Knockout to Probe Proton Contributions to the B(E2) Transition Strength in the C Isotopes

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Overview

- B(E2) and proton contributions in the C isotopes
  - Current status and systematics along Z=6
- Proton knockout at NSCL
  - NSCL e09085 – experimental details
  - Status of analysis
- Preliminary results for proton amplitudes

Weak Binding in Nuclei

- In a well bound nucleus
  - steady evolution of energy levels in a 1 body potential
  - modified by 2-body NN interaction (i.e. tensor)

- A second distinct effect is due to weakly bound levels
  - low *l* levels (s, p) --> extended wavefunctions (‘halos’)
  - valence nucleons can decouple from the core
  - coupling to continuum states can modify structure

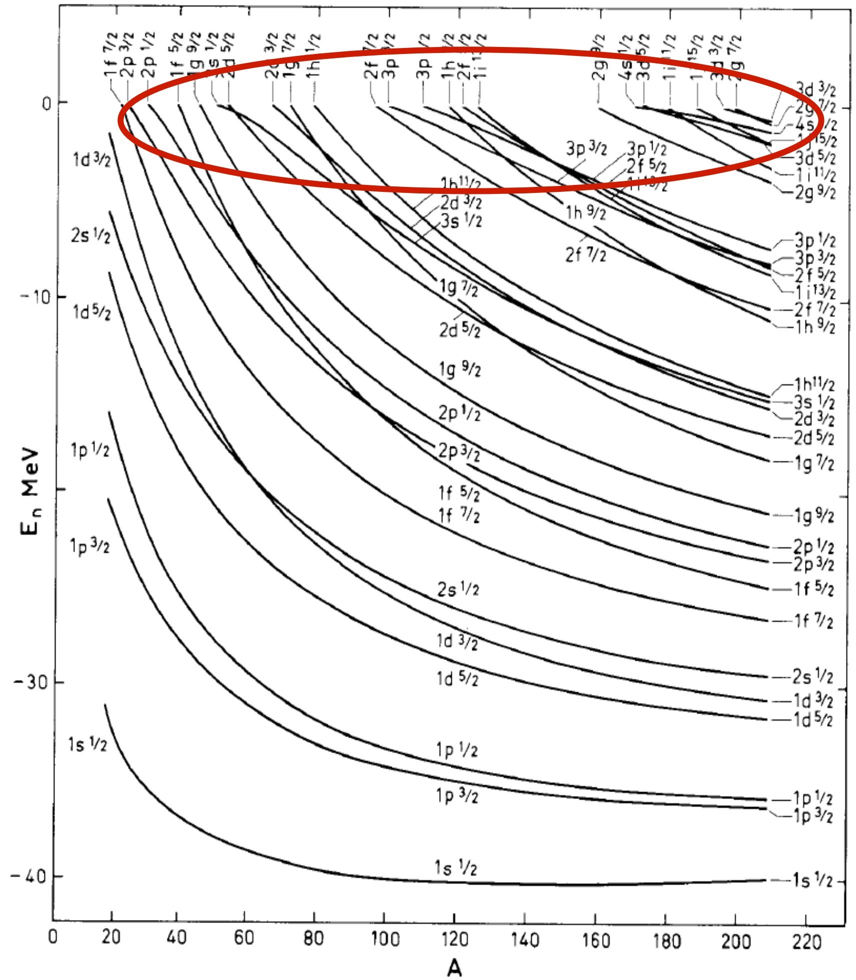
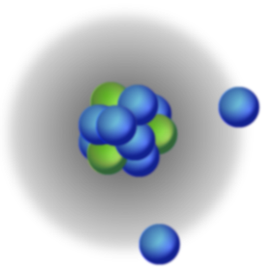
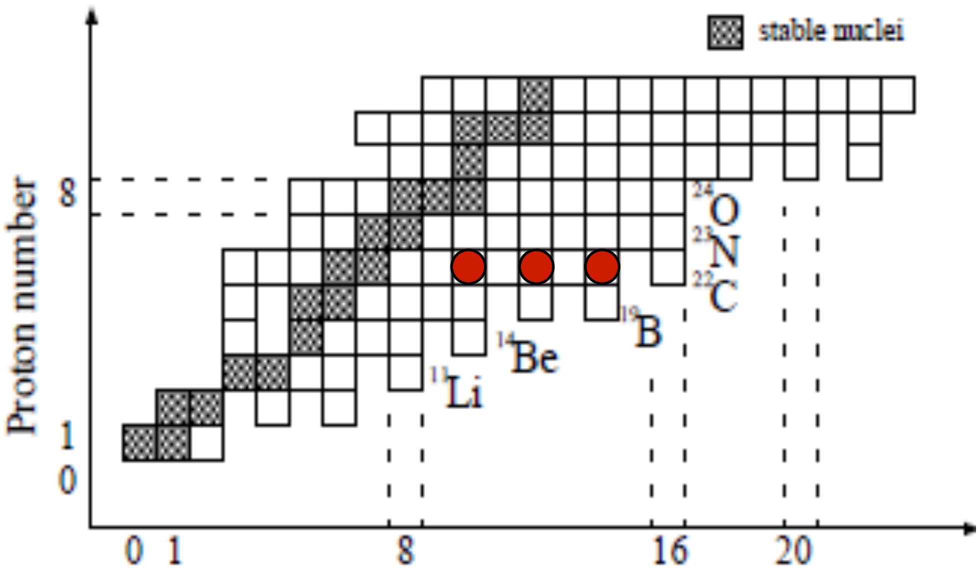


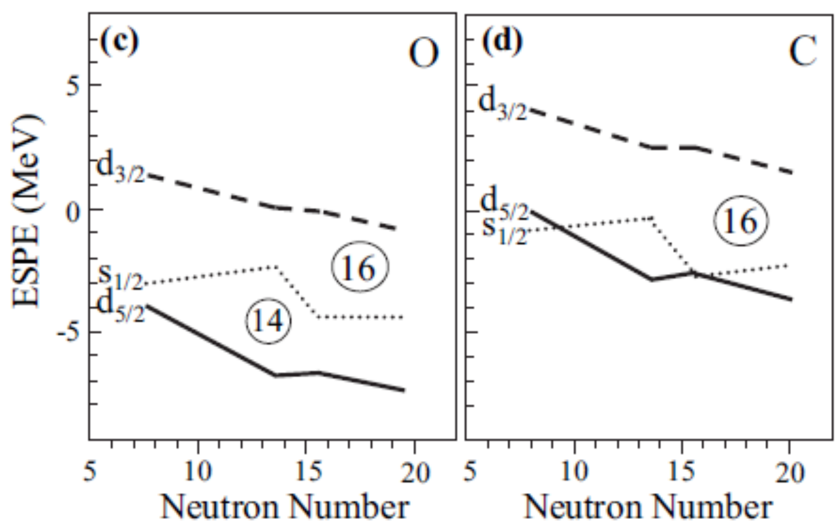
Figure 2-30 Energies of neutron orbits calculated by C. J. Veje (private communication).



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

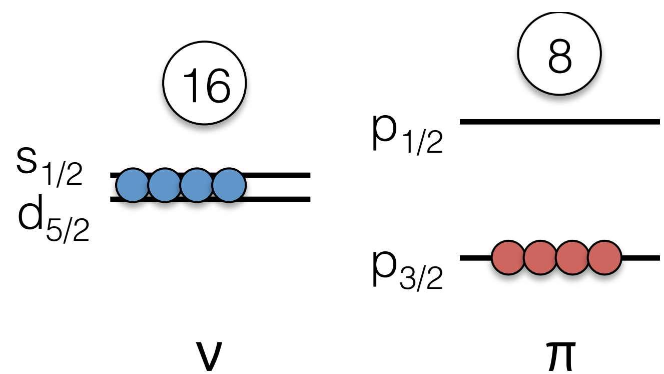
Carbon Isotopes





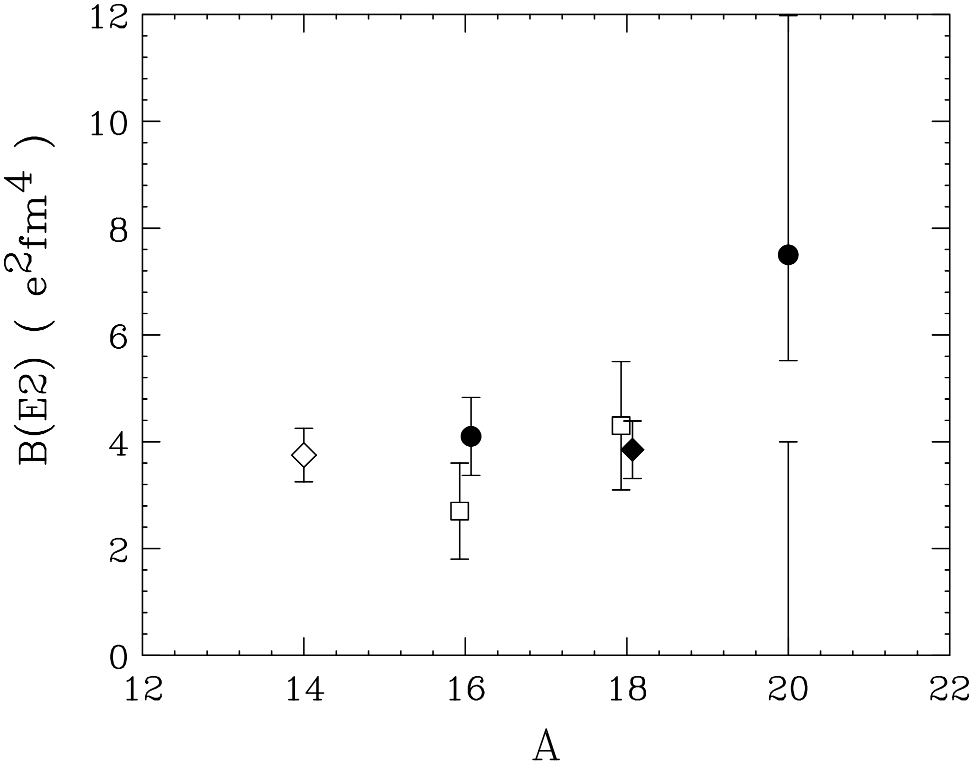
- Carbon isotopes provide a testing ground for structure theories with experimental access to both driplines
- *N*=8 closed proton shell (^{14}C)
- *N*=16 --> dripline (^{22}C)
- *N* > 8 – g.s. with large $\nu s_{1/2}$ component and dominant neutron excitation 2^+

$$0.55|(s_{1/2})^2\rangle + 0.84|(d_{5/2})^2\rangle$$



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

B(E2) in the Carbon Isotopes

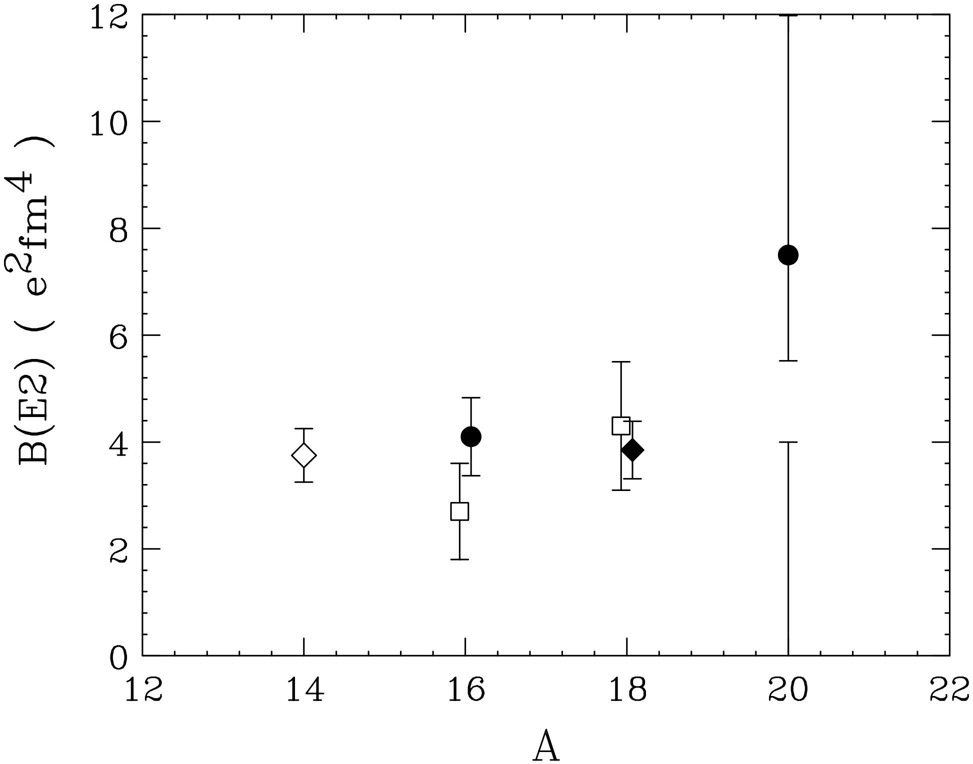


$$B(E2) = 1/(2J_i+1) * | M_n*e_n + M_p*e_p |^2$$

- Effects of spatially extended valence particles?
- Core polarization? Effective charges?

M. Wiedeking et al., PRL **100**, 152501 (2008).
H. J. Ong et al., PRC **78**, 014308 (2008). -- P. Voss et al., PRC **86**, 011303(R) (2012).
M. Petri et al., PRC **86**, 044329 (2012). -- M. Petri et al., PRL **107**, 102501 (2011).

B(E2) in the Carbon Isotopes



- Effects of spatially extended valence particles?
- Core polarization? Effective charges?

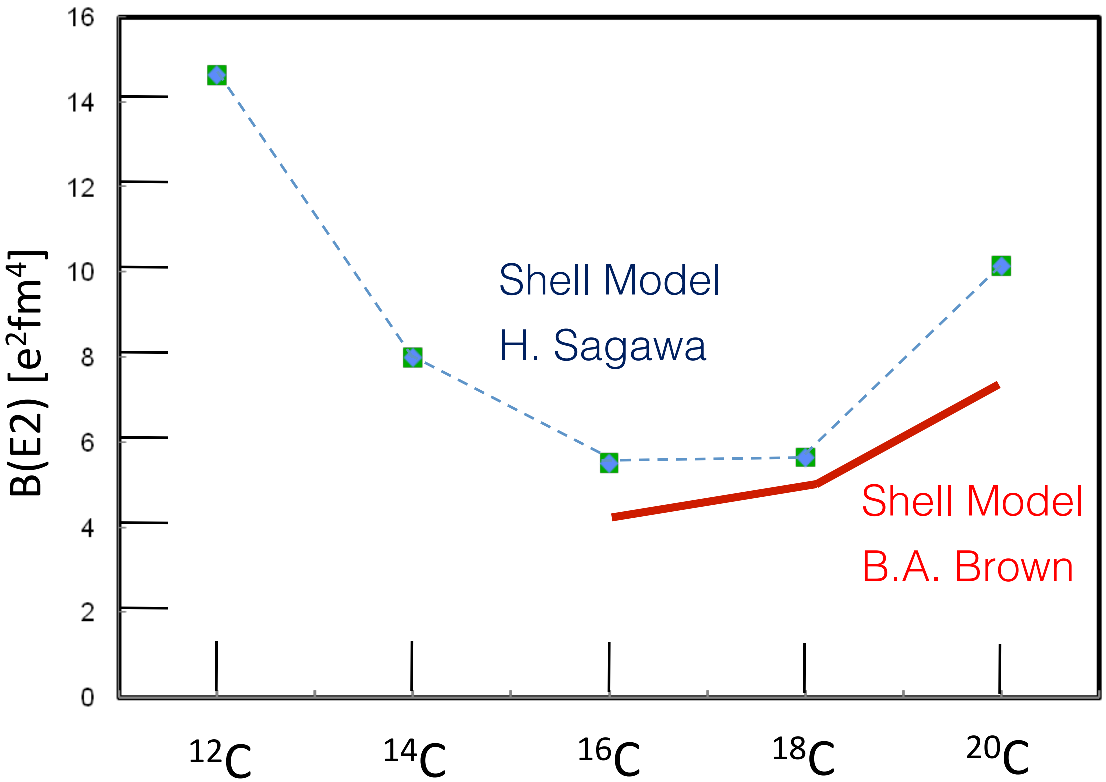
$$B(E2) = 1/(2J_i+1) * | M_n*e_n + M_p*e_p|^2$$

M_n and M_p contributions changes with isospin…

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

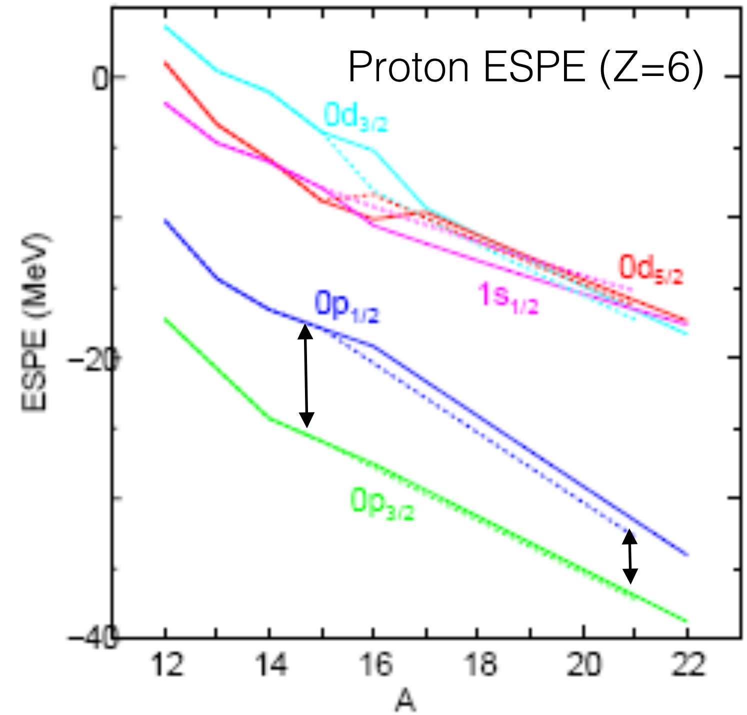
Understanding B(E2) along Z=6



“↑ proton” “neutron” “↑ proton”

2⁺ state dominant component

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



- Reduced $p_{3/2}$-$p_{1/2}$ gap

V_{pn}

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

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

Probing Proton Contribution to B(E2)

A. O. Macchiavelli et al., PRC **90**, 67305 (2014).

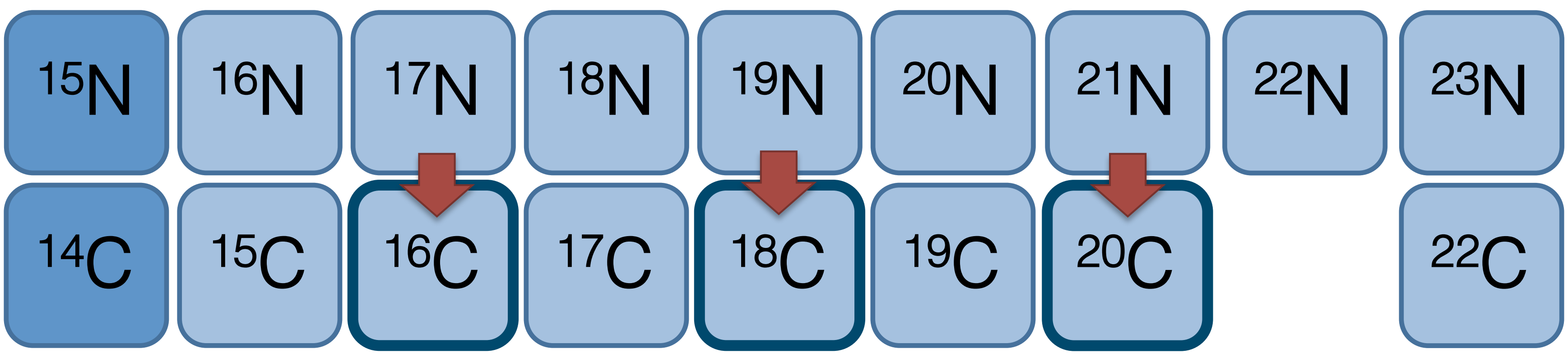
The 2+ state can be written as

$$|2_1^+; {}^A\mathrm{C}\rangle = \alpha|\nu(sd)^n; J=2\rangle \otimes |\pi(p_{3/2})^4; J=0\rangle + \beta|\nu(sd)^n; J=0\rangle \otimes |\pi(p_{3/2})^3(p_{1/2})^1; J=2\rangle$$

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

Sum rule arguments

$$\mathrm{SF}(2^+/0^+) = \sigma(2^+/0^+) \sim 5/2\ \beta^2$$



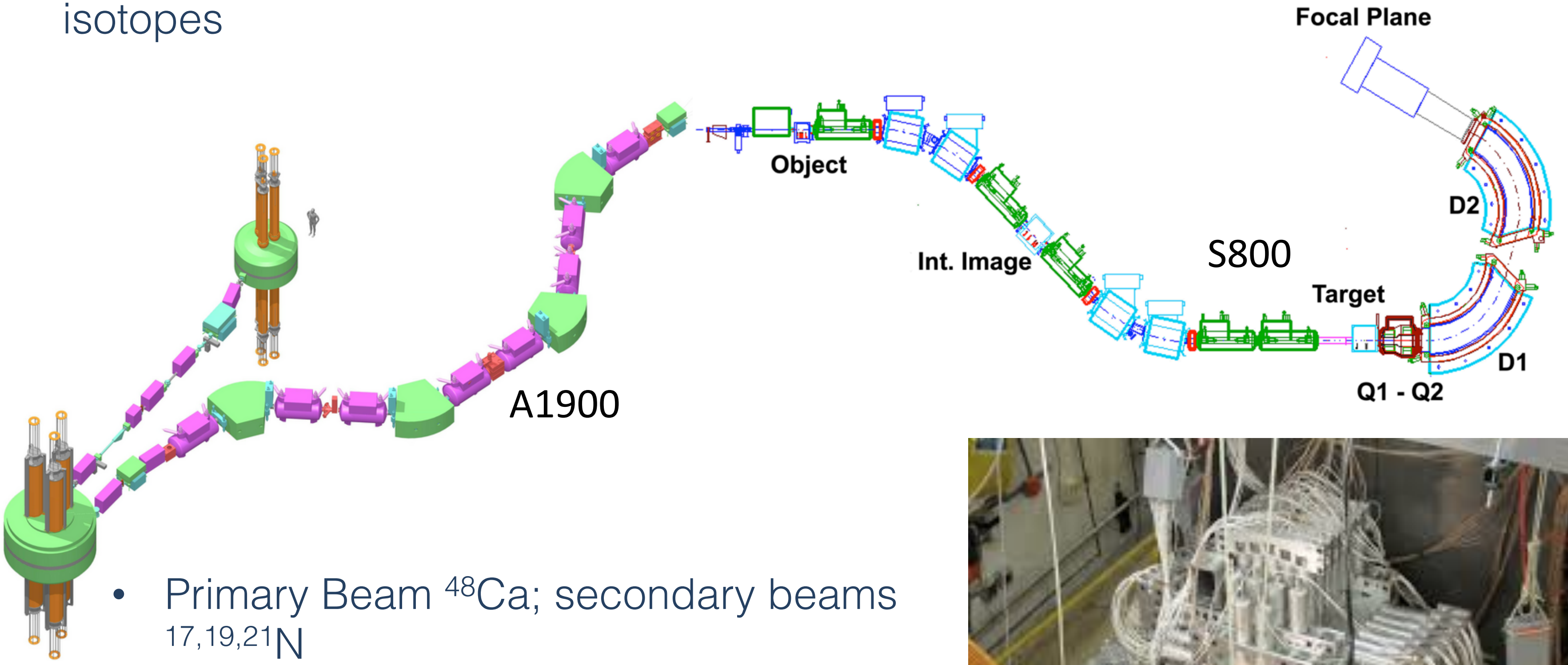
Knockout Calculations for N(-1p)

Reaction	Energy	SF	Sigma (Theory)	$2^+:0^+$ (%)	β^2 (%)
$^{17}N(-1p)^{16}C$	0^+ (g.s.)	1.03	22.85	13.0	5.2
	2^+ (1.8MeV)	0.14	2.97		
$^{19}N(-1p)^{18}C$	0^+ (g.s.)	0.87	15.08	21.0	8.4
	2^+ (1.6MeV)	0.18	3.17		
$^{21}N(-1p)^{20}C$	0^+ (g.s.)	0.74	10.22	56.5	22.6
	2^+ (2.1MeV)	0.41	5.77		

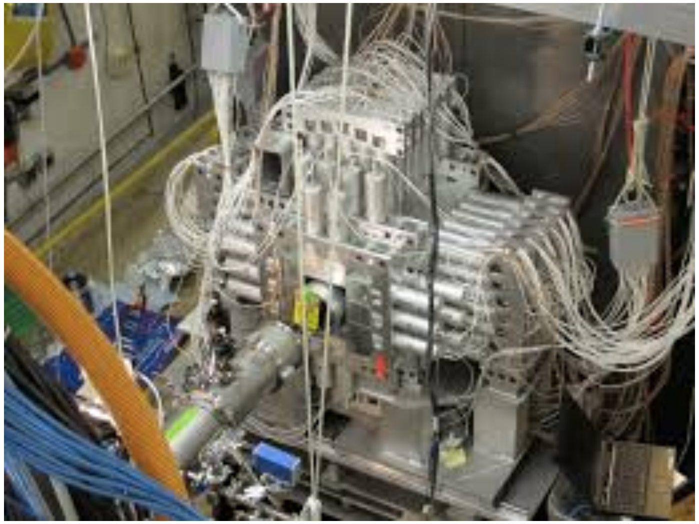
Limited data available for ^{16}C suggested a cross-section ratio of 0.28, or $\beta^2 \sim 13\%$, and a value in ^{18}C modestly higher, in line with the calculations.

NSCL Experiment e09085

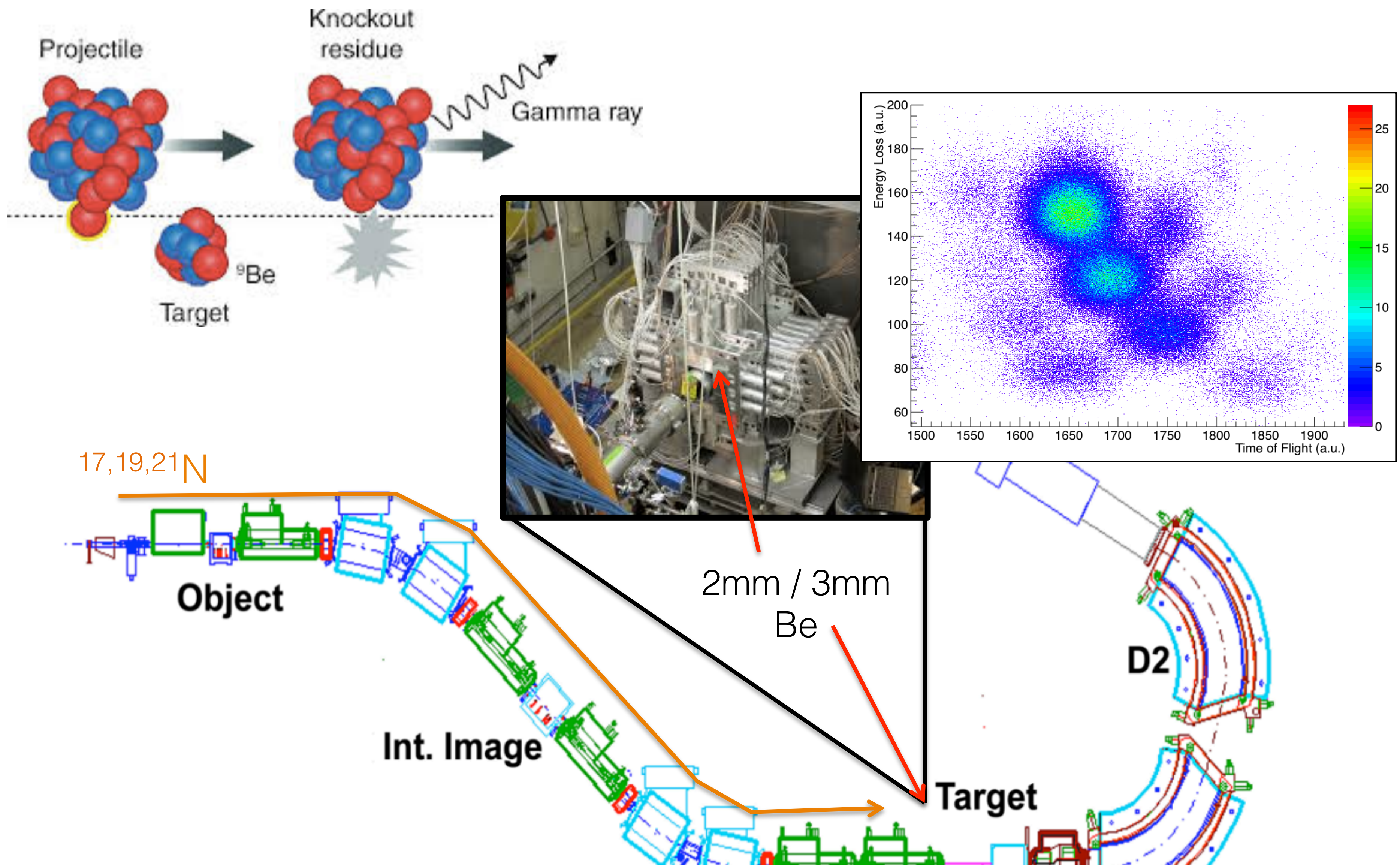
- GOAL: Quantify proton contribution to 2^{+} excitations in neutron-rich C isotopes



- Primary Beam ^{48}Ca; secondary beams ^{17,19,21}N
- Direct proton knockout into C isotopes
- CAESAR: High efficiency gamma-ray detection covering large solid angle

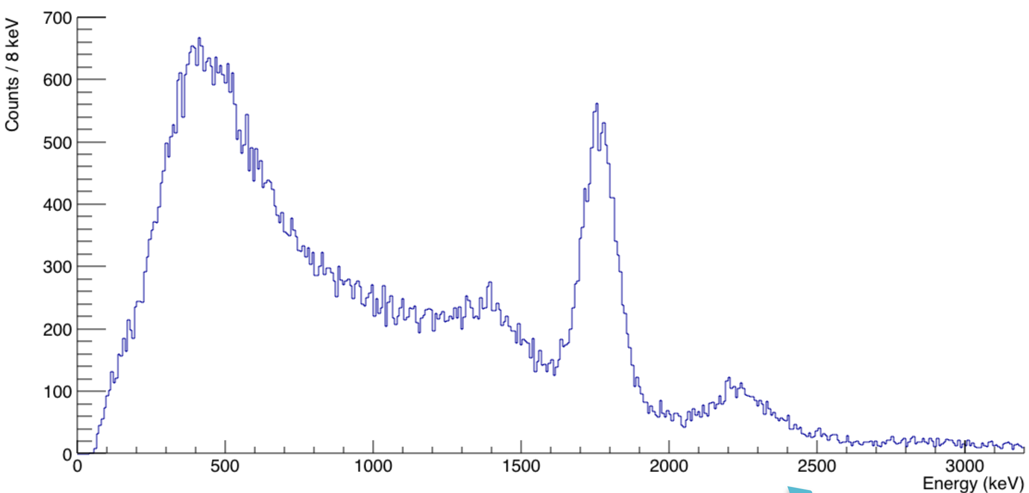


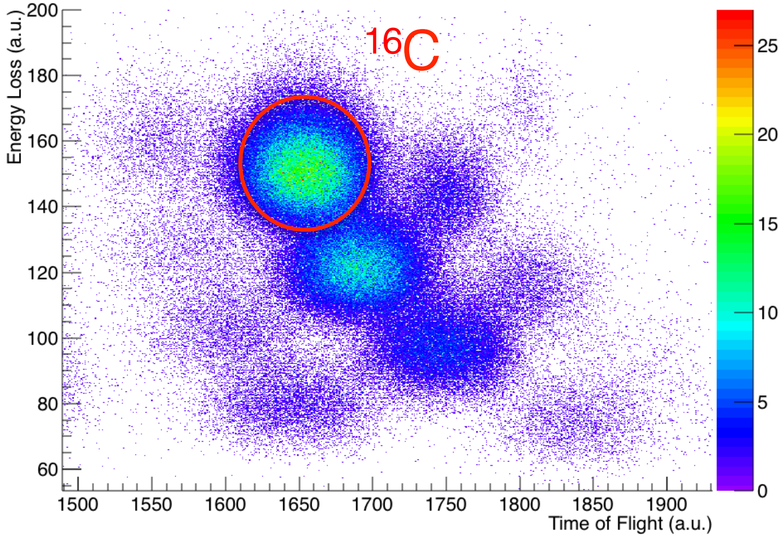
S800 + CAESAR



Projectile
Knockout residue
Gamma ray
^{9}Be
Target
17,19,21N
Object
Int. Image
2mm / 3mm Be
Target
D2
Energy Loss (a.u.)
Time of Flight (a.u.)
200
180
160
140
120
100
80
60
1500
1550
1600
1650
1700
1750
1800
1850
1900
25
20
15
10
5
0

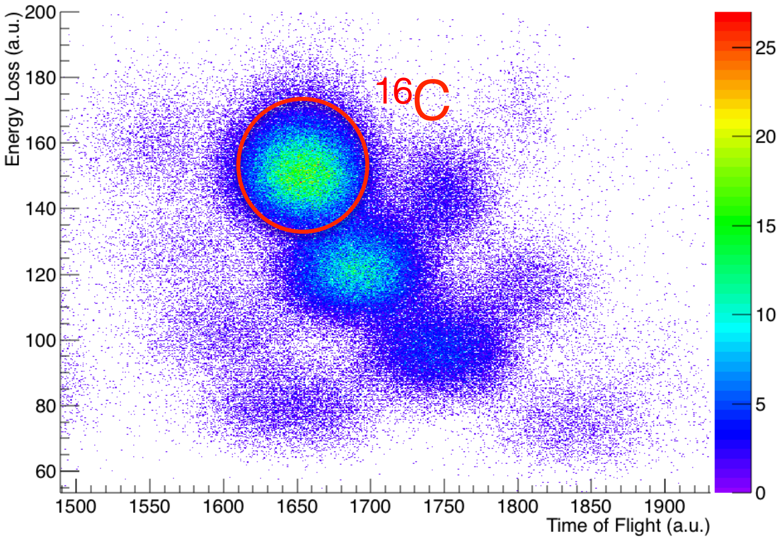
^{16}C from ^{17}N

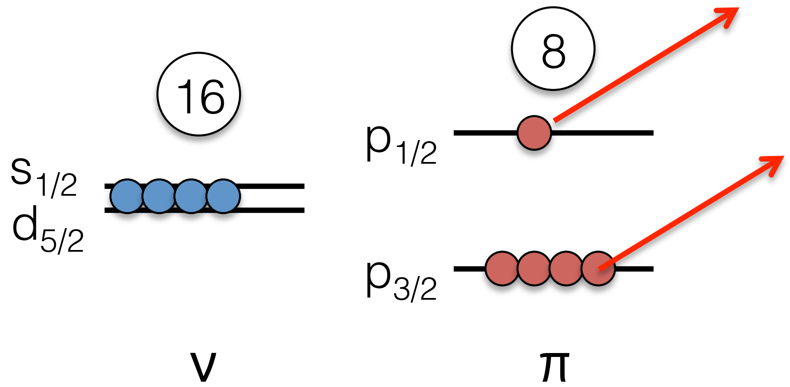

Counts / 8 keV
700
600
500
400
300
200
100
0
0
500
1000
1500
2000
2500
3000
Energy (keV)


16C
Energy Loss (a.u.)
200
180
160
140
120
100
80
60
1500
1550
1600
1650
1700
1750
1800
1850
1900
Time of Flight (a.u.)
25
20
15
10
5
0


Object
Int. Image
Target
D2

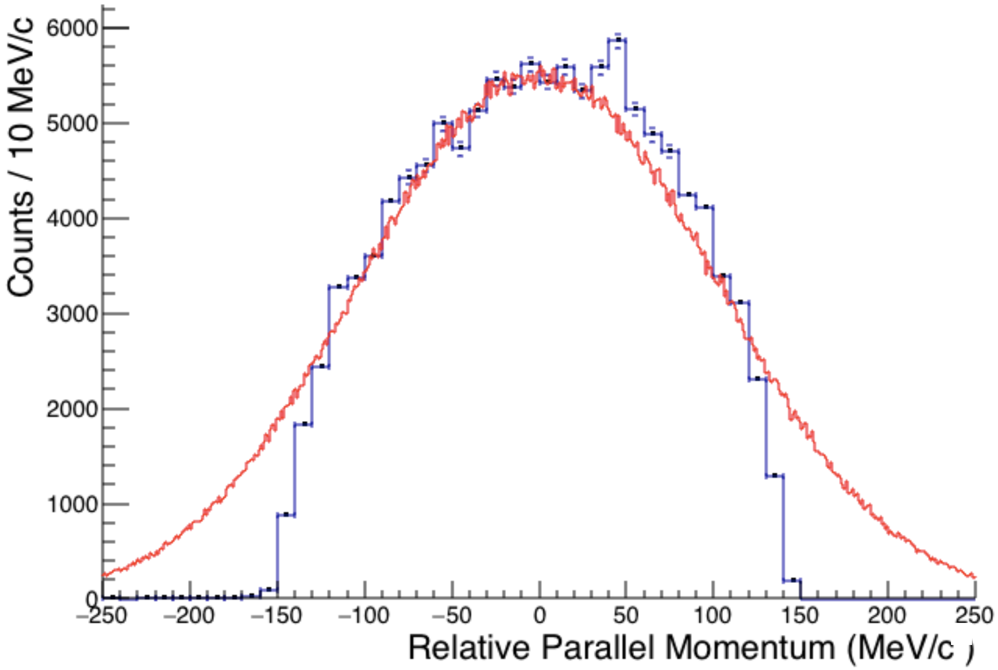
^{16}C from ^{17}N -- Momentum Transfer



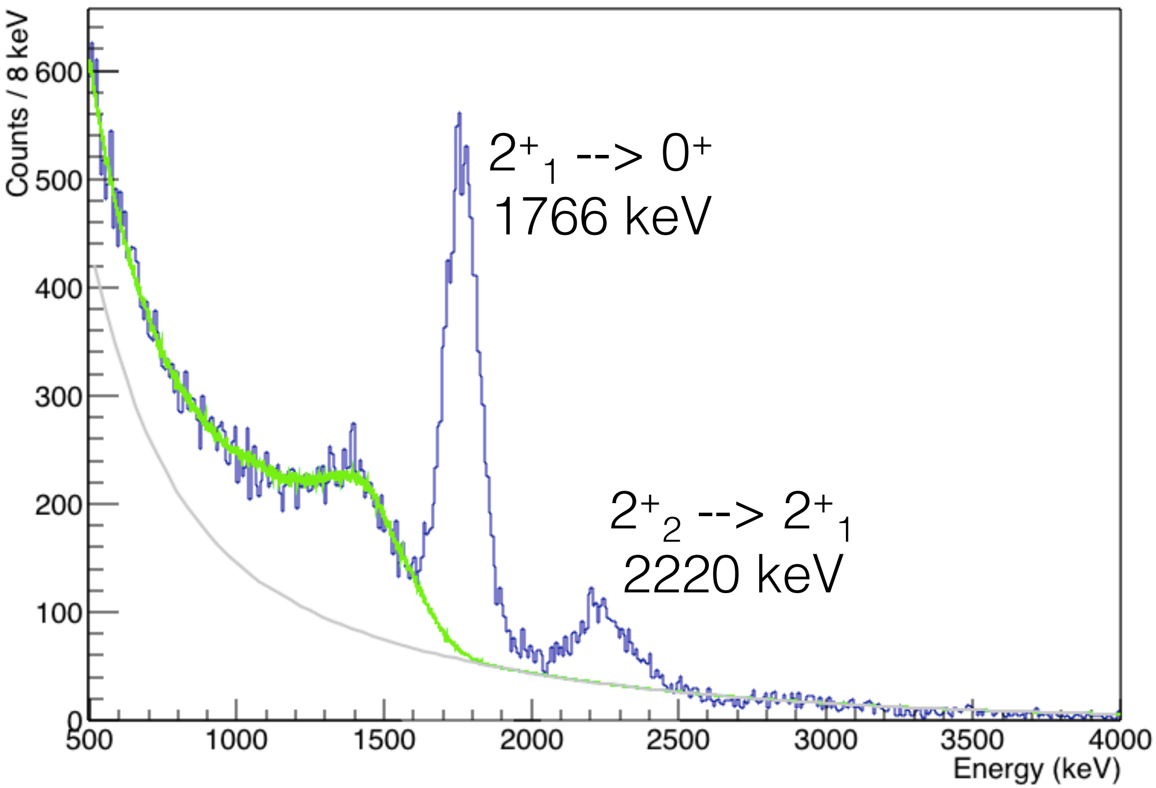


Parallel momentum distribution matches very well with calculated p (l=1) proton knockout.

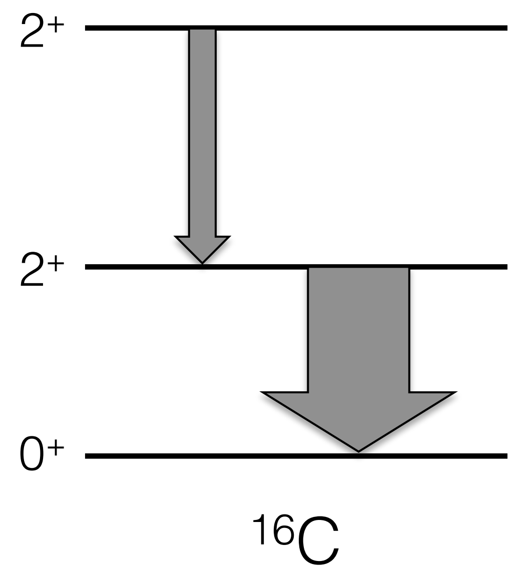
--> Confidence in the direct nature of the reaction mechanism.



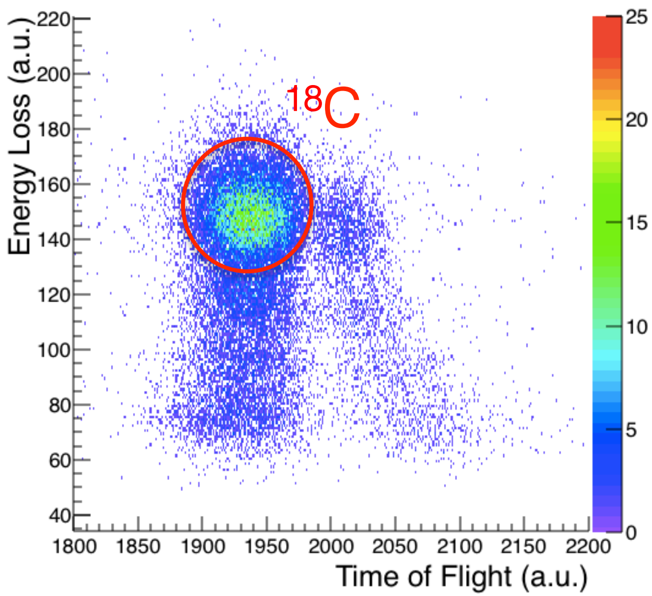
^{16}C from ^{17}N



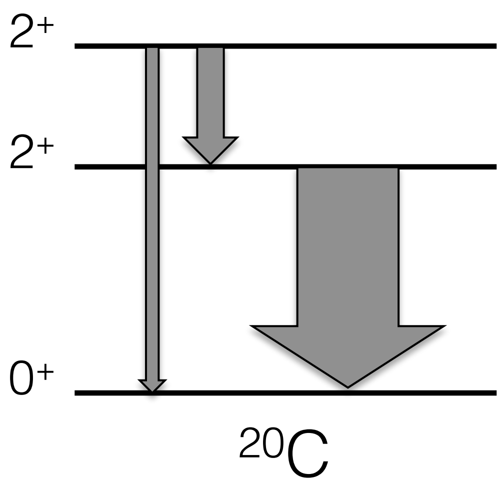
121165 ^{16}C observed in total



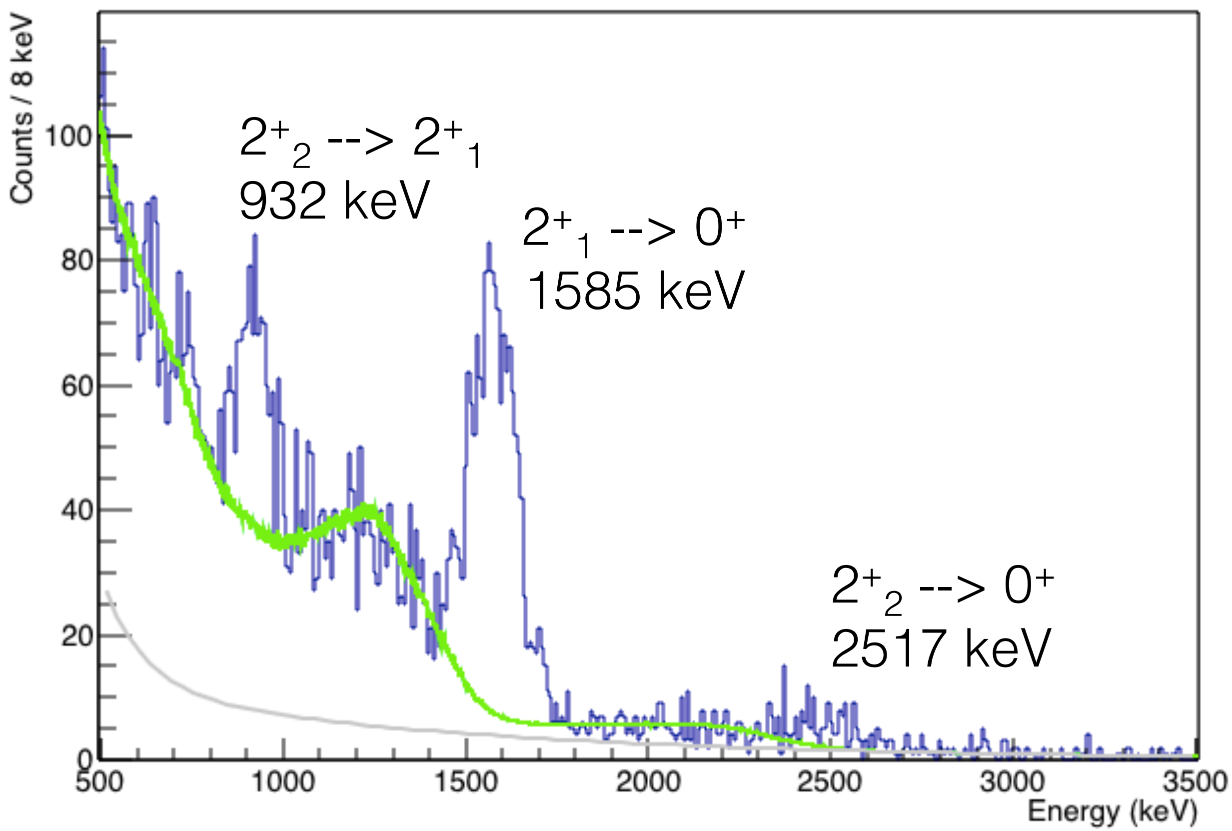
^{18}C from ^{19}N



Energy Loss (a.u.)
Time of Flight (a.u.)
18C

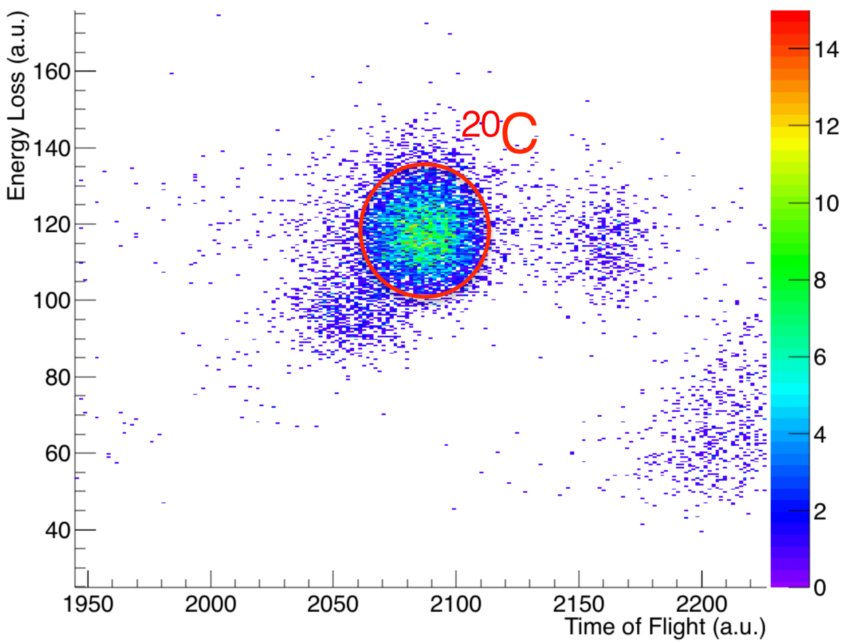


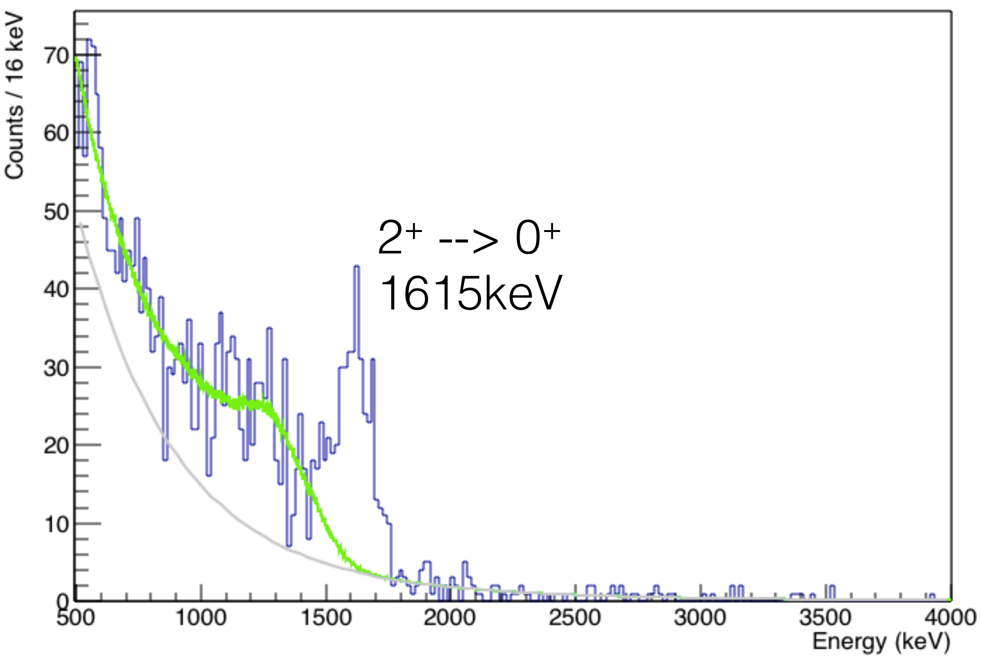
2+
2+
0+
20C



Counts / 8 keV
Energy (keV)
2+2 --> 2+1
932 keV
2+1 --> 0+
1585 keV
2+2 --> 0+
2517 keV

^{20}C from ^{21}N

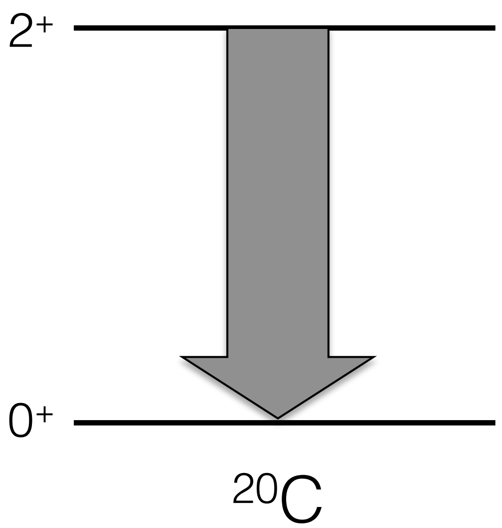


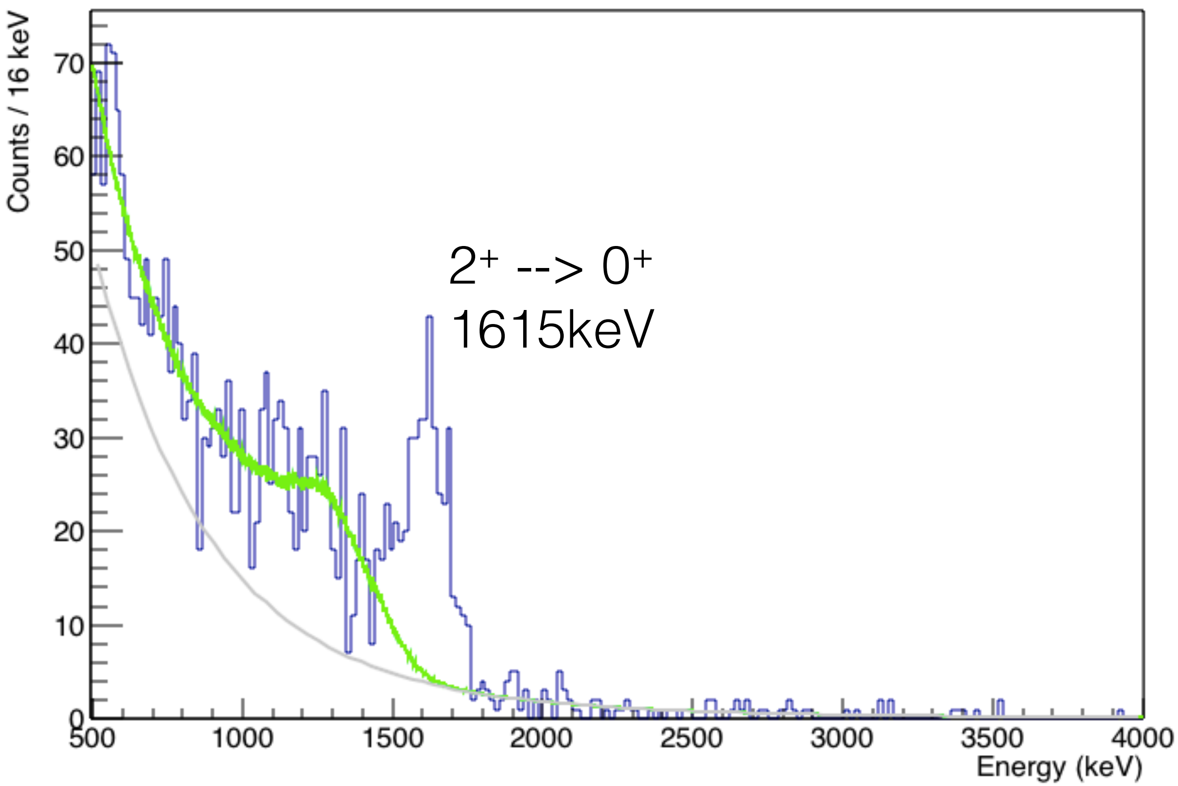


- At the edge of the current experimental capabilities we can study ^{20}C populated from ^{21}N
- $^{21}N(-1p)^{20}C$ yields a very clean spectrum, with only a single bound state in this system

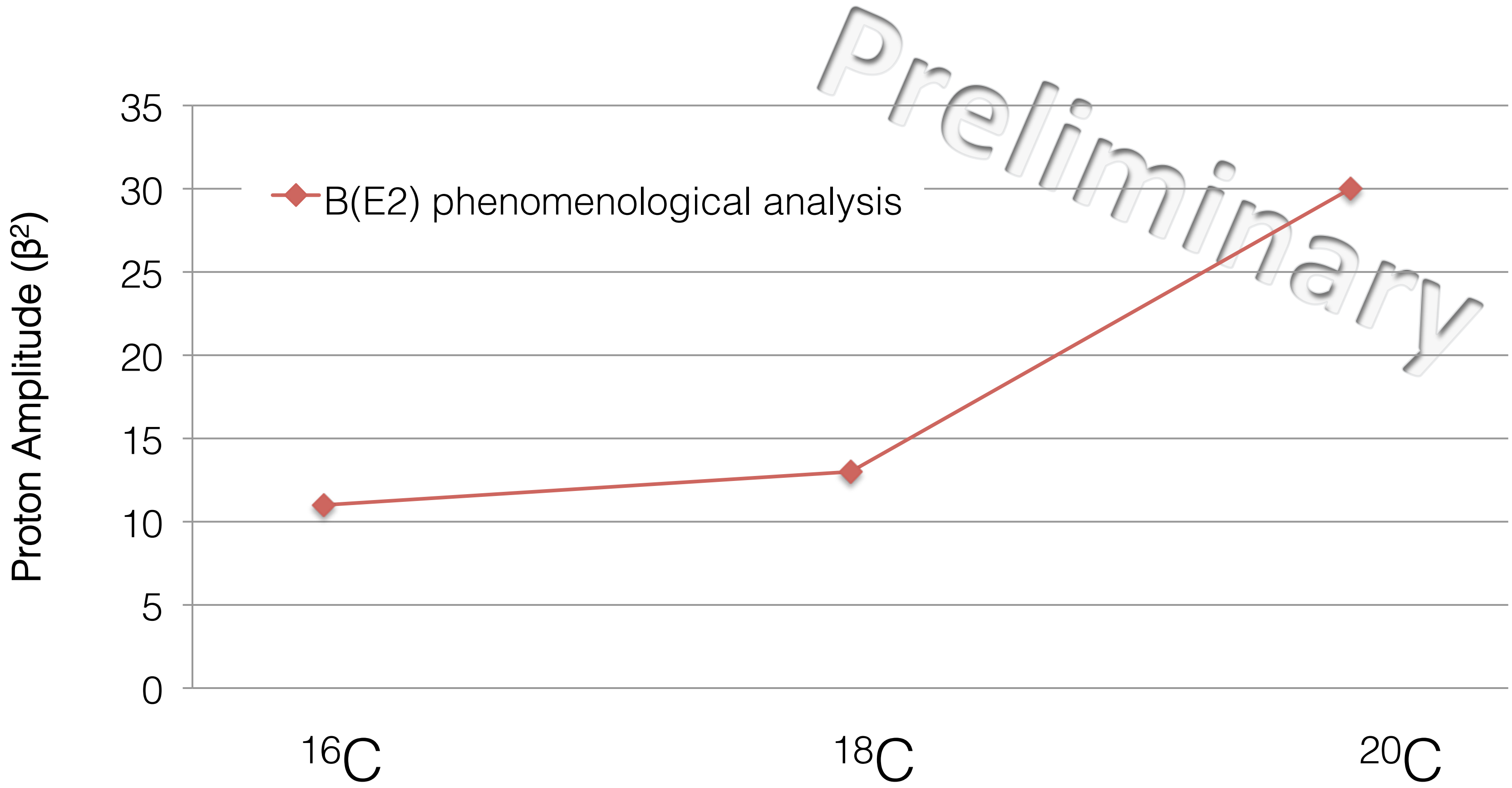
^{20}C from ^{21}N

7342 ^{20}C observed in total





Preliminary Systematic Analysis



--> Experimental proton amplitude remains ~constant from N=10 to 14 in C isotopes

A. O. Macchiavelli et al., PRC **90**, 67305 (2014).

What Might This Mean?

Approximately constant proton knockout σ(2+)/σ(0+) across the neutron-rich C nuclei

--> ~constant proton contribution to the lowest 2^+ excitation

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

Interpretation is still an open question…

Summary

- The C isotopes continue to be an important testing ground for comparison with theoretical calculations, with experimental access to both driplines
- The B(E2) systematic trend in the neutron-rich C isotopes has been interpreted as an indication of increasing proton contribution
- Proton knockout from the N isotopes into $^{16,18,20}C$ at NSCL suggests a relatively constant proton amplitude in the lowest 2^+ states as a function of isospin
- Another origin for the increased B(E2) must be considered --> increased radii? Modified effective charges at the limit of binding?

A (re-)opened question…

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