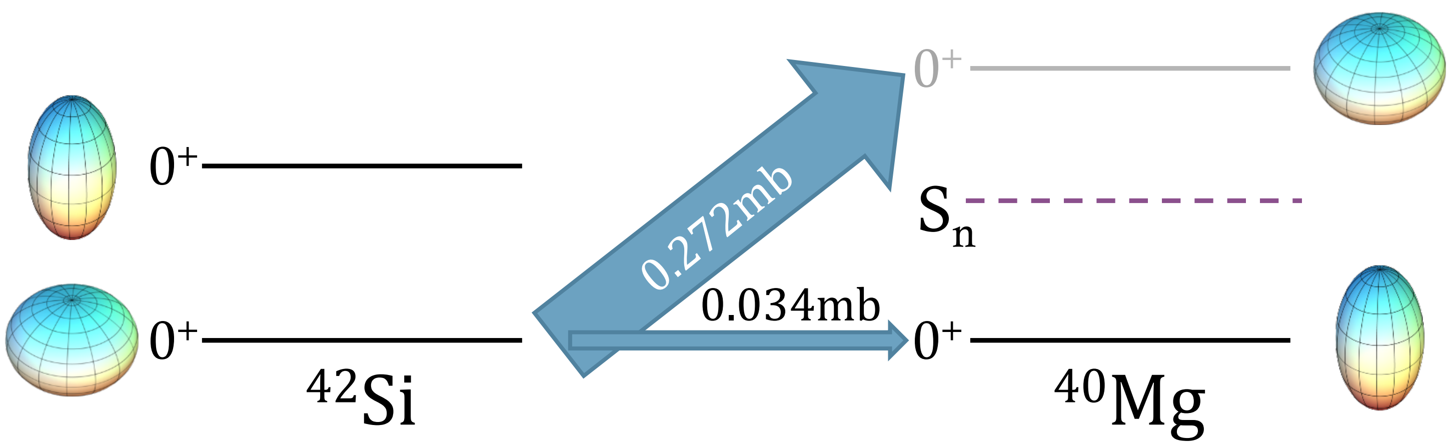
If we assume that $^{42}Si \rightarrow {}^{40}Mg + 2p$ should have a suppression of ~0.5, what can we learn from the shell-model?

Fallon *et al.*, PRC **81**, 041302(R) (2010).

Shell Model Interpretation

Using TNAs from shell-model calculations using the SDPFU(Si) effective interaction, reaction theory predicts the following for ^{42}Si 2p knockout:

^{40}Mg State	Calculated σ (mb)
0+ (g.s.)	0.034
2+	0.008
4+ (unbound)	0.001
0_2+ (unbound)	0.272



Knockout from the ^{42}Si g.s.

Calculations from. B.A. Brown and J. Tostevin
Nowacki and Poves, PRC **79**, 014310 (2009).

Shell Model Interpretation

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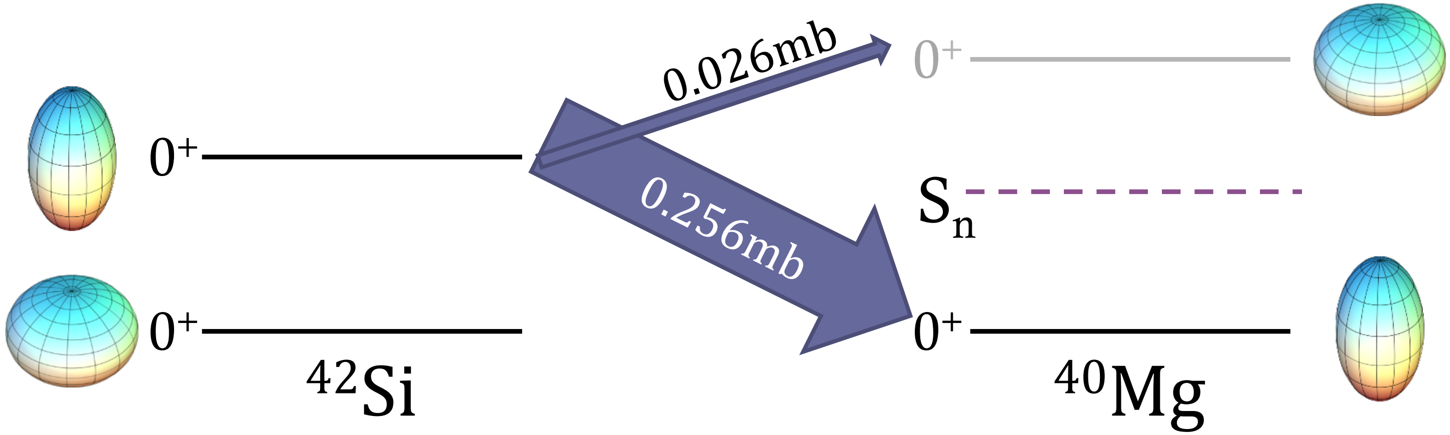


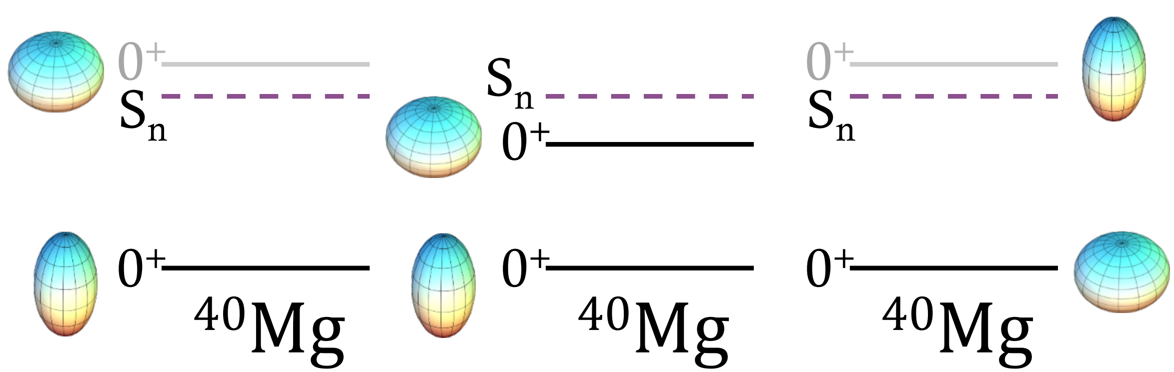
Knockout from the ^{42}Si first excited 0+ state

Calculations from. B.A. Brown and J. Tostevin
Nowacki and Poves, PRC **79**, 014310 (2009).

Accounting for Suppression in ^{40}Mg

- Based on suppression of well-described two-nucleon knockouts, expect 2p knockout to have a similar suppression of ~0.5
- Assuming a 0.5 suppression, we can consider the structural possibilities for ^{40}Mg

^{40}Mg State	Experiment (μb)	Calculated σ (μb)	Calculated σ (μb)	Calculated σ (μb)
0+ (g.s.)	--	17	17	17
2+	--	4	4	4
4+	--	0.5	0.5	0.5
0_2+	--	136	136	136
Inclusive	**40(20)**	**21**	**158**	**136**



Summary

- Carbon isotopes are an interesting system to study the evolution of shell structure with isospin and the influence of weak binding.
  - E2 Transition rates can isolate these effects.

- Extracted transition rates from $^{16}C \rightarrow {}^{20}C$ (near dripline)
  - Quantitative test of model(s) - require a consistent description from stable →”dripline” nuclei

- A “well-bound” shell model appears to be able to track $E(2^+)$ and B(E2),
  - increase in B(E2) due to increased proton excitations in the p-shell.

- NCSM *ab initio* calculations overall reasonable agreement for $^{10-20}C$
  - ^{16}C: find that branching ratios very sensitive to the details of the interaction, particularly inclusion of 3N

- ^{40}Mg “first information” on its structure

  Under the assumption of an expected 0.5 suppression relative to shell-model + reaction theory, ^{40}Mg appears to have a ground state configuration different than ^{42}Si (i.e. prolate vs. oblate), while the second major configuration (i.e. oblate configuration) is unbound

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THANK YOU!

END