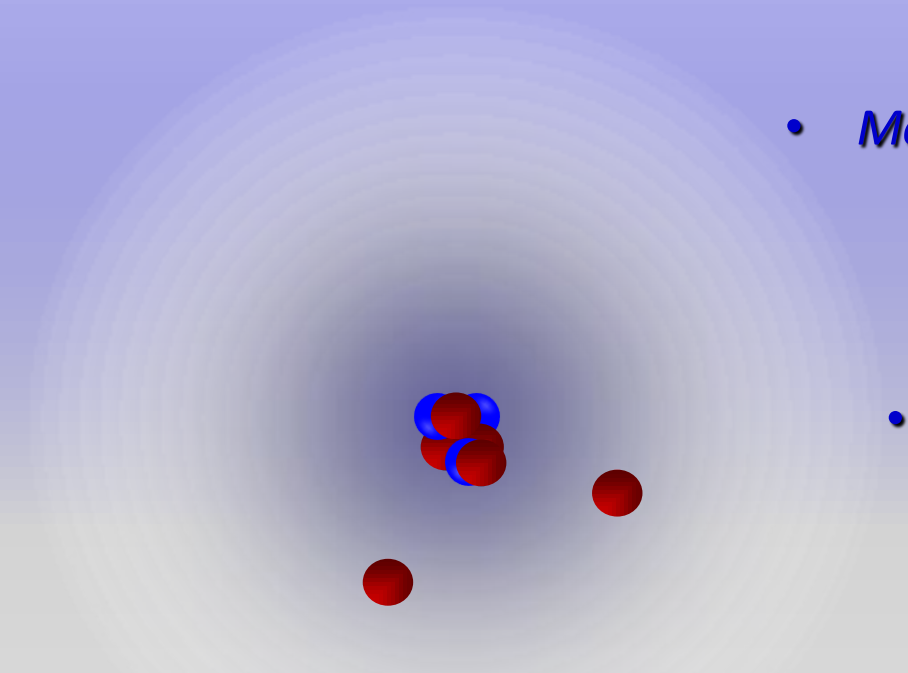
Structure at and beyond the dripline below the oxygen anomaly

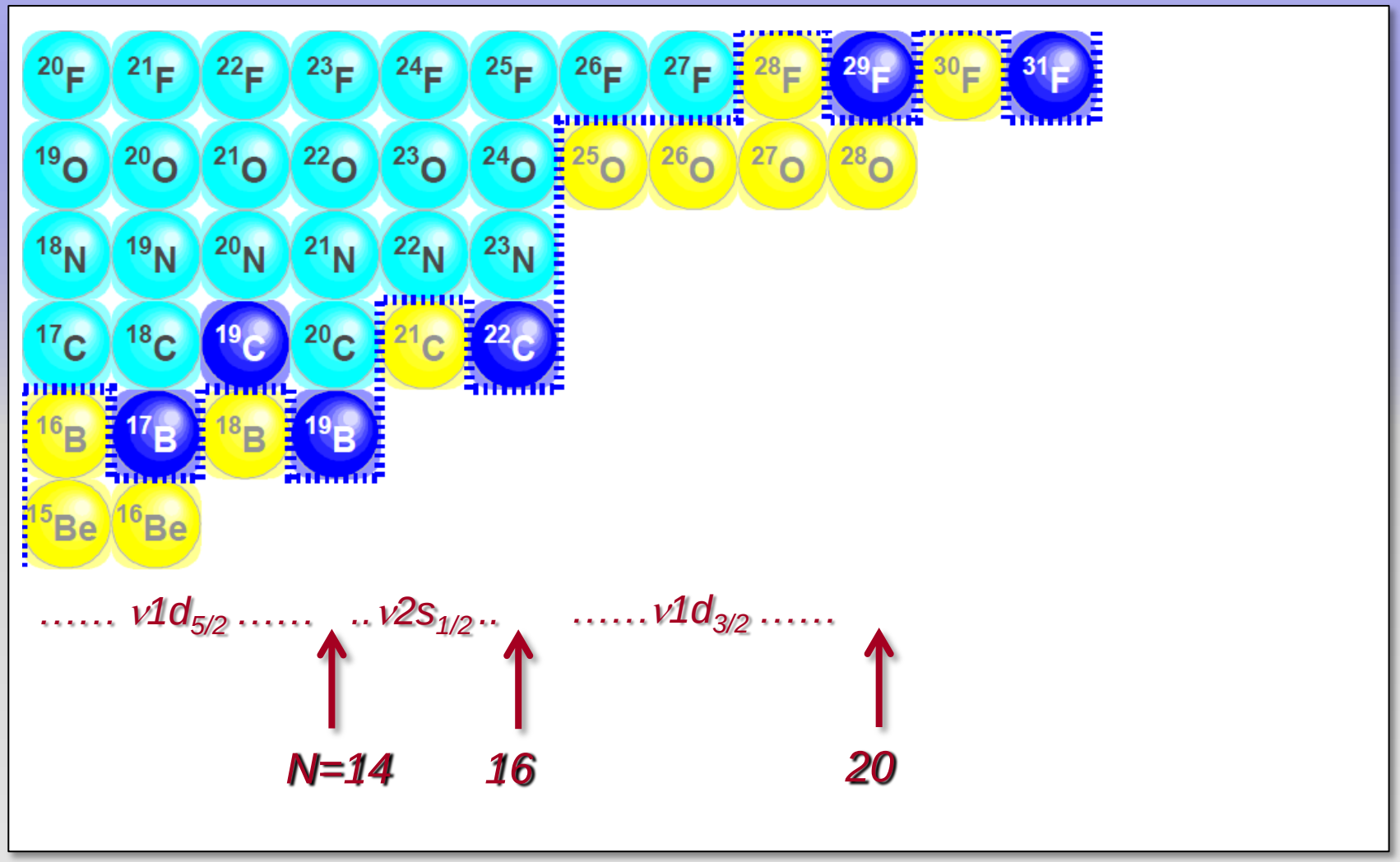


- ***Motivation: shell structure Z=5-8, N~14-16***
- ***Inclusive momentum distributions***
- ***Invariant mass spectroscopy: $^{19}C^*$, ^{21}C***
- ***Search for $^{24,25}N$***
- ***Conclusions & Perspectives***

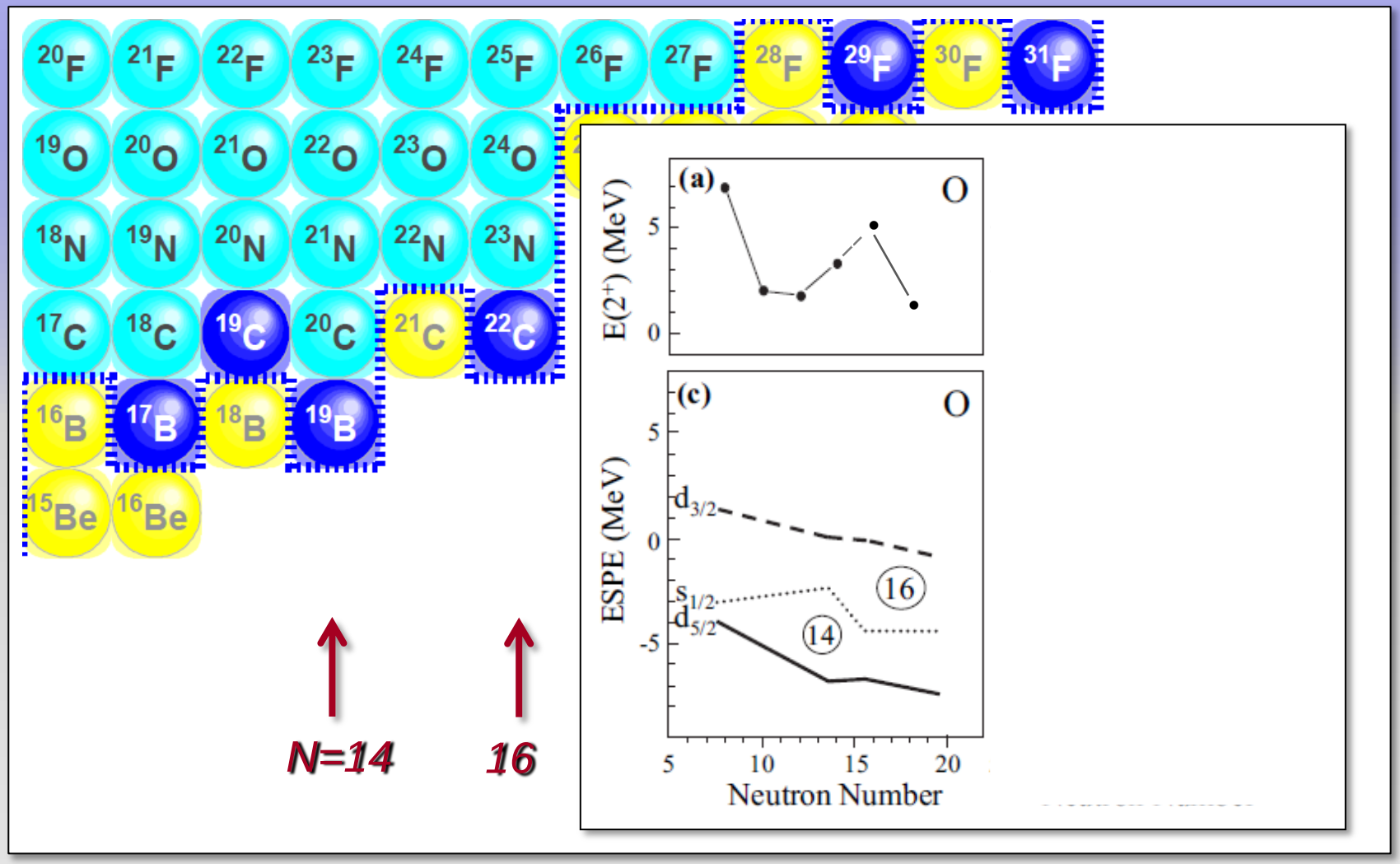
[… ^{20}B, $^{22}C(2^+)$]

"GROUPE STRUCTURE NUCLÉAIRE": S LEBLOND, Q DESHAYES, FM MARQUÉS, J GIBELIN, NAO, ET AL.
J HWANG, Y SATOU (SNU), N KOBAYASHI ET AL.(TOKYOTECH)
& THE SAMURAI COLLABORATION

STRUCTURE IN THE REGION OF N~14 – 16 (ν 2s1d) …

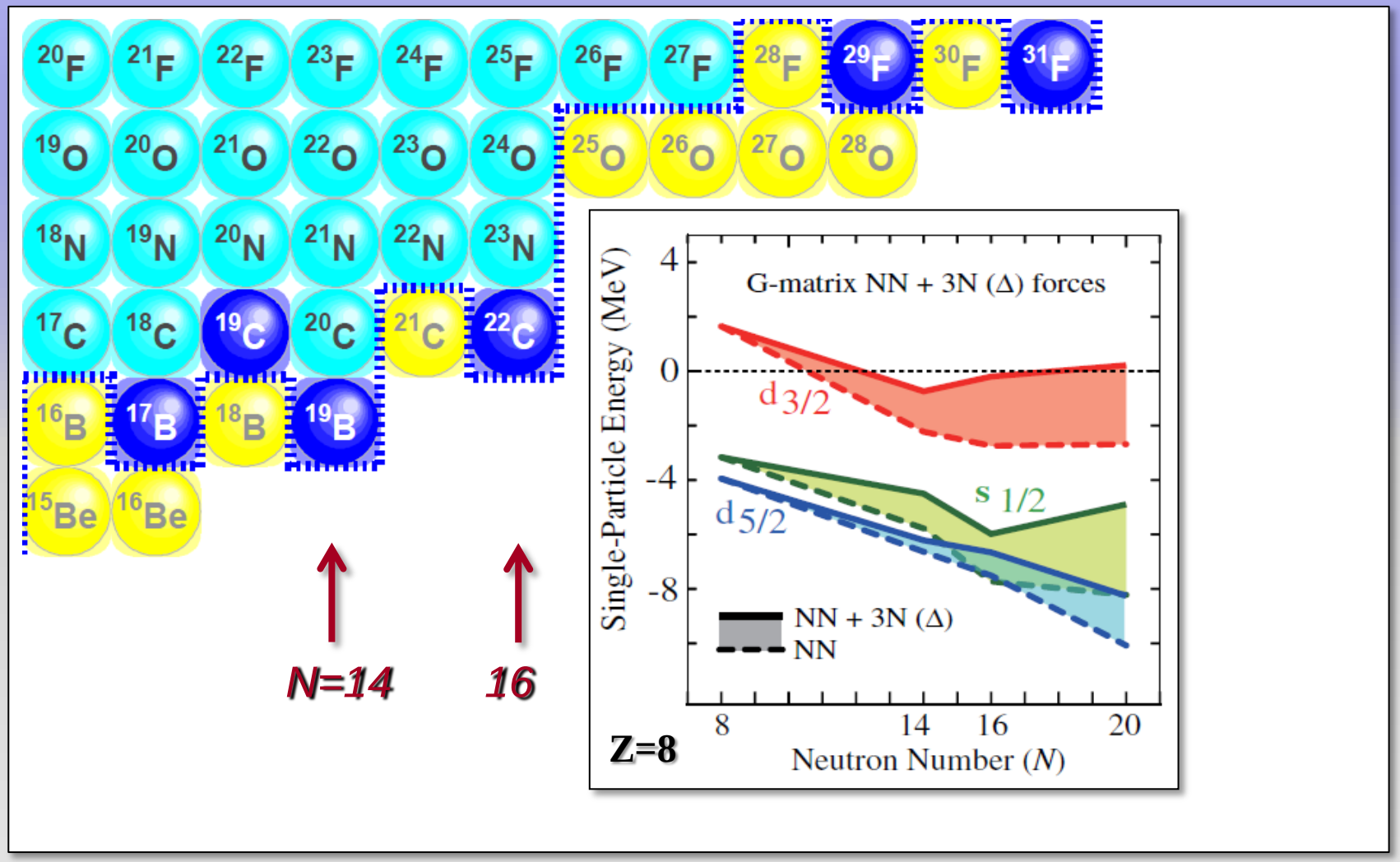


Z=8: STRUCTURE IN THE REGION OF N~14 – 16 (ν 2s1d) …



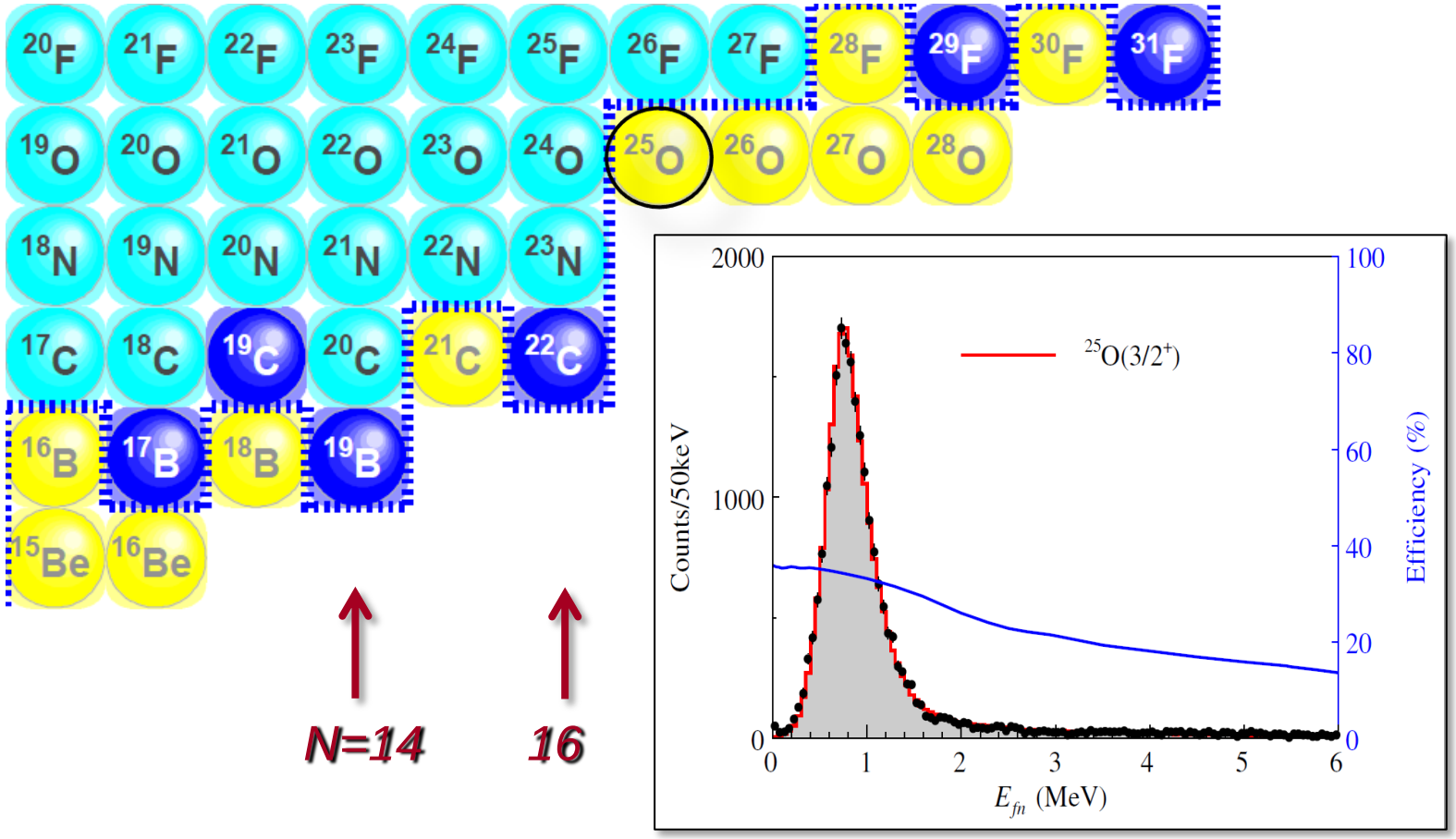
WBT Shell Model Interaction: M Stanoiu et al., PRC (2008)

STRUCTURE IN THE REGION OF N ~ 16 - 20 …



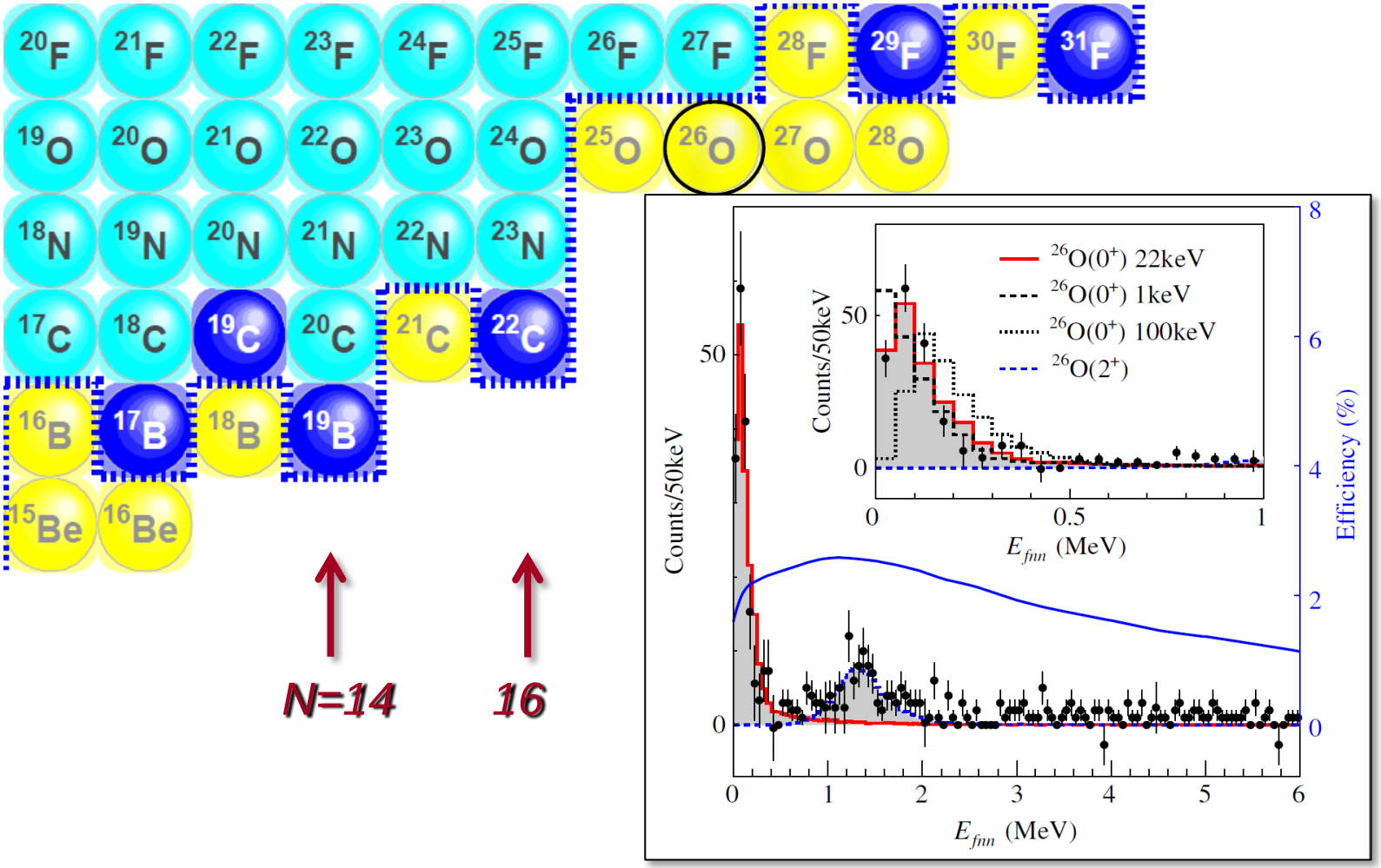
ESPE O isotopes - Otsuka et al., PRL (2010)

^{25}O: STRUCTURE IN THE REGION OF N~16-20 …



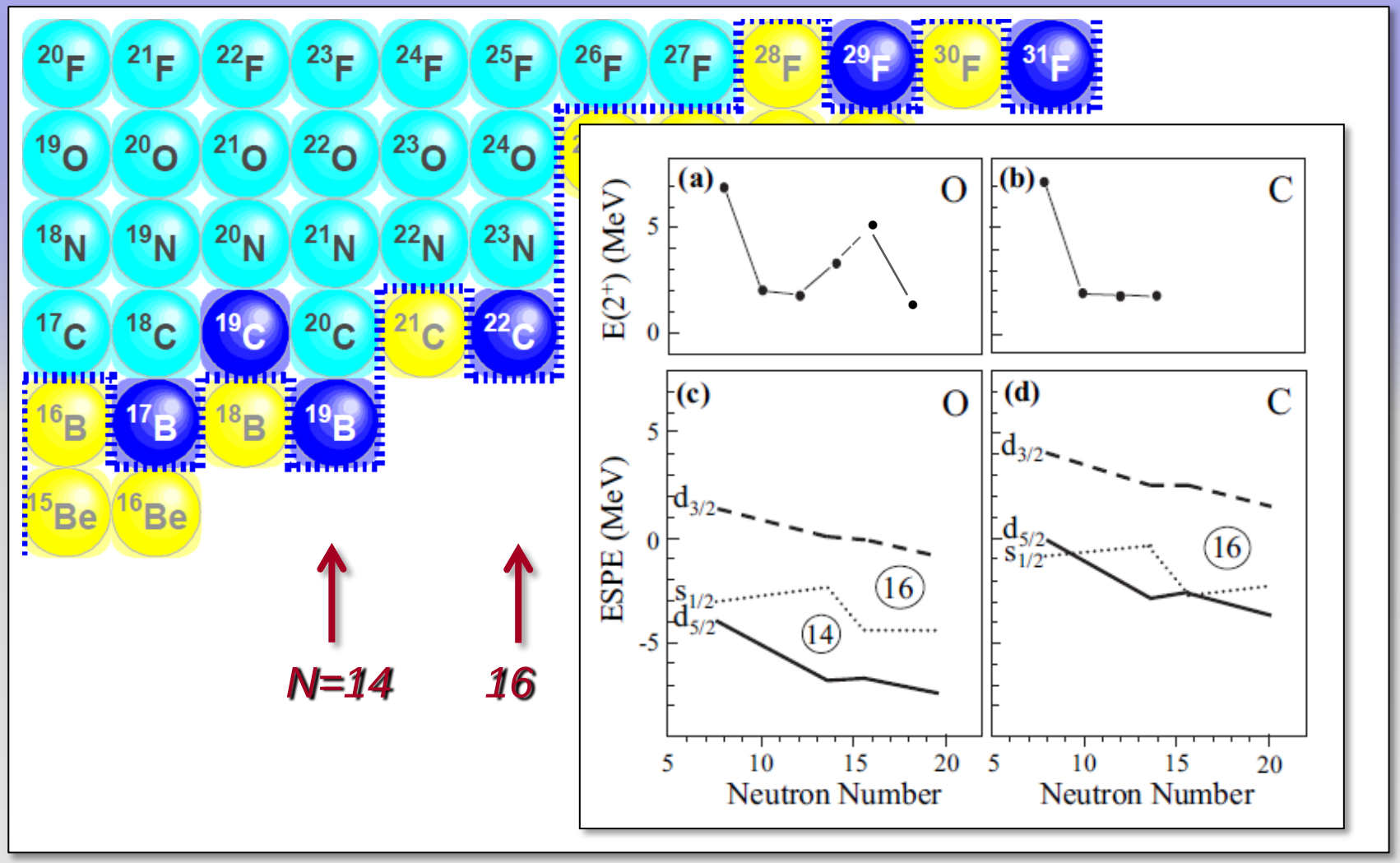
SAMURAI Collaboration: Y Kondo et al., PRL (2016)

^{26}O: STRUCTURE IN THE REGION OF N~16-20 …



SAMURAI Collaboration: Y Kondo et al., PRL (2016)

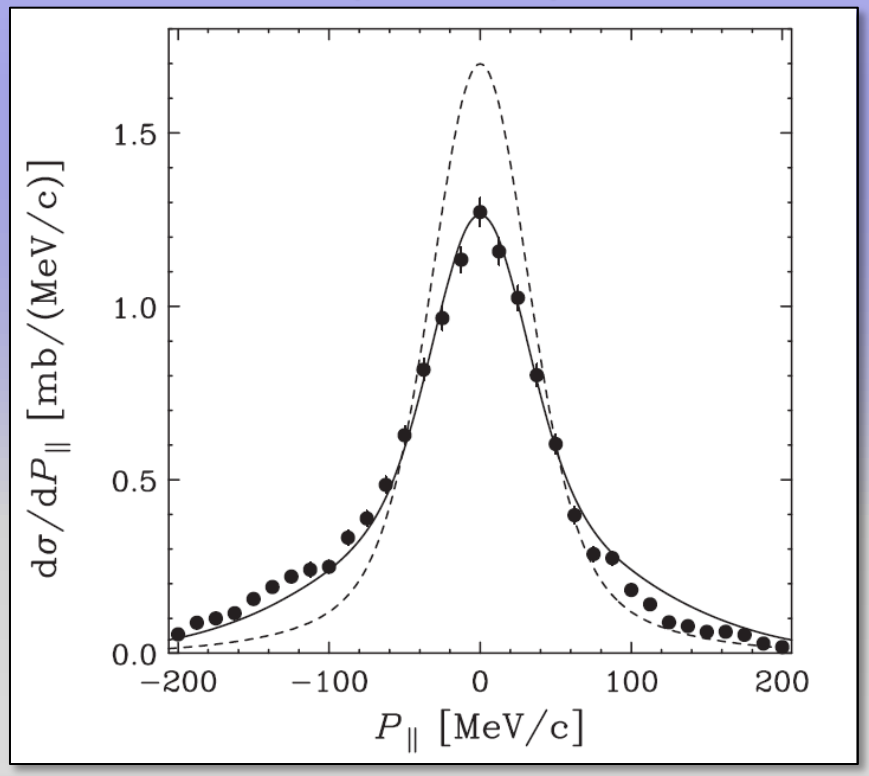
Z=6: STRUCTURE IN THE REGION OF N~14 – 16 ($\nu 2s_{1/2} - \nu 1d_{5/2}$)



WBT Shell Model Interaction: M Stanoiu et al., PRC (2008)

^{19}C: INCLUSIVE CORE MOMENTUM DISTRIBUTION @ 240 MeV/nucleon …

$C(^{19}C,^{18}C)$

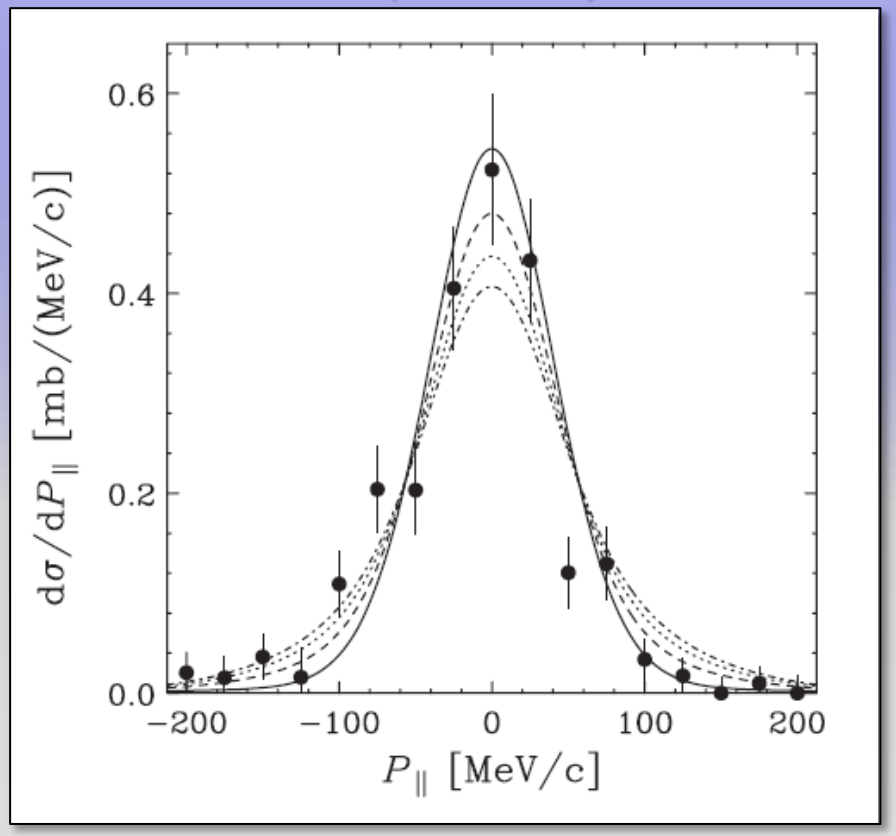


Reaction	E_x (MeV)	J^π	ℓ	σ_{sp} (mb)	C^2S	σ^{th}_{-1n} (mb)	σ^{exp}_{-1n} (mb)	R_s
$[^{19}C(1/2^+),^{18}C(J^\pi)]$	0.000	0^+_1	0	104.7	0.580	67.63		
$S_{1n}(^{19}C) = 0.58$ MeV	2.114	2^+_1	2	29.91	0.479	15.96		
	3.639	2^+_2	2	25.91	0.104	3.00		
	3.988	0^+_2	0	39.35	0.319	13.97		
	4.915[a]	3^+_1	2	23.60	1.523	40.04		
	4.975[a]	2^+_3	2	23.50	0.922	24.15		
		Inclusive				164.8	163(12)	0.99(7)

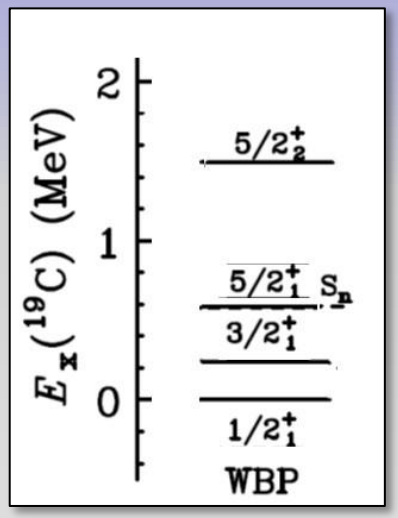
INCLUSIVE Measurement (ZDS): N Kobayashi et al., PRC (2012)

^{20}C: INCLUSIVE CORE MOMENTUM DISTRIBUTION @ 240 MeV/nucleon …

$C(^{20}C,^{19}C)$



$\ell_n=0$

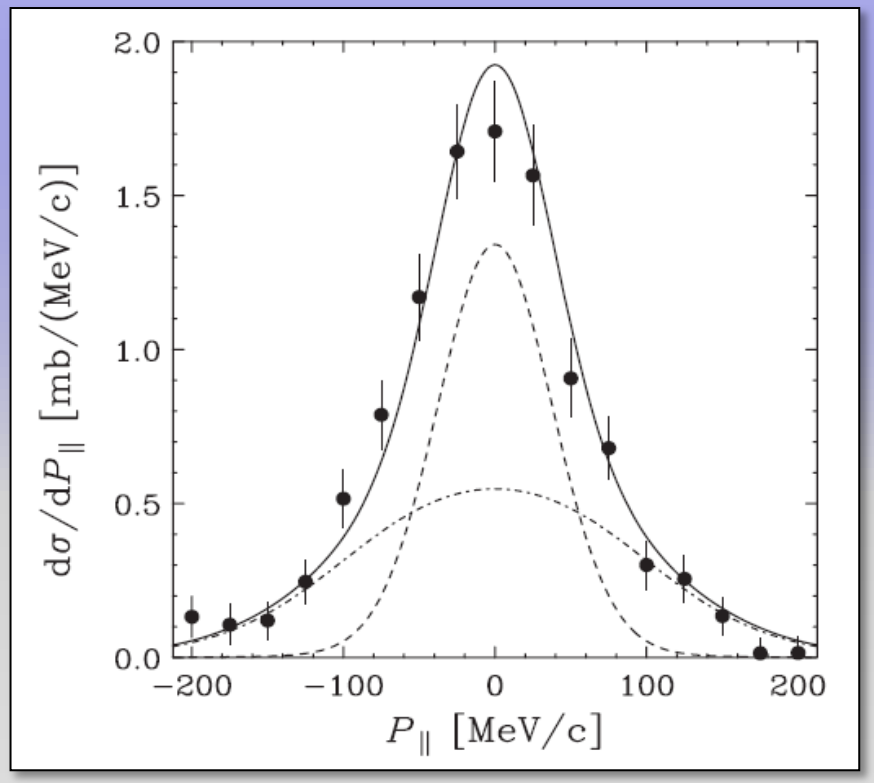


Reaction	E_x (MeV)	J^π	ℓ	σ_{sp} (mb)	C^2S	σ^{th}_{-1n} (mb)	σ^{exp}_{-1n} (mb)	R_s
$[^{20}C(0^+),^{19}C(J^\pi)]$	0.000[b]	$1/2_1^+$	0	48.37	1.099	58.92		
$S_{1n}(^{20}C) = 2.90$ MeV		Inclusive				58.92	58(5)	0.98(8)

INCLUSIVE Measurement (ZDS): N Kobayashi et al., PRC (2012)

^{22}C: INCLUSIVE CORE MOMENTUM DISTRIBUTIONS @ 240 MeV/nucleon …

$C(^{22}C,^{20}C)$



$\ell_n=0$

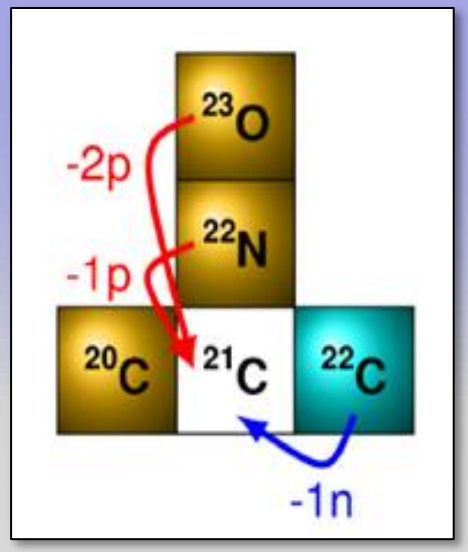
$\ell_n=2$

Reaction	E_x (MeV)	J^π	ℓ	σ_{sp} (mb)	C^2S	σ^{th}_{-1n} (mb)	σ^{exp}_{-1n} (mb)	R_s
$[^{22}C(0^+),^{21}C(J^\pi)]$	0.000	$1/2^+_1$	0	89.35	1.403	137.55		
$S_{1n}(^{22}C) = 0.70$ MeV	1.109	$5/2^+_1$	2	29.39	4.212	135.87		
	2.191	$3/2^+_1$	2	25.44	0.342	9.55		
		Inclusive				283.0	266(19)	<0.94(7)

INCLUSIVE Measurement (BigRIPS+ZDS): N Kobayashi et al., PRC (2012)

SPECTROSCOPY OF UNBOUND SYSTEMS: HIGH-ENERGY DIRECT REACTIONS …

EXAMPLE: ^{21}C



Neutron removal *

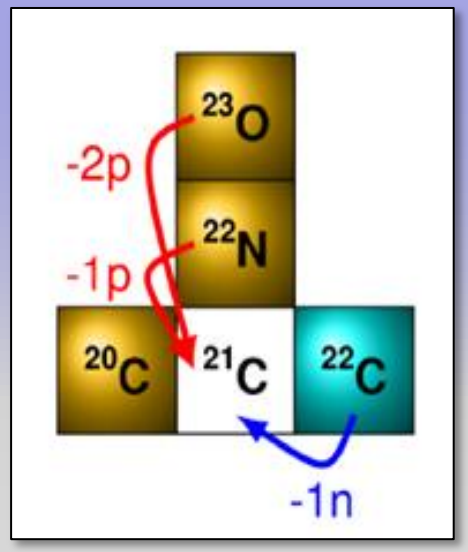
$\Rightarrow$ halo "hole" states core $\otimes\, \nu\, n\ell j^2 \rightarrow$ core $\otimes\, \nu\, n\ell j$

p(core+n) distribution $\Rightarrow \ell_n$ halo

* ~10% of <u>observed</u> yield via 3-body continuum: eg., (^{22}C,$^{22}C^* \rightarrow {}^{20}C$+n+n)

SPECTROSCOPY OF UNBOUND SYSTEMS: HIGH-ENERGY DIRECT REACTIONS …

EXAMPLE: ^{21}C



Neutron removal *

$\Rightarrow$ halo "hole" states core $\otimes\, \nu\, n\ell j^2 \rightarrow$ core $\otimes\, \nu\, n\ell j$

p(core+n) distribution $\Rightarrow \ell_n$ halo

Proton removal

$\Rightarrow$ projectile valence $\nu\, n\ell j$ unperturbed

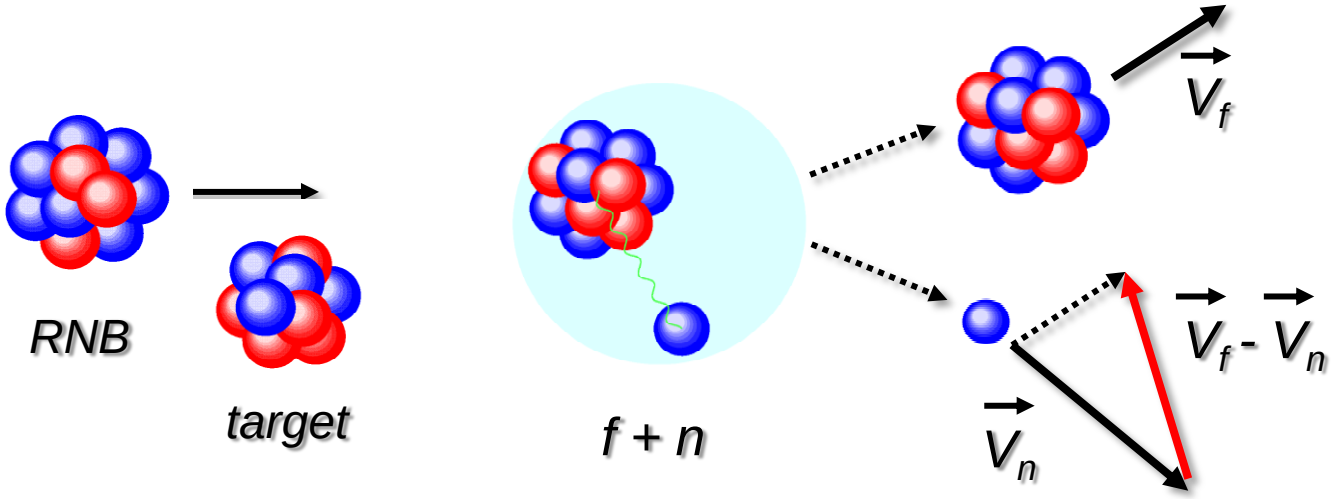
$[\, \Delta\ell_n \approx 0 \,]$

* ~10% of <u>observed</u> yield via 3-body continuum: eg., (^{22}C,$^{22}C^* \rightarrow {}^{20}C$+n+n)

INVARIANT MASS SPECTROSCOPY BEYOND THE DRIPLINE …

… nucleon "knockout" or breakup($\beta \approx 0.6$) + in-flight decay

$\Rightarrow$ fragment – n FSI



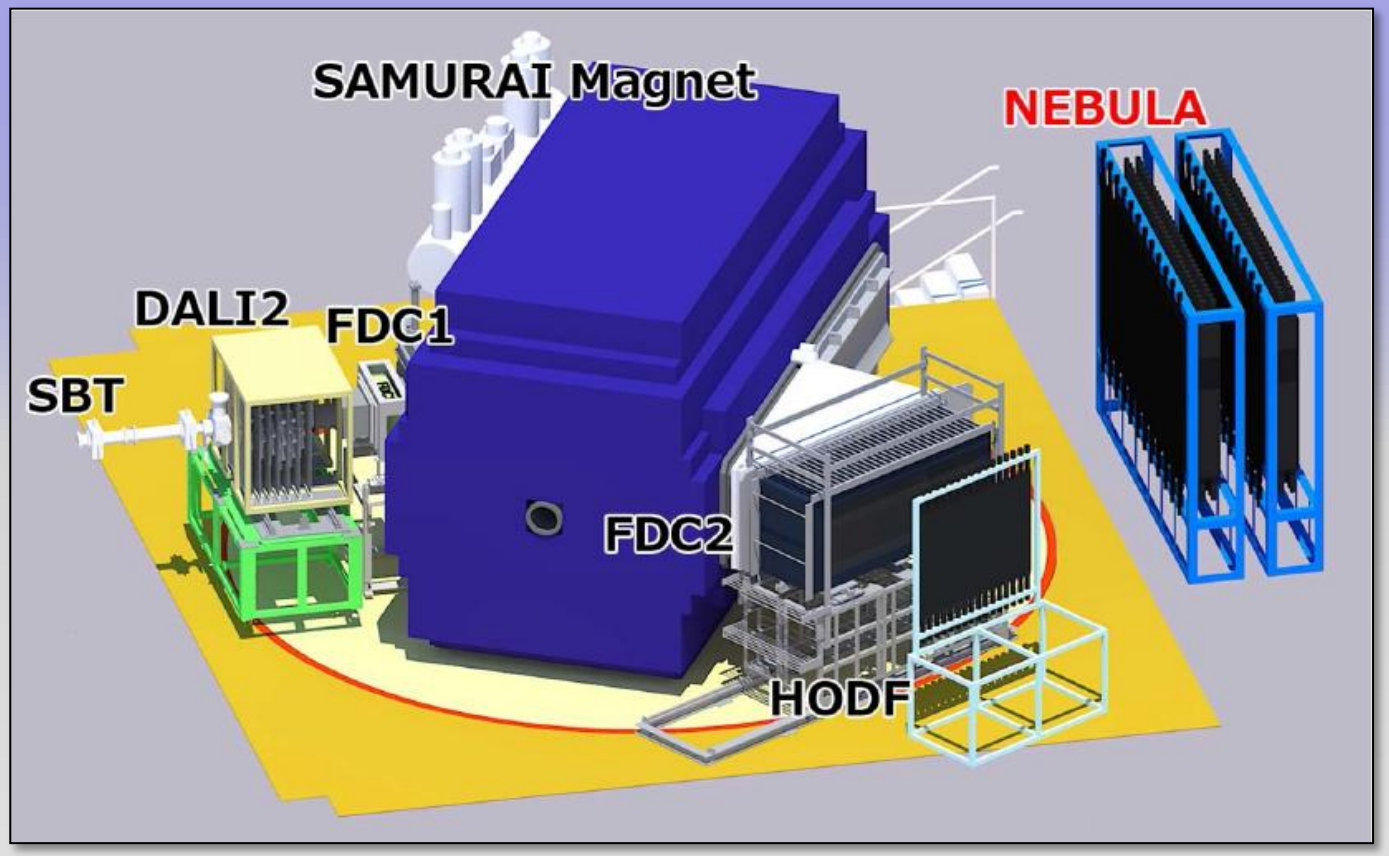
$$E_d = \frac{1}{2}\mu (v_f - v_n)^2$$

$$E_d({}^{A+1}_{Z}X) = \sqrt{(E_f + E_n)^2 - (\vec{p}_f + \vec{p}_n)^2 c^2} - (M_f + M_n)c^2$$

NOTE: excited state of core also should be included where populated… γ-ray decay

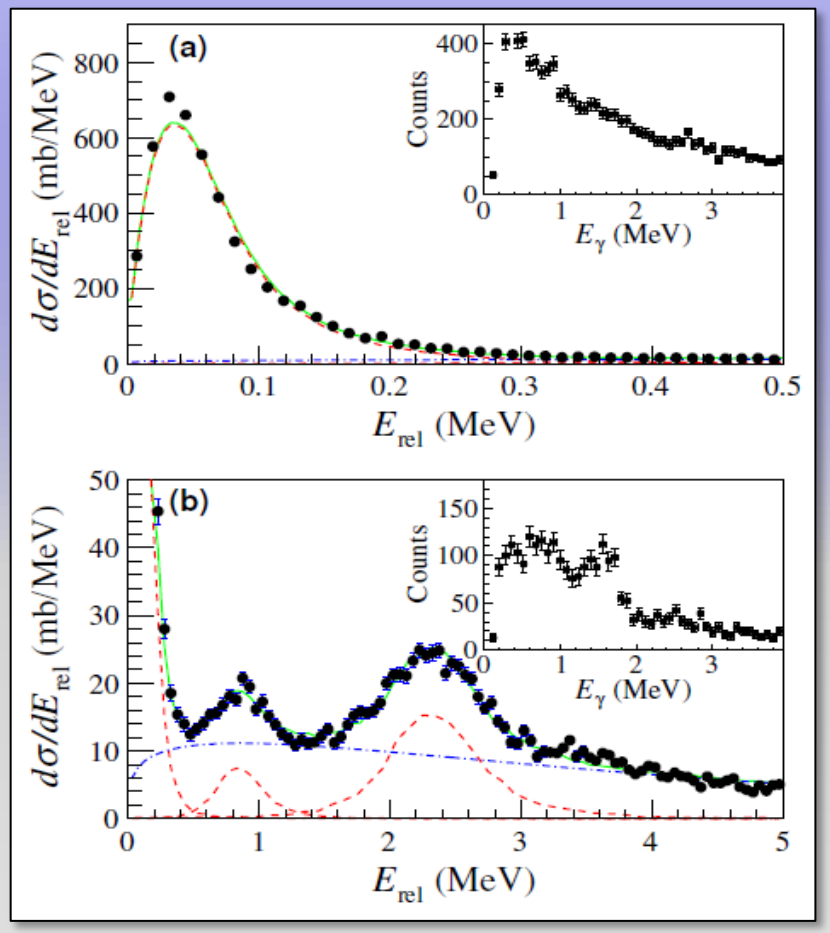
"KINEMATICALLY COMPLETE" MEASUREMENTS: core + γ + n …

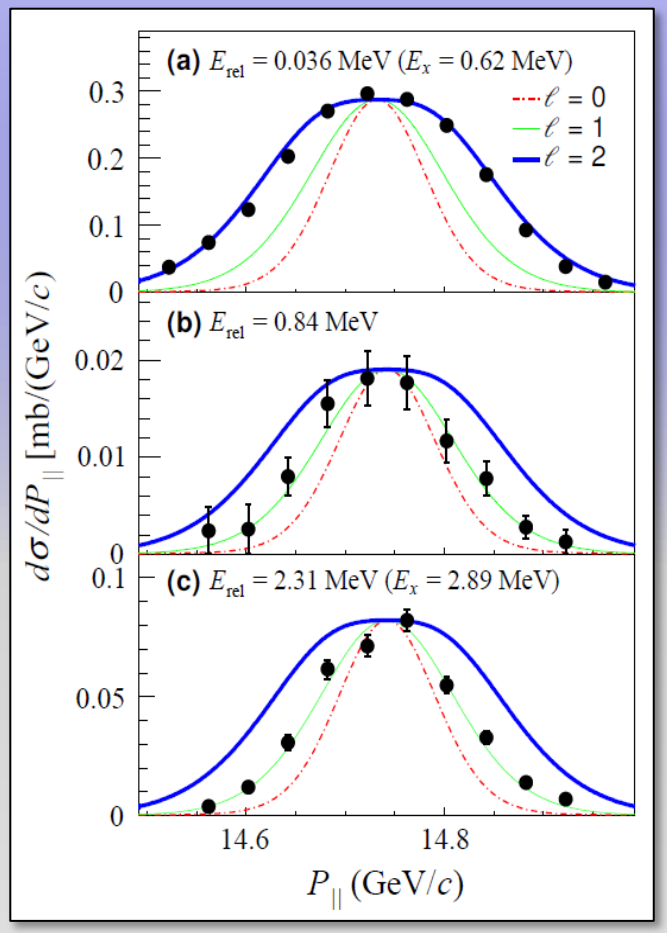
… @ ~240 MeV/nucleon



SAMURAI

$^{19}C^*$: $C(^{20}C,^{18}C+n)$ @ 280 MeV/nucleon …

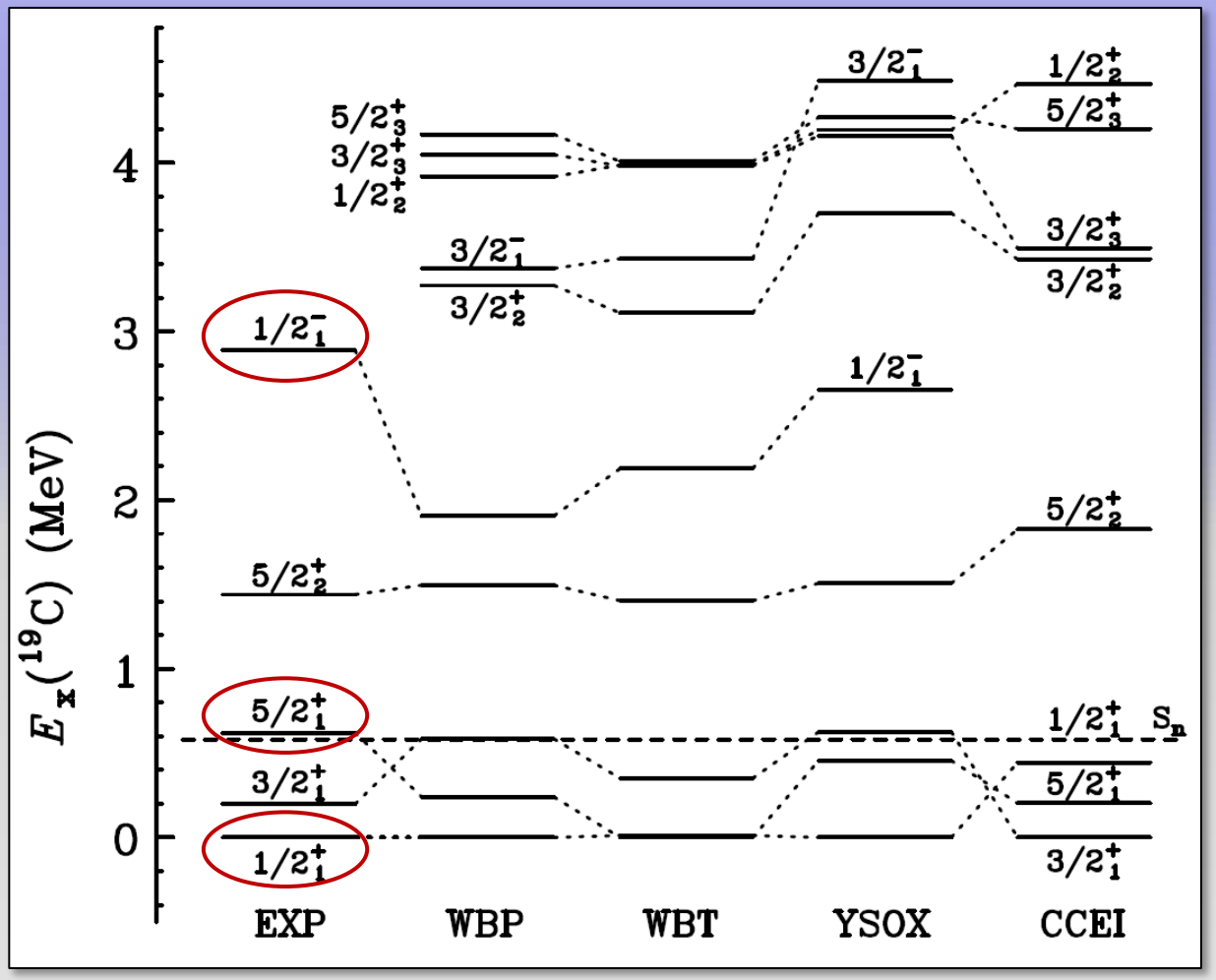




E_{rel} (MeV)	E_x (MeV)	Γ (MeV)	ℓ ($\hbar$)	σ^{exp}_{-1n} (mb)	σ_{sp} (mb) [a,b]	C^2S^{exp} [a]	C^2S^{th}	E_x^{th} (MeV)	J^π
0.036(1)	0.62(9)	< 0.015	2	61(5)	22.9	2.40(20)	3.80	0.240	$5/2^+_1$
0.84(4)		< 0.02		4(1)					
2.31(3)	2.89(10)	0.20(7)	1	15(3)	18.6	0.77(15)	1.38	1.907	$1/2^-_1$

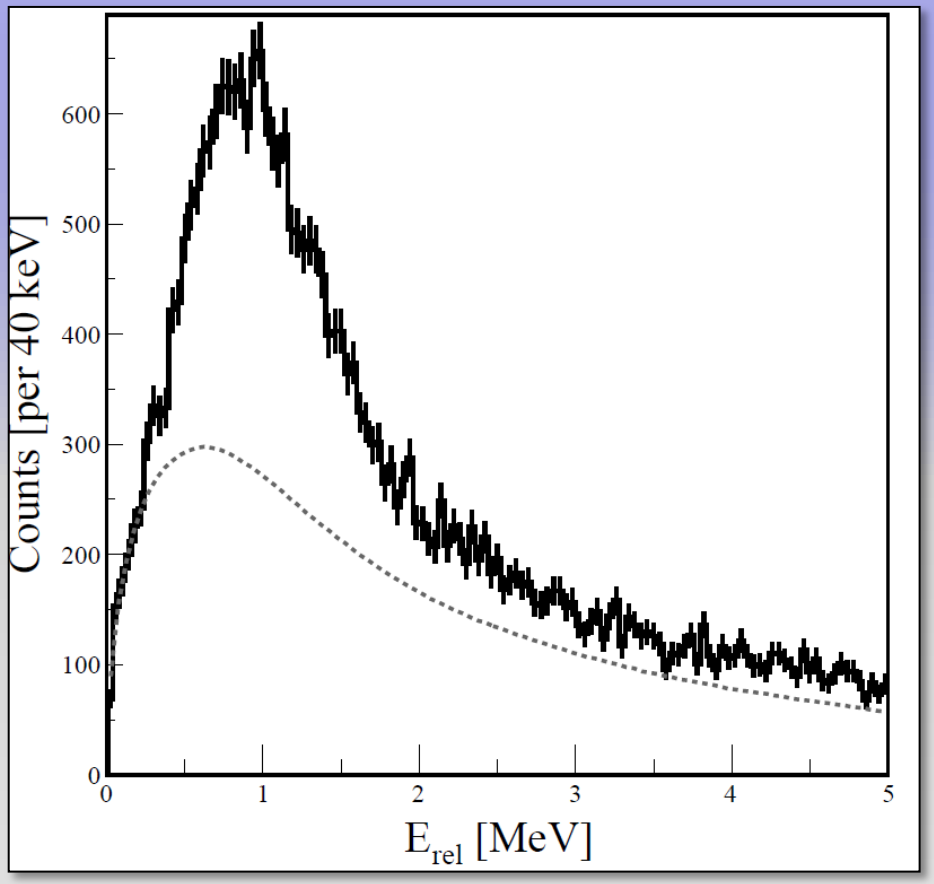
SAMURAI Collaboration: J Hwang et al., PLB (2017)

^{19}C: LEVEL SCHEME …



SAMURAI Collaboration: J Hwang et al., PLB (2017)

^{21}C: $C(^{22}N,^{20}C+n)$ @ 245 MeV/nucleon …

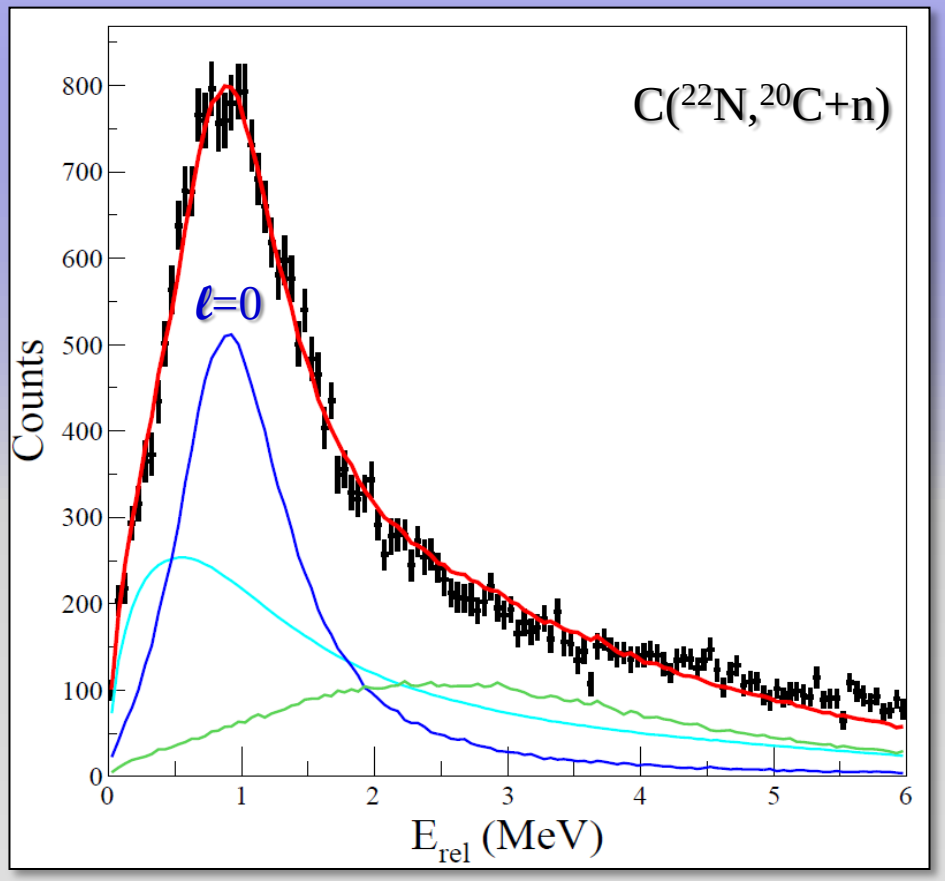


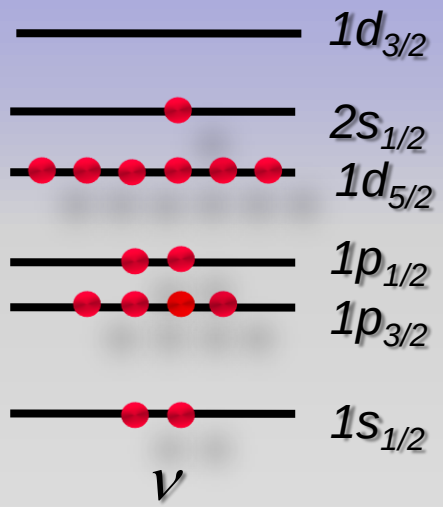
····· uncorrelated f+n events / non resonant continuum *

* generated via event mixing

S Leblond et al., NP1106-SAMURAI04

^{21}C: $C(^{22}N,^{20}C+n)$ @ 245 MeV/nucleon …



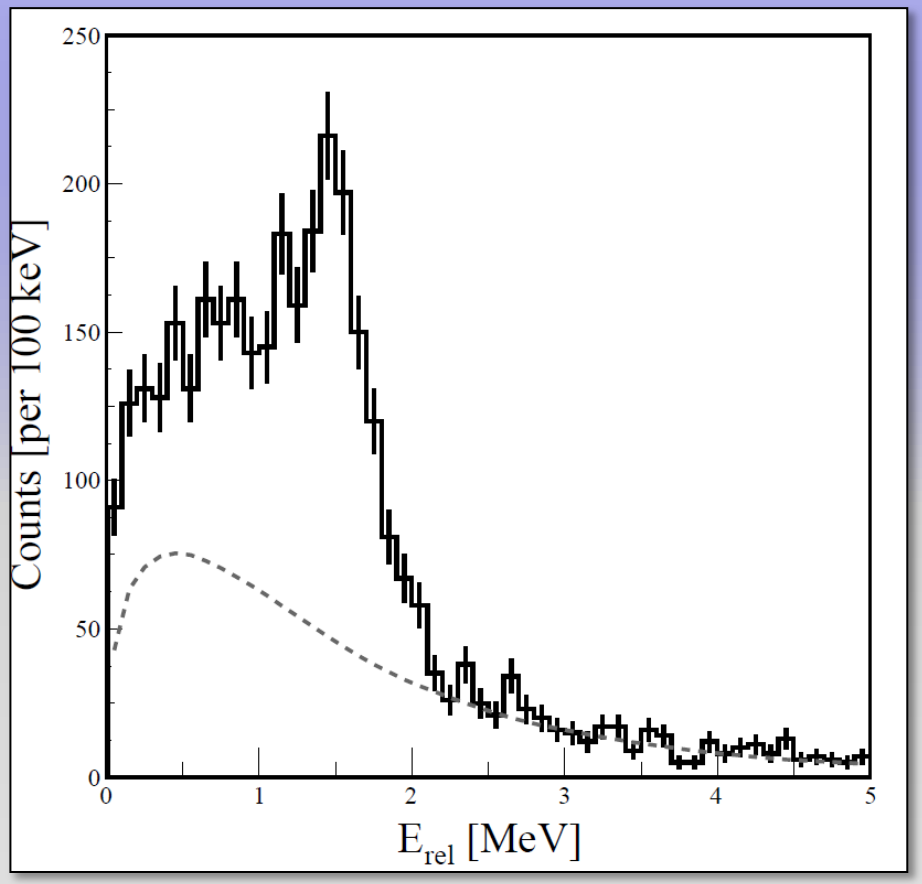


$^{22}N \rightarrow {}^{21}C$

$\ell = 0$ (R-Matrix) $E_R = 0.90 \pm 0.10$ MeV; $\Gamma = 0.80 \pm 0.50$ MeV + non resonant continuum

S Leblond et al., NP1106-SAMURAI04

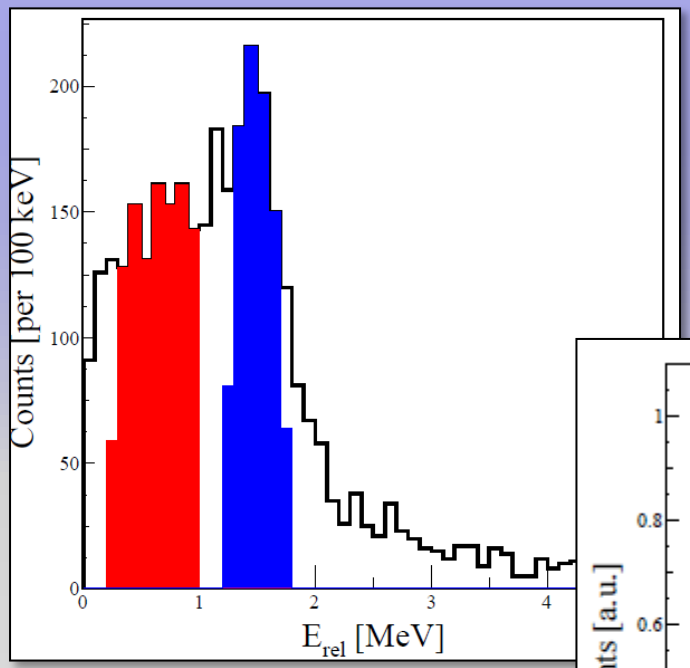
^{21}C: $C(^{22}C,^{20}C+n)$ @ 245 MeV/nucleon …

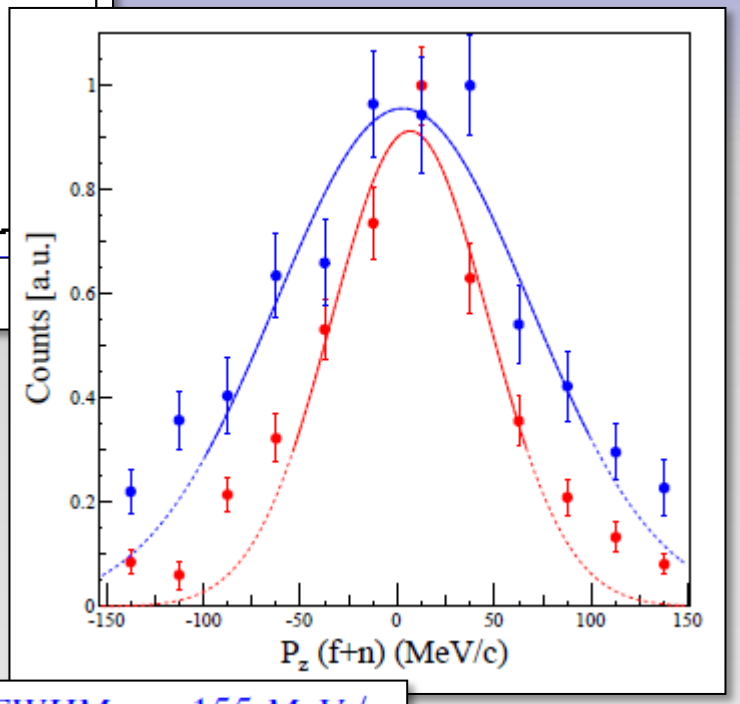


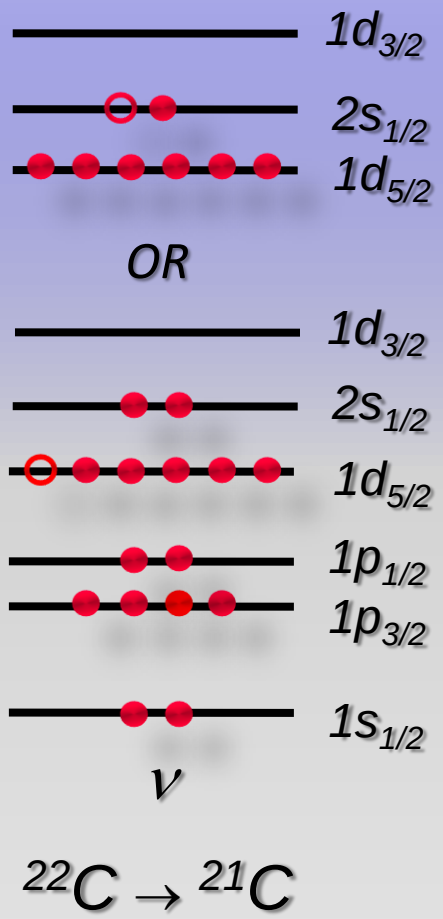
non resonant continuum

S Leblond et al., NP1106-SAMURAI04

^{21}C: $C(^{22}C,^{20}C+n)$ @ 245 MeV/nucleon – $^{20}C+n$ MOMENTUM DISTRIBUTIONS …



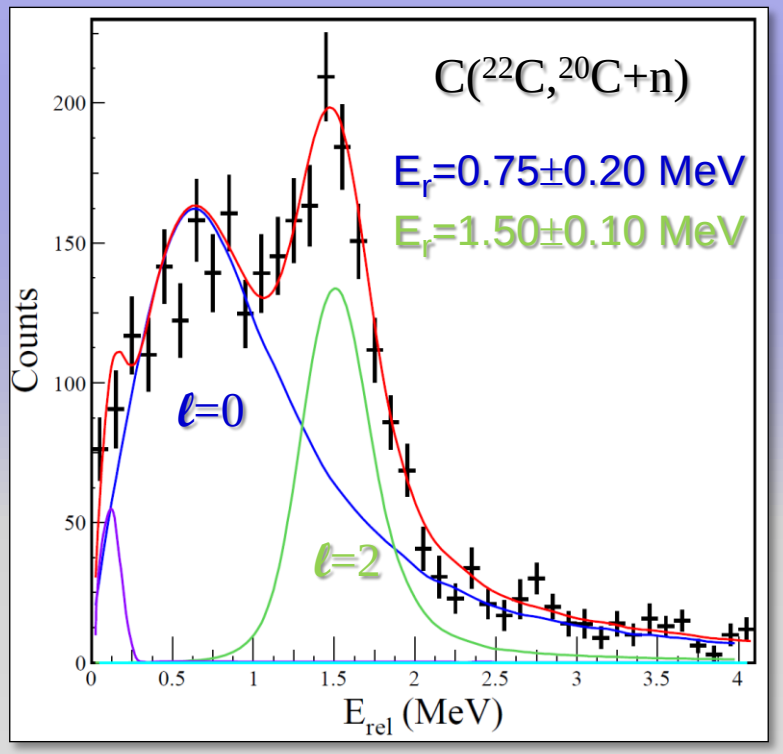


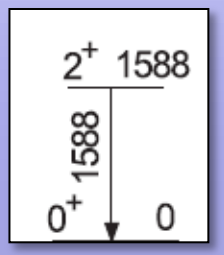


$FWHM \approx 95\ MeV/c \quad < \quad FWHM \approx 155\ MeV/c$

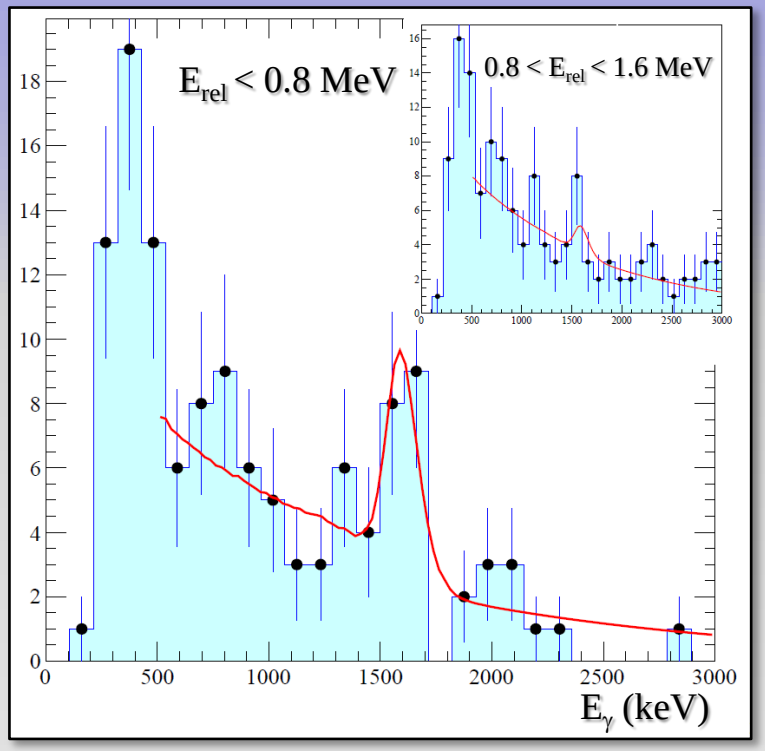
S Leblond et al., NP1106-SAMURAI04

^{21}C: $C(^{22}C,^{20}C+n)$ @ 245 MeV/nucleon …



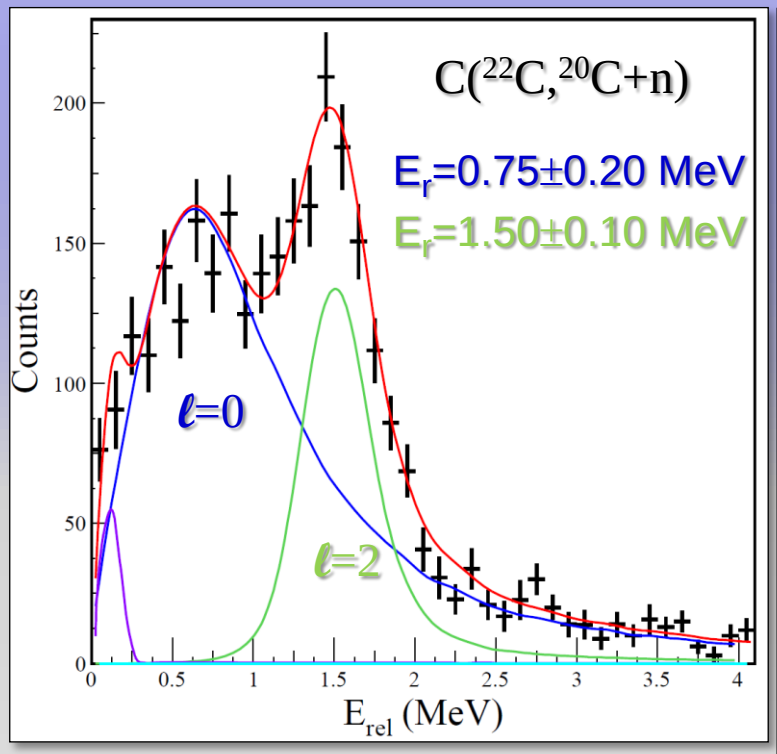


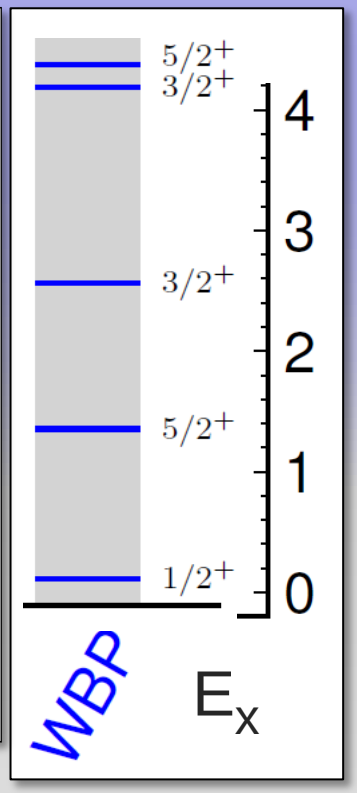
^{20}C



S Leblond et al., NP1106-SAMURAI04

^{21}C: $C(^{22}C,^{20}C+n)$ @ 245 MeV/nucleon …





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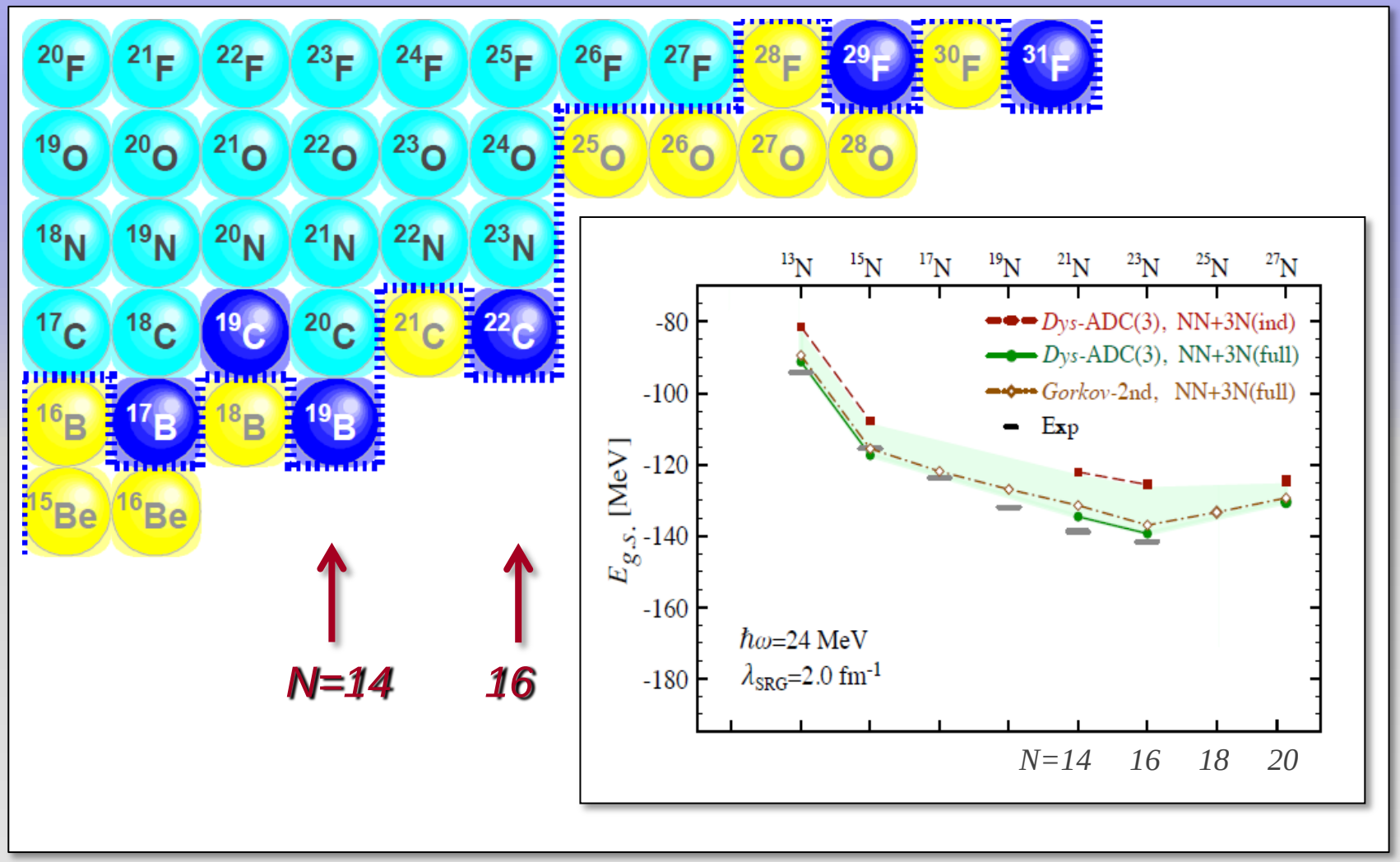
$[^{22}C(0^+),^{21}C(J^\pi)]$	0.000	$1/2^+_1$	0	89.35	1.403	137.55
	1.109	$5/2^+_1$	2	29.39	4.212	135.87
	2.191	$3/2^+_1$	2	25.44	0.342	9.55

Eikonal + shell model C^2S

JA Tostevin

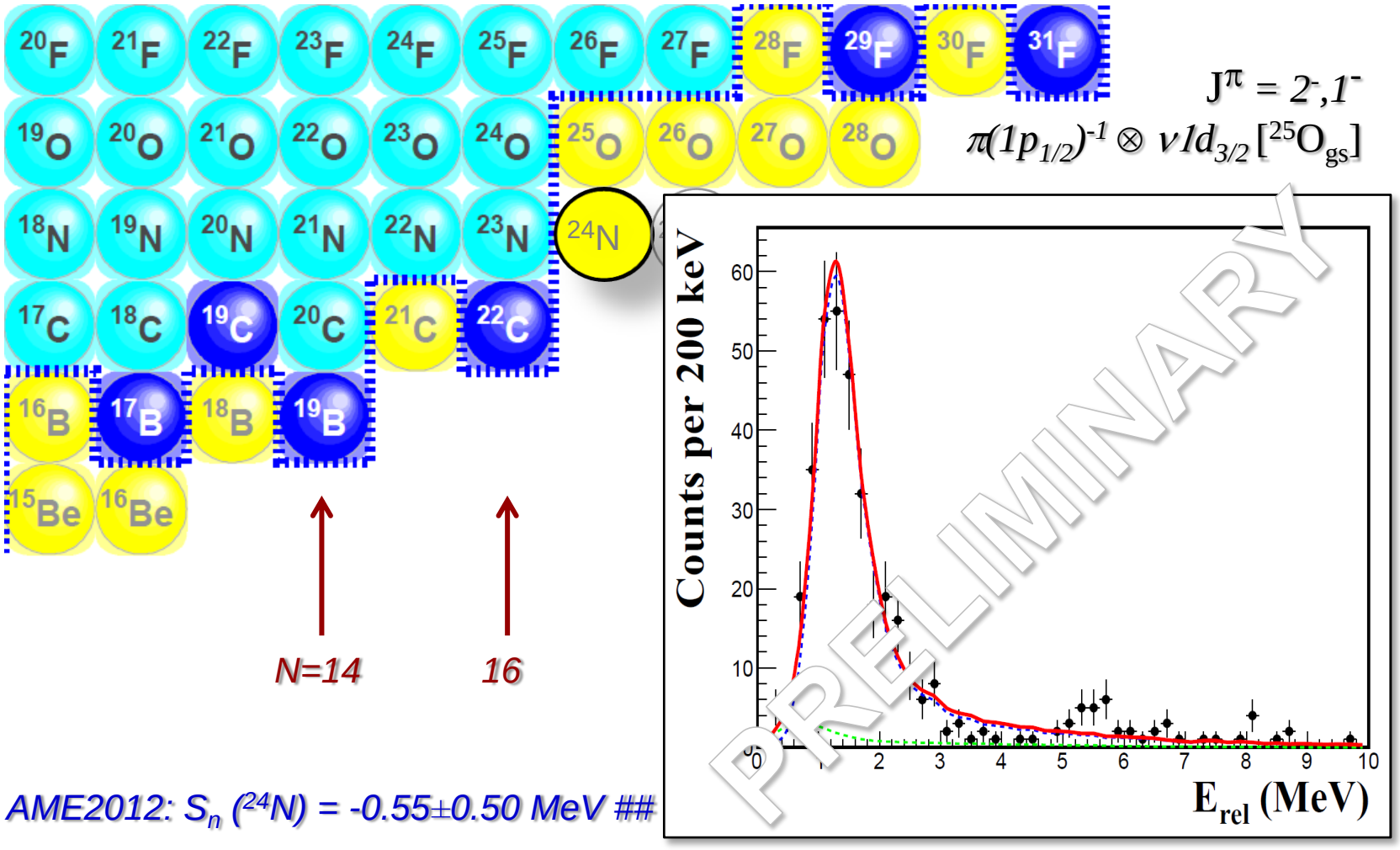
S Leblond et al., NP1106-SAMURAI04

Z=7: Structure in Region of N ~ 16 …



Binding E wrt ^{A}O : N isotopes with SCGF - Cipollone et al., PRC (2015)

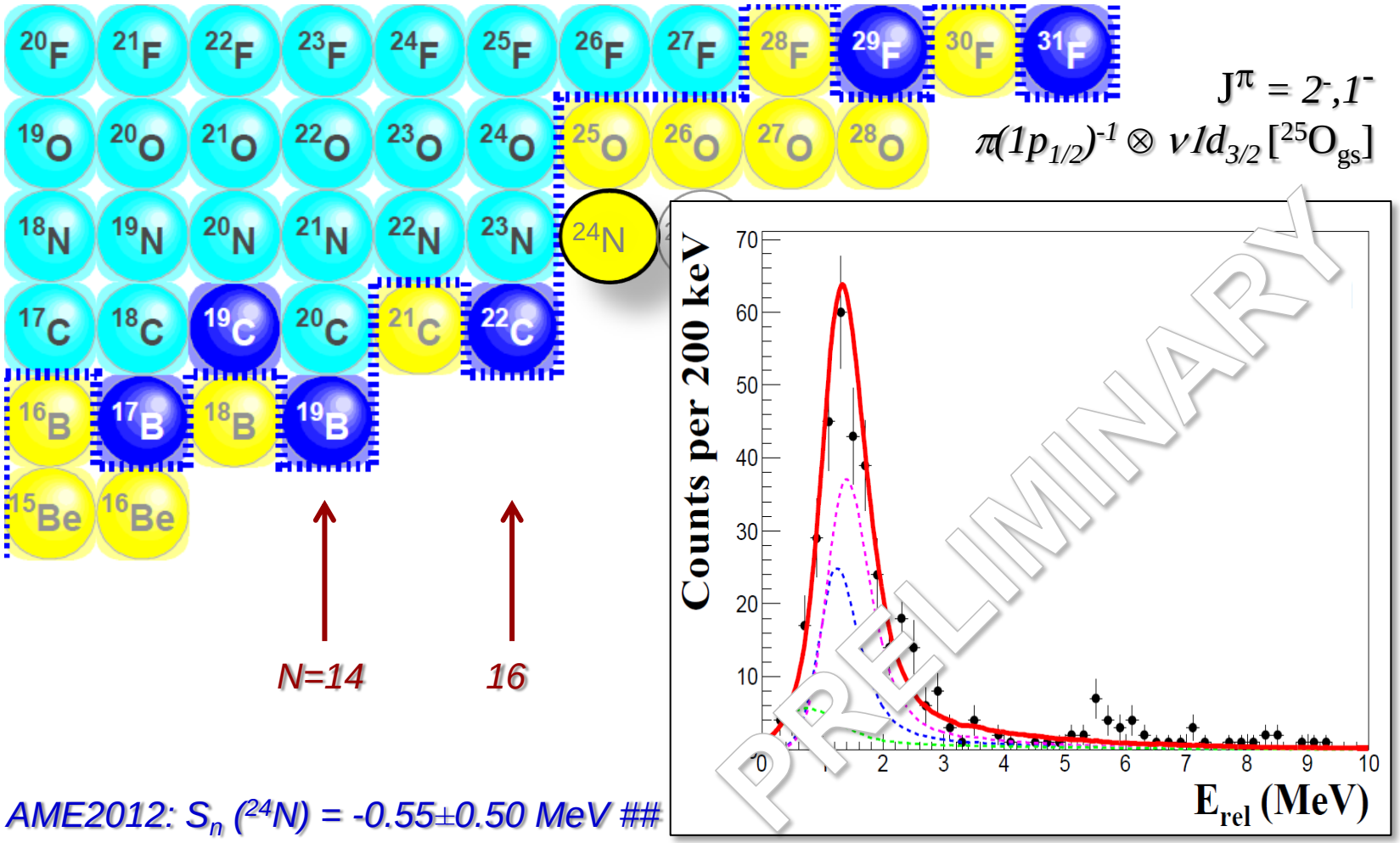
FIRST OBSERVATION OF ^{24}N: C(^{26}F,^{23}N+n) @ 200 MeV/nucleon ...



AME2012: S_n (^{24}N) = -0.55±0.50 MeV ##

Q Deshayes (LPC), PhD Thesis in progress

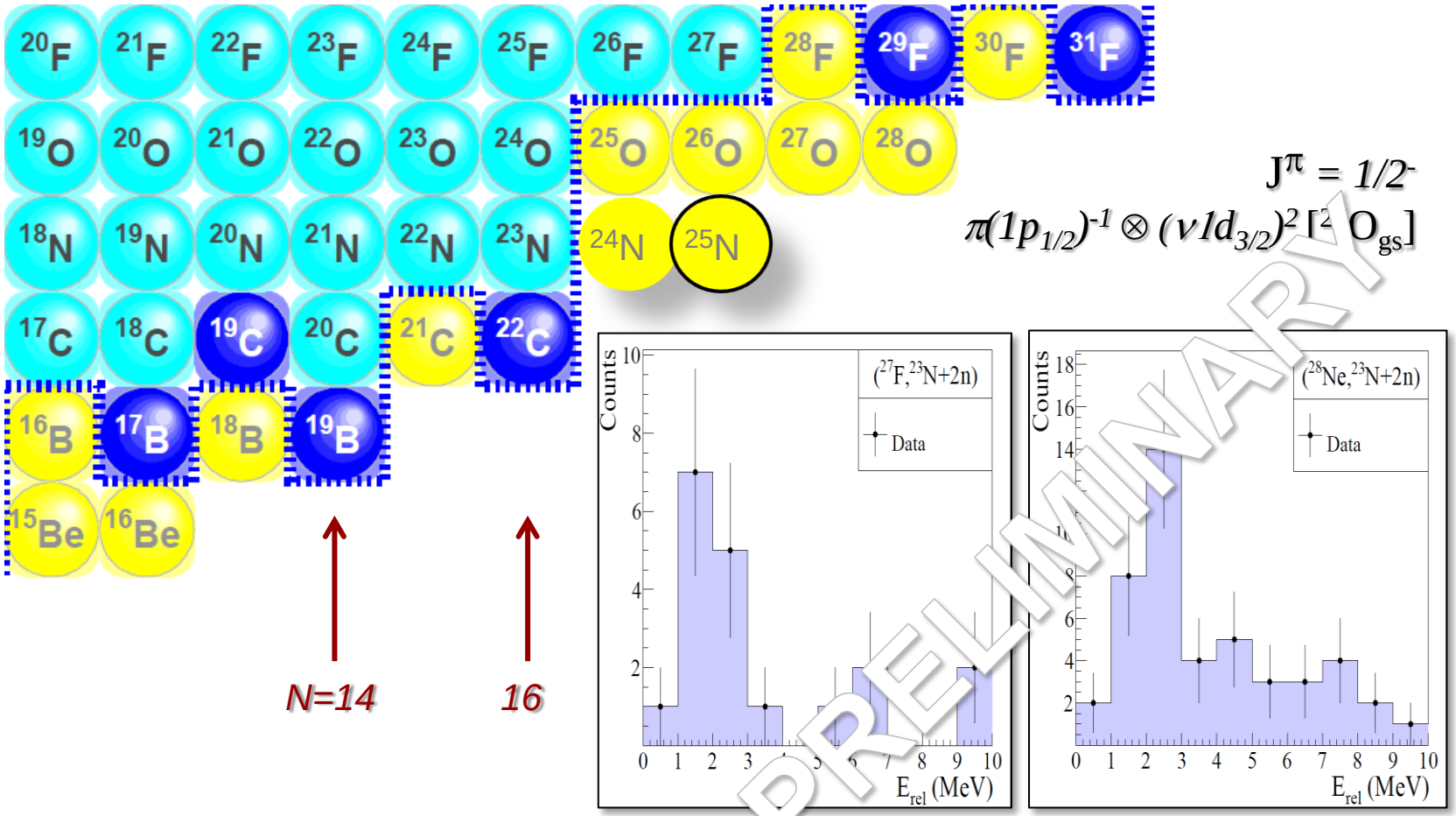
FIRST OBSERVATION OF ^{24}N: C(^{26}F,^{23}N+n) @ 200 MeV/nucleon ...



AME2012: S_n (^{24}N) = -0.55±0.50 MeV ##

Q Deshayes (LPC), PhD Thesis in progress

EVIDENCE FOR ^{25}N: C(^{27}F / ^{28}Ne,^{23}N+n+n) @ 200 MeV/nucleon ...



AME2012: S_{2n} (^{25}N) = -1.52±0.59 MeV ##

Q Deshayes (LPC), PhD Thesis in progress

Conclusions & Perspectives…

- ^{19}C : $1/2^+$ – $5/2^+$ "inversion" confirmed with $5/2^+_1$ found at threshold (E_x=0.6 MeV)
- ^{22}C : valence/halo configurations $\nu\,(2s_{1/2})^2 + \nu\,(1d_{5/2})^2$
- ^{21}C : $1/2^+$ – $5/2^+$ "inversion" ; $3/2^+$ located
- ^{24}N: observed for first time – ~1.4 MeV above 1n threshold
- ^{25}N: evidence for structure ~2 MeV above 2n threshold

In Progress…

- Detailed comparison of momentum distributions with theory: $C(^{22}C,^{20}C+n)$
- Refining and finalising $^{23\text{-}25}N$ results + ^{20}B

Perspectives …

- $^{20,21}B$ (N=15, 16) – [re] measured SAMURAI36-1 Nov 2016
- $^{24,25}N$ (N=17,18) – beamtime approved for re-measurement [with MINOS ? … (p,3p)?]
- ^{23}C search – to be re-proposed …

… Charge exchange to reach beyond the neutron dripline ?

PERSPECTIVES: CHARGE-EXCHANGE …