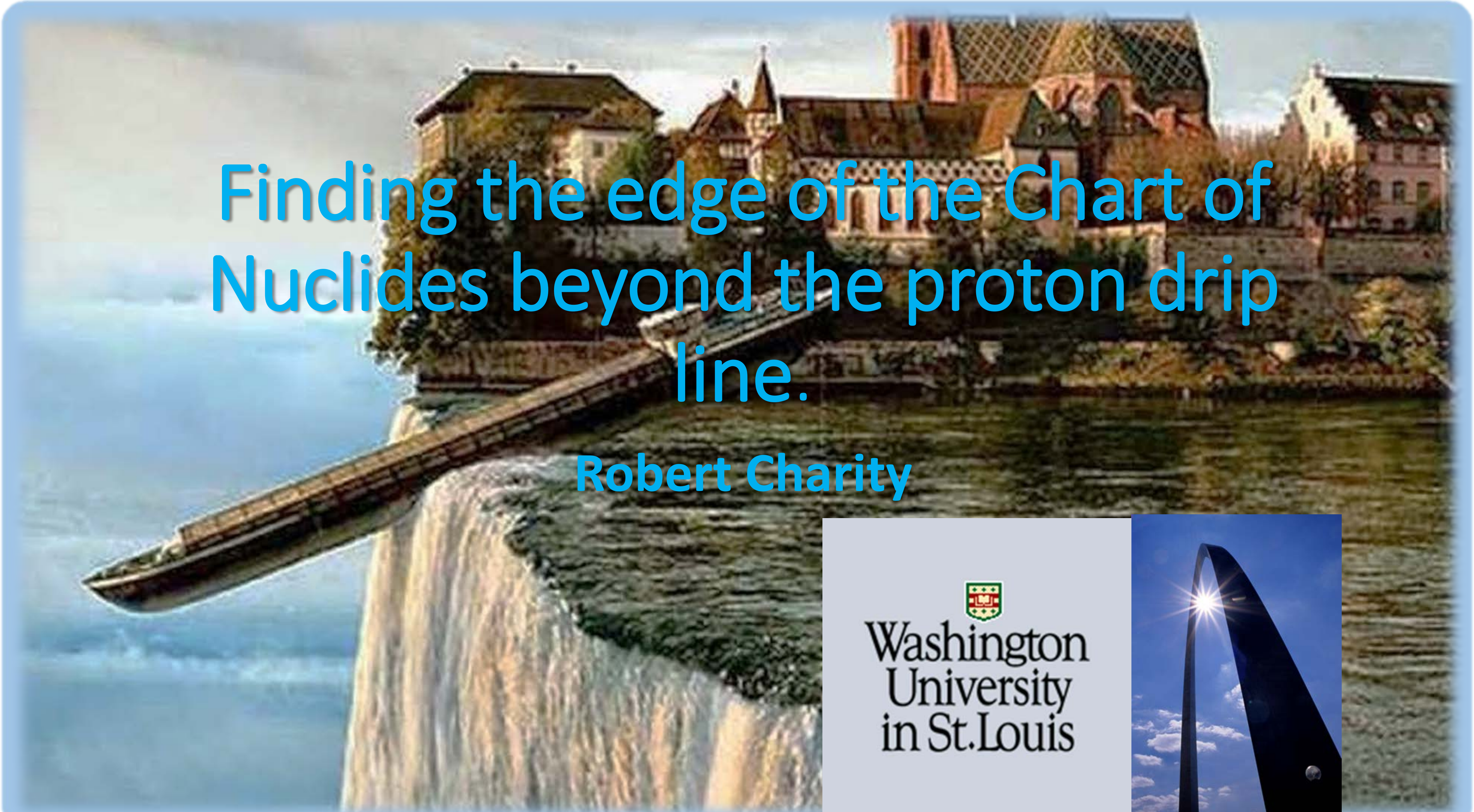


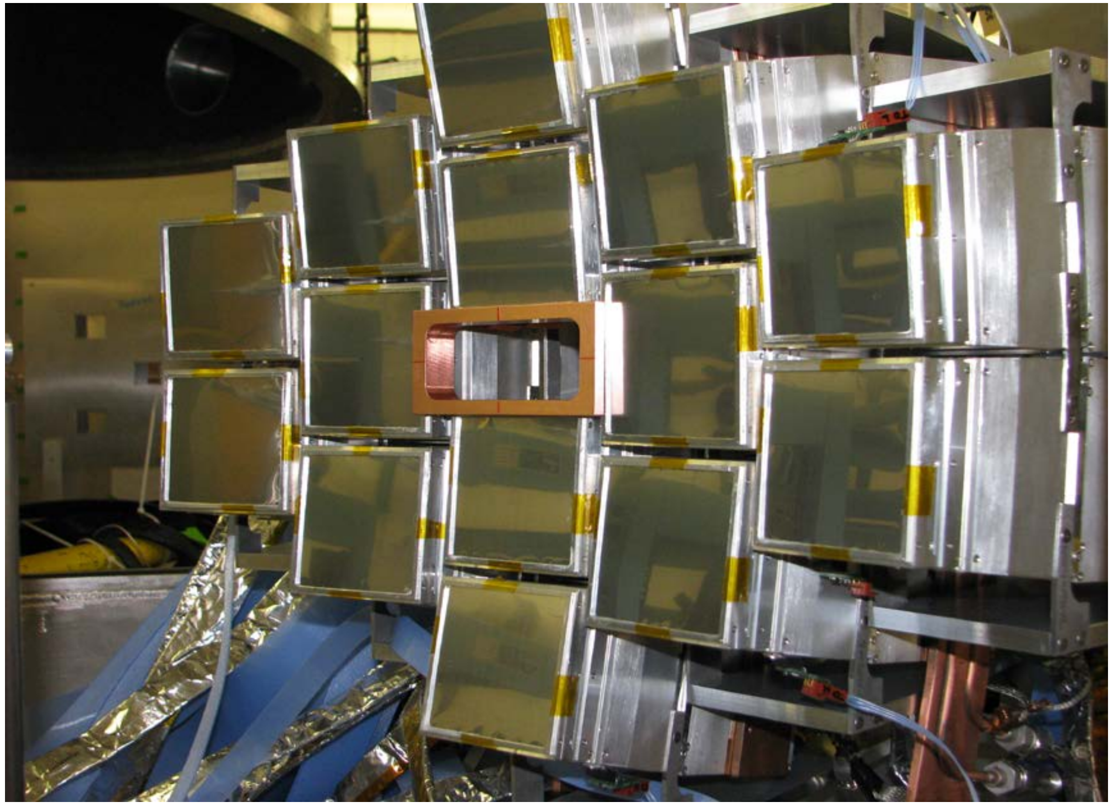
Finding the edge of the Chart of Nuclides beyond the proton drip line.

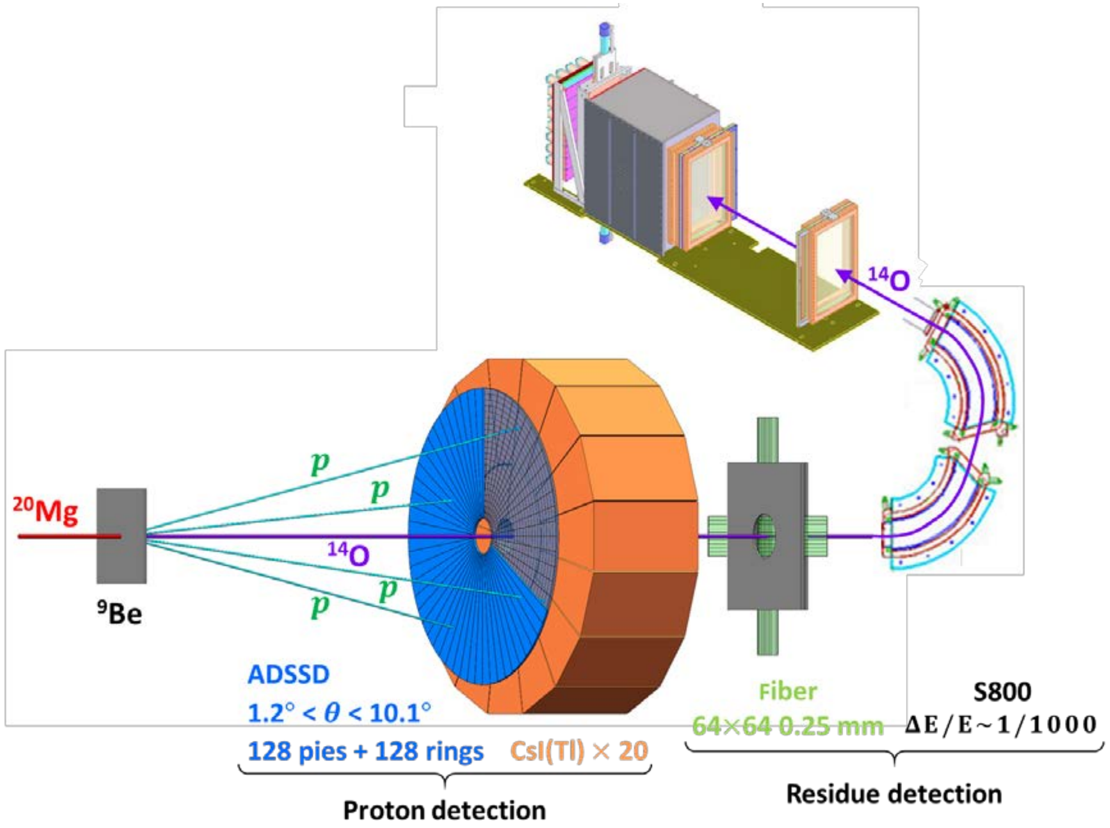
Robert Charity

Washington
University
in St. Louis

Invariant-mass spectrometry

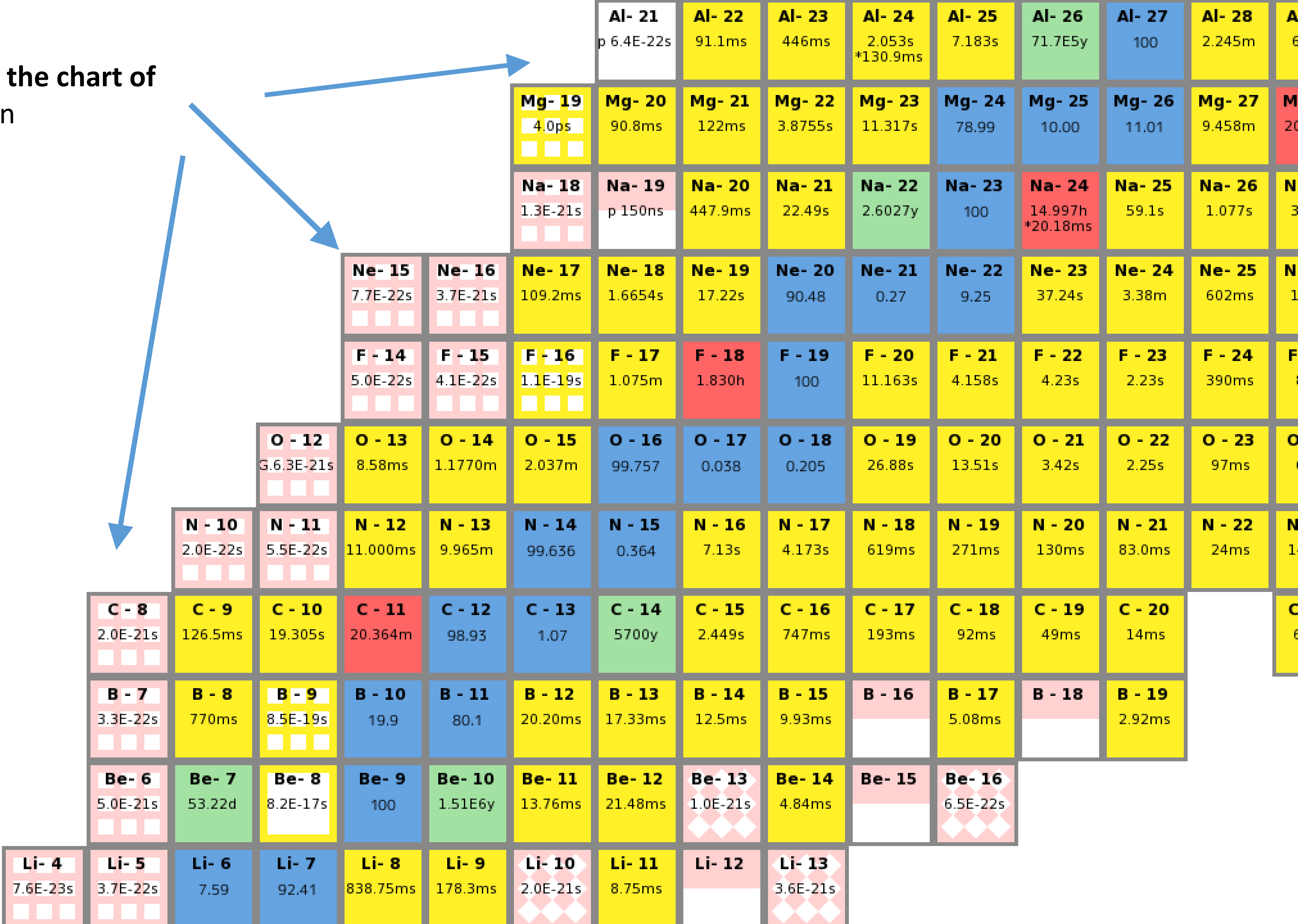
Most of the experimental data I will show come from experiments at NSCL (MSU) using the HiRA apparatus – 14 Si-CsI(Tl) E-ΔE telescopes. For heavier resonances we the S800 spectrometer with an annual Si-Csi(Tl) array instead.





Measured energy and angle of charged decay products to construct invariant-mass spectra

Where is **the edge of the chart of Nuclid**es in this region



							Al- 21 p 6.4E-22s	Al- 22 91.1ms	Al- 23 446ms	Al- 24 2.053s *130.9ms	Al- 25 7.183s	Al- 26 71.7E5y	Al- 27 100	Al- 28 2.245m	A 6
						Mg- 19 4.0ps	Mg- 20 90.8ms	Mg- 21 122ms	Mg- 22 3.8755s	Mg- 23 11.317s	Mg- 24 78.99	Mg- 25 10.00	Mg- 26 11.01	Mg- 27 9.458m	M 20
						Na- 18 1.3E-21s	Na- 19 p 150ns	Na- 20 447.9ms	Na- 21 22.49s	Na- 22 2.6027y	Na- 23 100	Na- 24 14.997h *20.18ms	Na- 25 59.1s	Na- 26 1.077s	N 3
				Ne- 15 7.7E-22s	Ne- 16 3.7E-21s	Ne- 17 109.2ms	Ne- 18 1.6654s	Ne- 19 17.22s	Ne- 20 90.48	Ne- 21 0.27	Ne- 22 9.25	Ne- 23 37.24s	Ne- 24 3.38m	Ne- 25 602ms	N 1
				F - 14 5.0E-22s	F - 15 4.1E-22s	F - 16 1.1E-19s	F - 17 1.075m	F - 18 1.830h	F - 19 100	F - 20 11.163s	F - 21 4.158s	F - 22 4.23s	F - 23 2.23s	F - 24 390ms	F 8
			O - 12 G.6.3E-21s	O - 13 8.58ms	O - 14 1.1770m	O - 15 2.037m	O - 16 99.757	O - 17 0.038	O - 18 0.205	O - 19 26.88s	O - 20 13.51s	O - 21 3.42s	O - 22 2.25s	O - 23 97ms	O (
		N - 10 2.0E-22s	N - 11 5.5E-22s	N - 12 11.000ms	N - 13 9.965m	N - 14 99.636	N - 15 0.364	N - 16 7.13s	N - 17 4.173s	N - 18 619ms	N - 19 271ms	N - 20 130ms	N - 21 83.0ms	N - 22 24ms	N 1
	C - 8 2.0E-21s	C - 9 126.5ms	C - 10 19.305s	C - 11 20.364m	C - 12 98.93	C - 13 1.07	C - 14 5700y	C - 15 2.449s	C - 16 747ms	C - 17 193ms	C - 18 92ms	C - 19 49ms	C - 20 14ms		C 6
	B - 7 3.3E-22s	B - 8 770ms	B - 9 8.5E-19s	B - 10 19.9	B - 11 80.1	B - 12 20.20ms	B - 13 17.33ms	B - 14 12.5ms	B - 15 9.93ms	B - 16	B - 17 5.08ms	B - 18	B - 19 2.92ms		
	Be- 6 5.0E-21s	Be- 7 53.22d	Be- 8 8.2E-17s	Be- 9 100	Be- 10 1.51E6y	Be- 11 13.76ms	Be- 12 21.48ms	Be- 13 1.0E-21s	Be- 14 4.84ms	Be- 15	Be- 16 6.5E-22s				
Li- 4 7.6E-23s	Li- 5 3.7E-22s	Li- 6 7.59	Li- 7 92.41	Li- 8 838.75ms	Li- 9 178.3ms	Li- 10 2.0E-21s	Li- 11 8.75ms	Li- 12	Li- 13 3.6E-21s						

The edge of chart of nuclides is diffuse – determined by when the width of resonances become so wide they melt into the continuum.

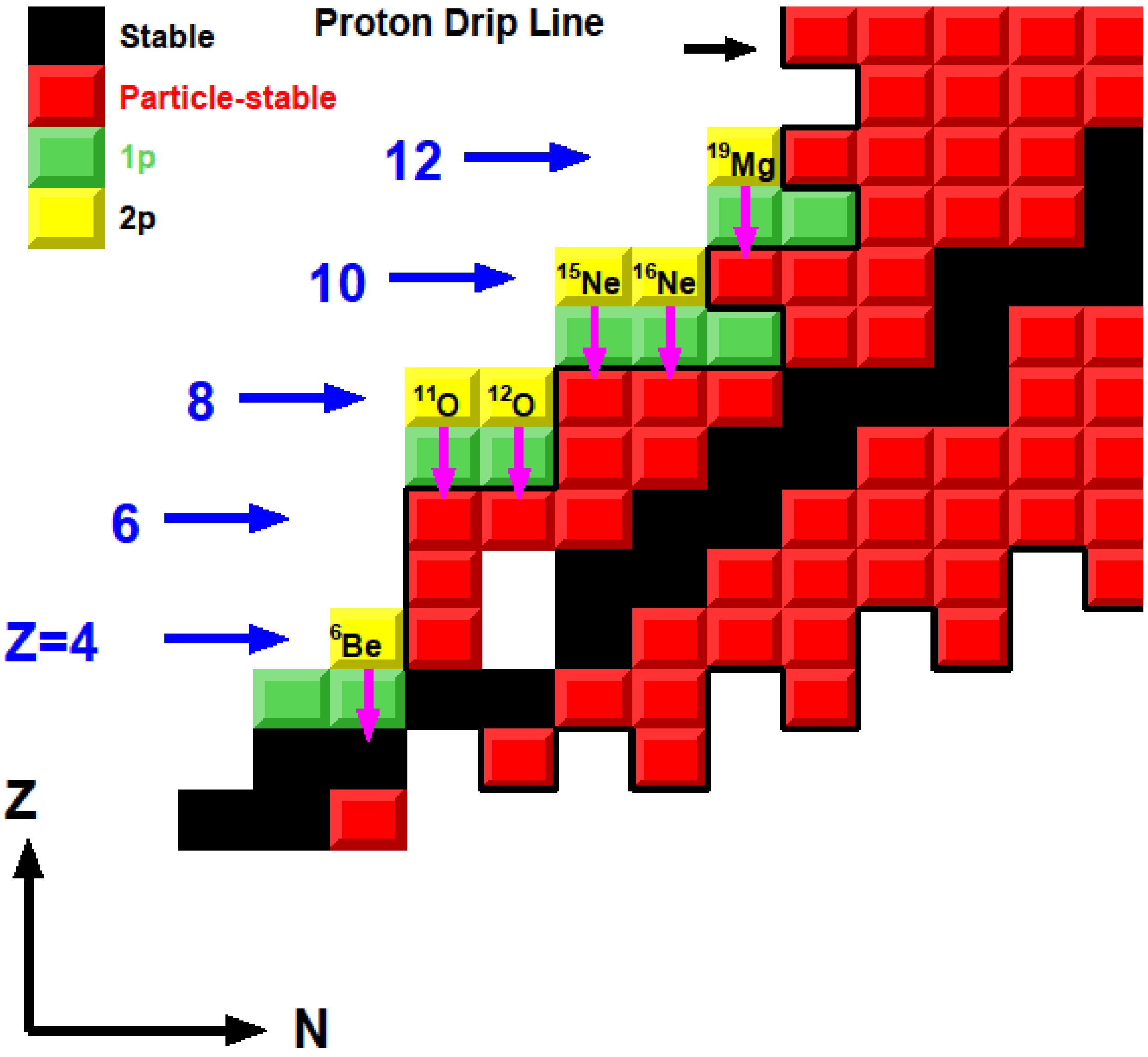
So what is the maximum width we can consider for an isotope?
In high-energy physics, the W-boson has a decay width of 2 GeV, but this is unrealistic for a nucleus.

Separation of timescales between formation and decay of resonance.
i.e., reaction timescale must be shorter that lifetime of resonance.
Typical reaction time is that in which 100 MeV/A projectile travels one diameter (9 fm) of target ~7x10^{-23} s ***Thus $\Gamma < 9$ MeV***.

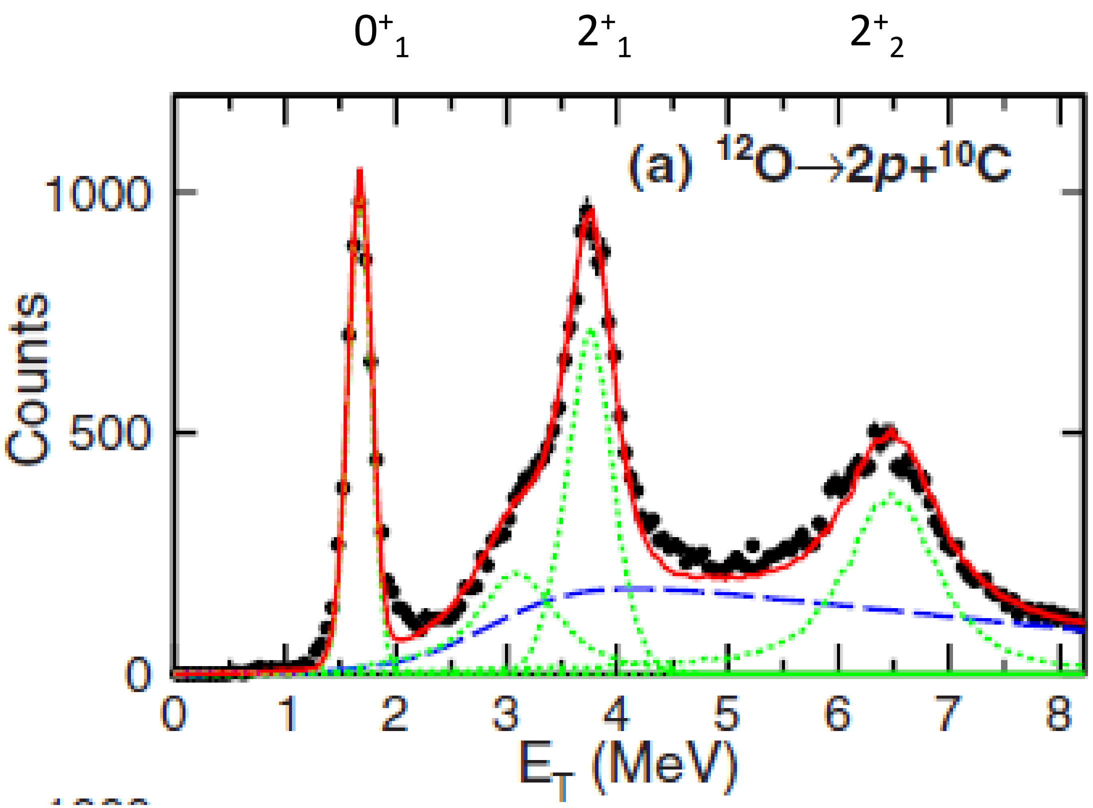
Decay time cannot be shorter than typical time scale of nuclear motion –
time for a valence nucleon (Ek~40MeV) to travel a nuclear diameter (9 fm), ***Thus $\Gamma < 6$ MeV***

Experimentally a resonance of width 6 MeV would be hard to find especially if there is some non-resonance background and/or multitude of states which overlap and form a continuum.

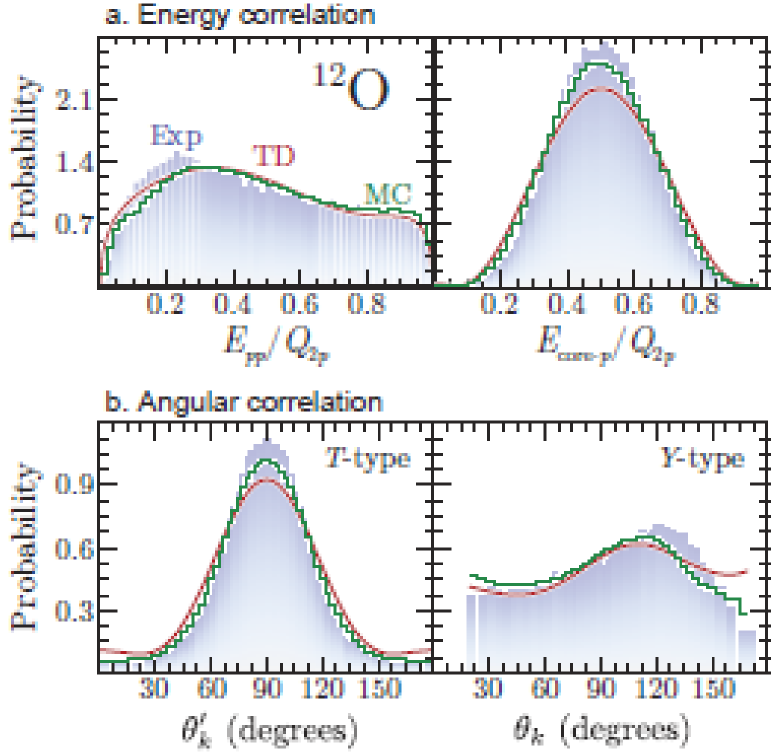
Just beyond the proton drip line we find 1*p* emitters for odd-Z isotopes and 2*p* emitter for even-Z isotopes



70 MeV/A ^{13}O beam
Webb et al PRC 100 (2019) 024306



Ground-state correlations

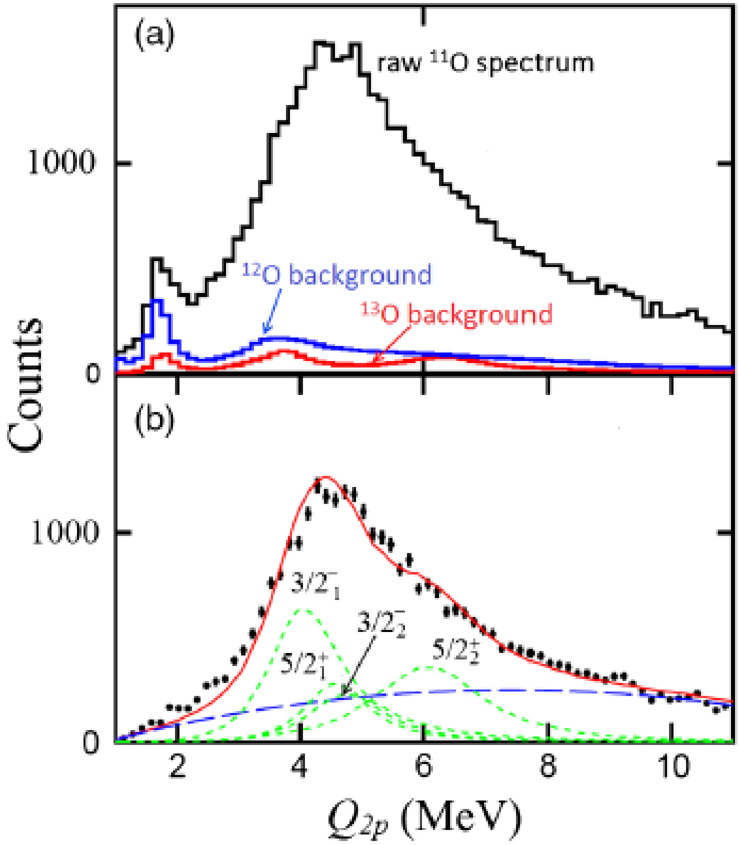


Correlations in decay can be explained in the time-dependent approach starting with Gamow Coupled Channel wavefunctions. Determined by nuclear structure and final-state interactions. Decay is dominated by the proton $(s_{1/2})^2$ configuration of the initial wavefunction. Wang *et al* , J. Phys. G to be published.

$^{11}O \rightarrow 2p + {}^{9}C$ mirror of ^{11}Li

Two-neutron knockout from ^{13}O beam

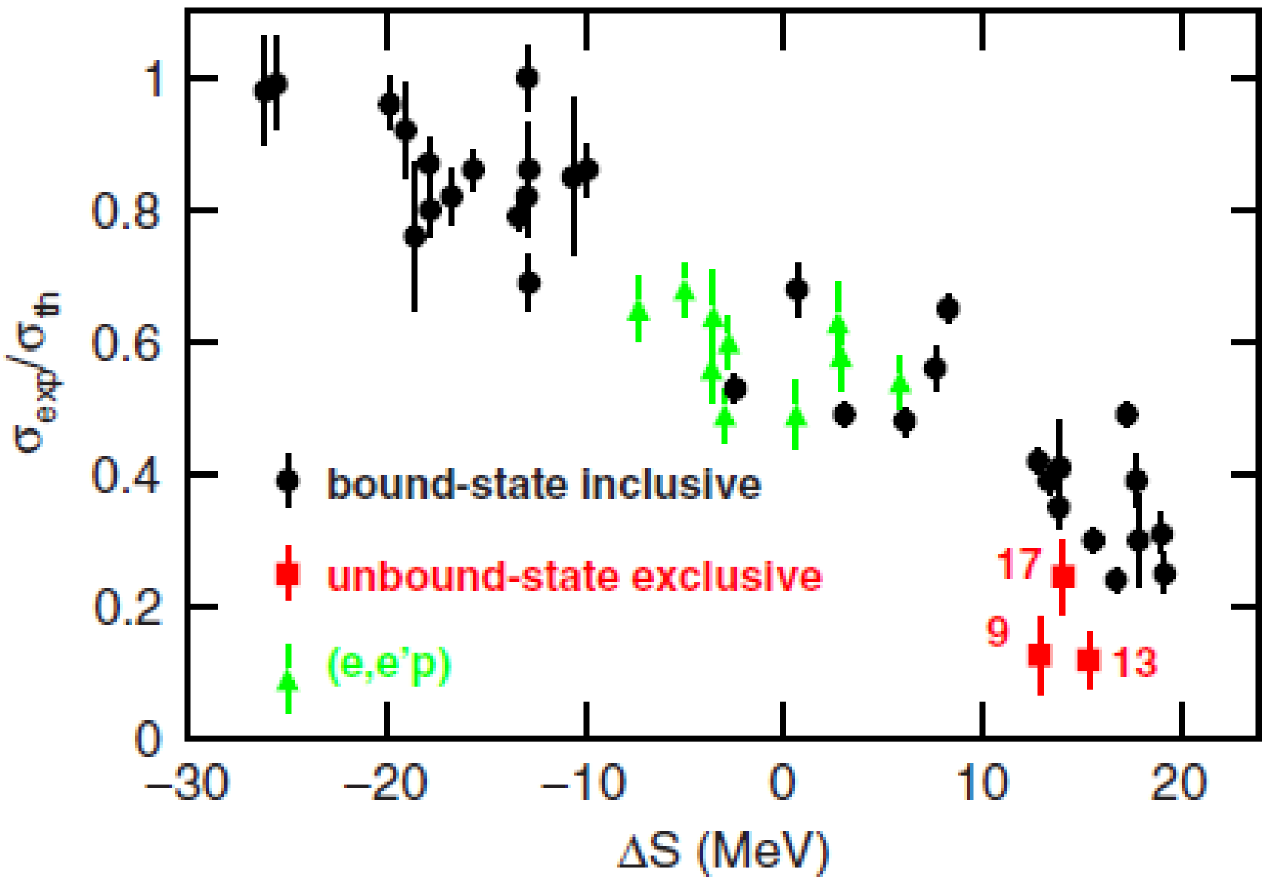
Webb *et al* PRL 122 (2019) 122501



Overlapping states:
Decomposition is done with the aid of
Gamow Coupled Channels model–
lots of interesting effects of the continuum here.

Knockout cross sections

Charity, Sobotka, Tostevin PRC 102(2020) 044614

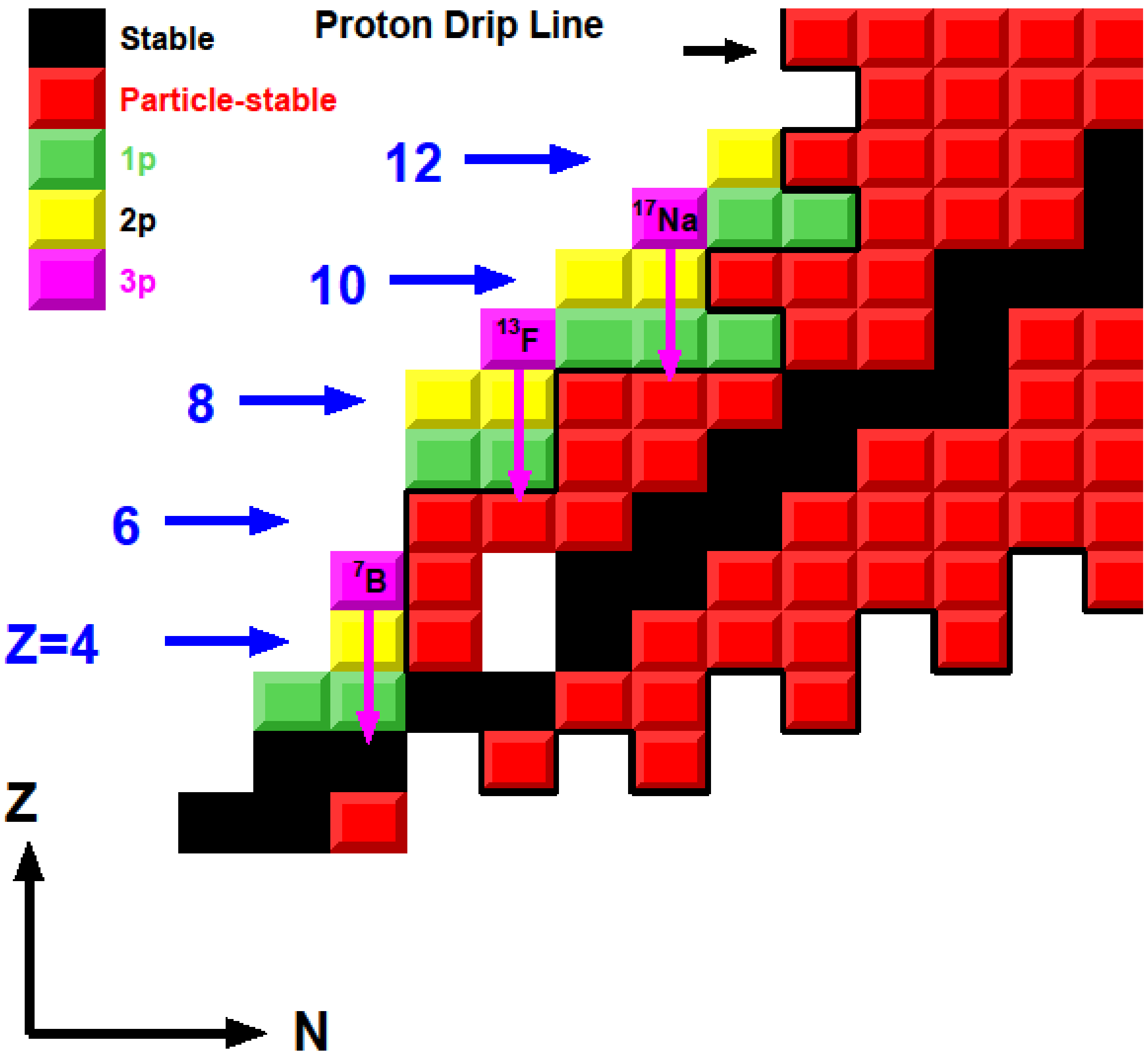


Three neutron knockout reactions to resonance states added.

^{17}Ne -> ^{16}Ne$_{g.s.}$
^{13}O -> ^{12}O$_{g.s.}$
^{9}C -> ^{8}C$_{g.s.}$

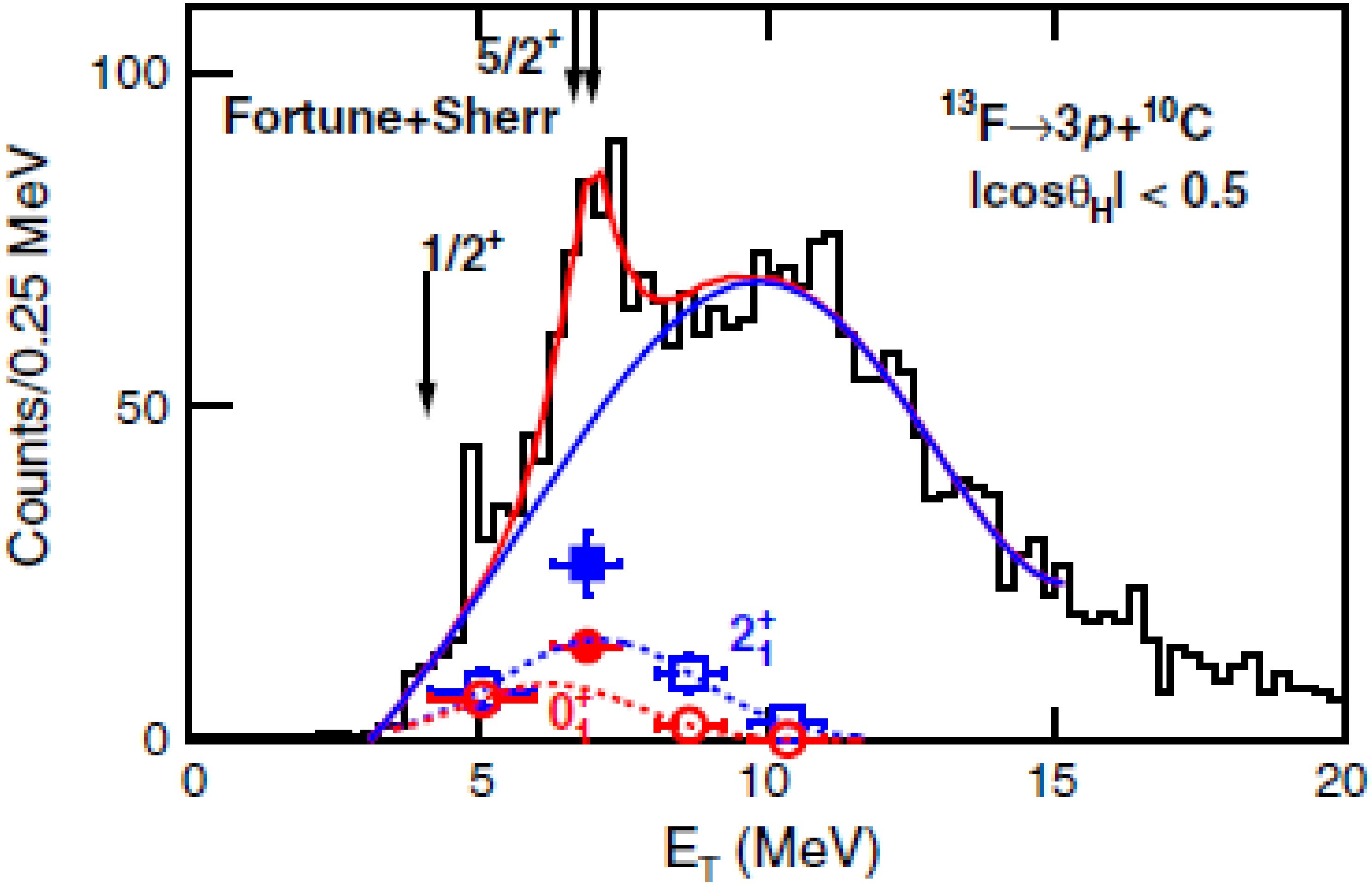
Nucleon knockout to resonant states is further suppressed compared to the Gade-Tostevin systematics.
We suggested that this extra suppression is a result of smaller spectroscopic factors influenced by the continuum coupling - This has been supported with theory calculations including the continuum.
[J. Wylie et al., Phys. Rev. C 104, L061301 (2021)]

Even further out we will see 3*p* emitters for odd-Z isotopes



Discovery of ^{13}F formed in a charge-exchange reaction with a ^{13}O beam with the invariant-mass method. Mirror of ^{13}B discussed by G. Rogachev

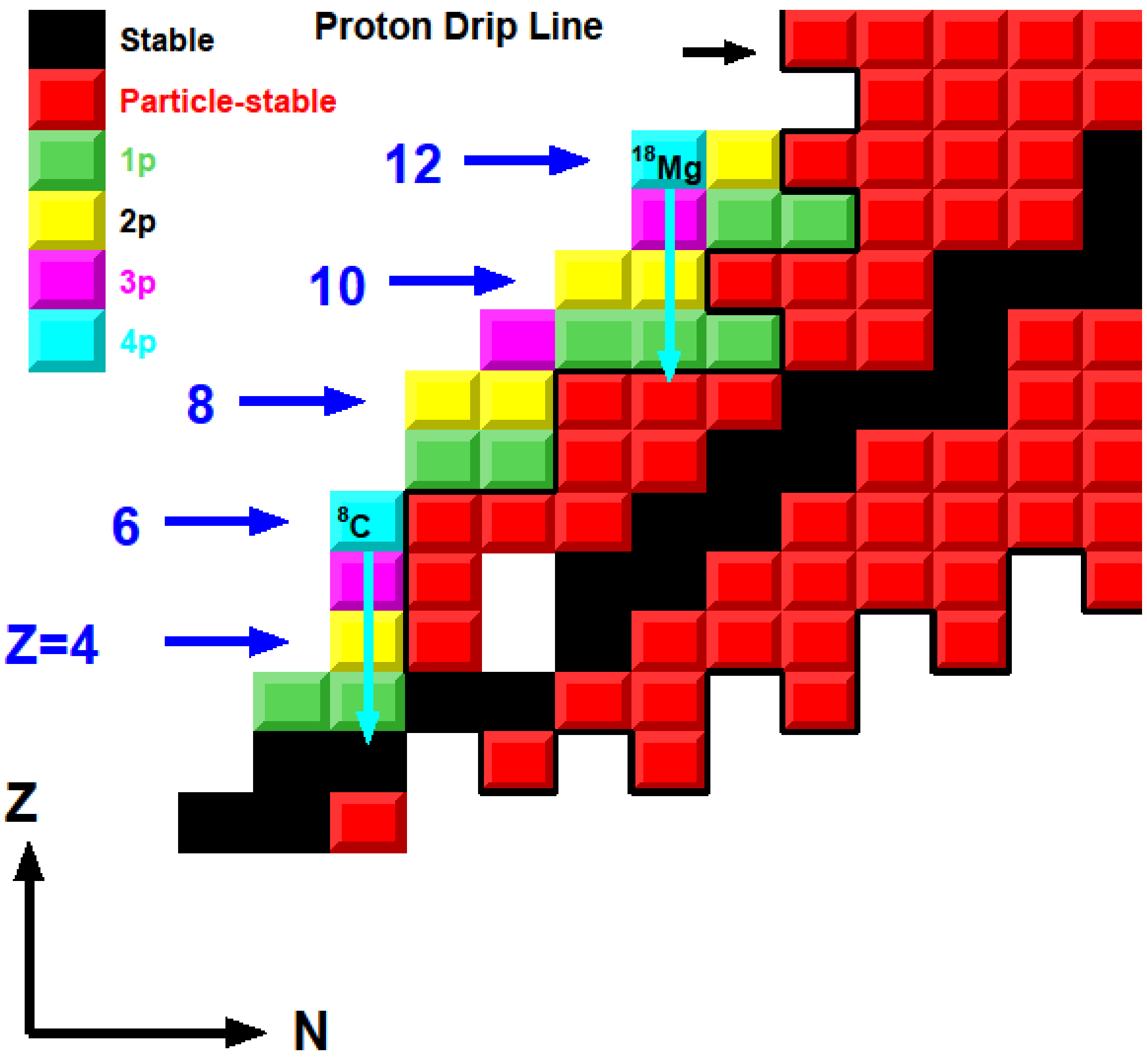
Only the $5/2^+$ first excited states was resolved.
Intermediate states in ^{12}O were identified



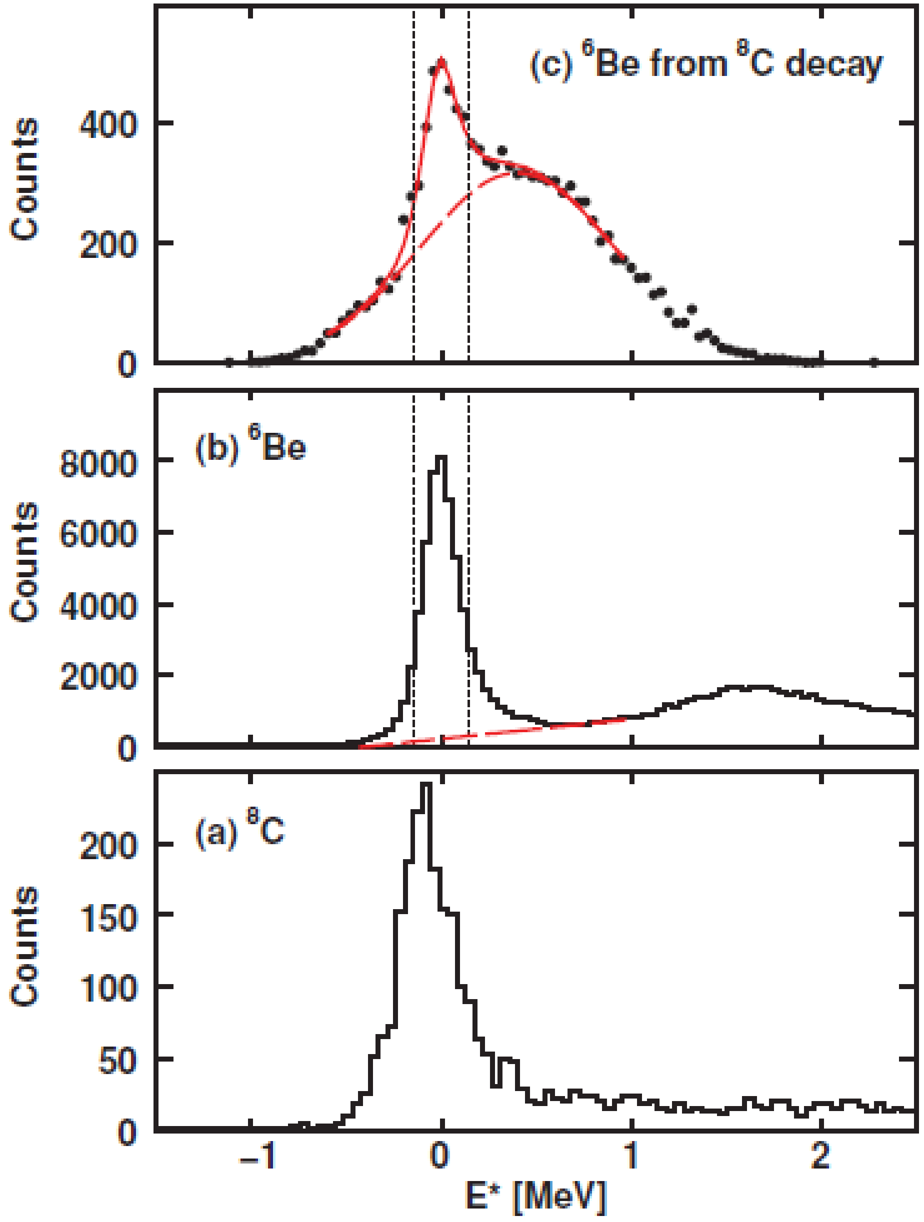
Fit gives:
Q_{3p} = 7.06 MeV
Γ = 1.01 MeV

Charity et al , PRL 1126 (2021) 132501

4*p* emitters for even-Z isotopes.



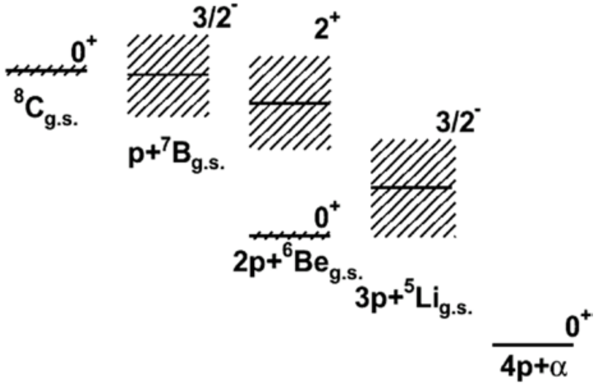
NSCL HiRA experiment PRC 82 041304(R) (2010)



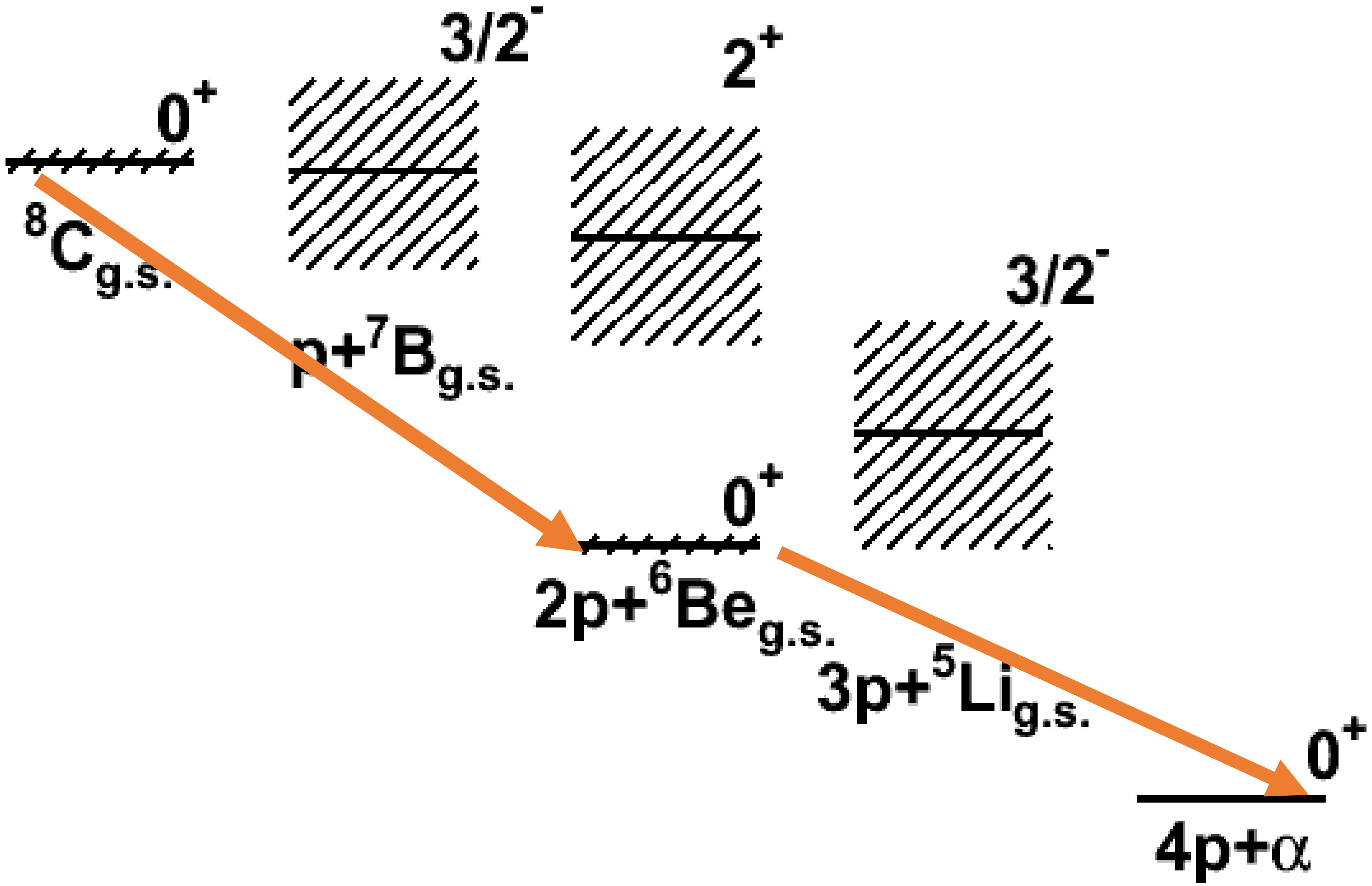
$2p+\alpha$ subevents from the detected $4p+\alpha$ events.
Six subevents per event.
All $^8C_{g.s.}$ events have a $^6Be_{g.s.}$ intermediate state.

$2p+\alpha$ events from a ^{7}Be beam following one-neutron knockout

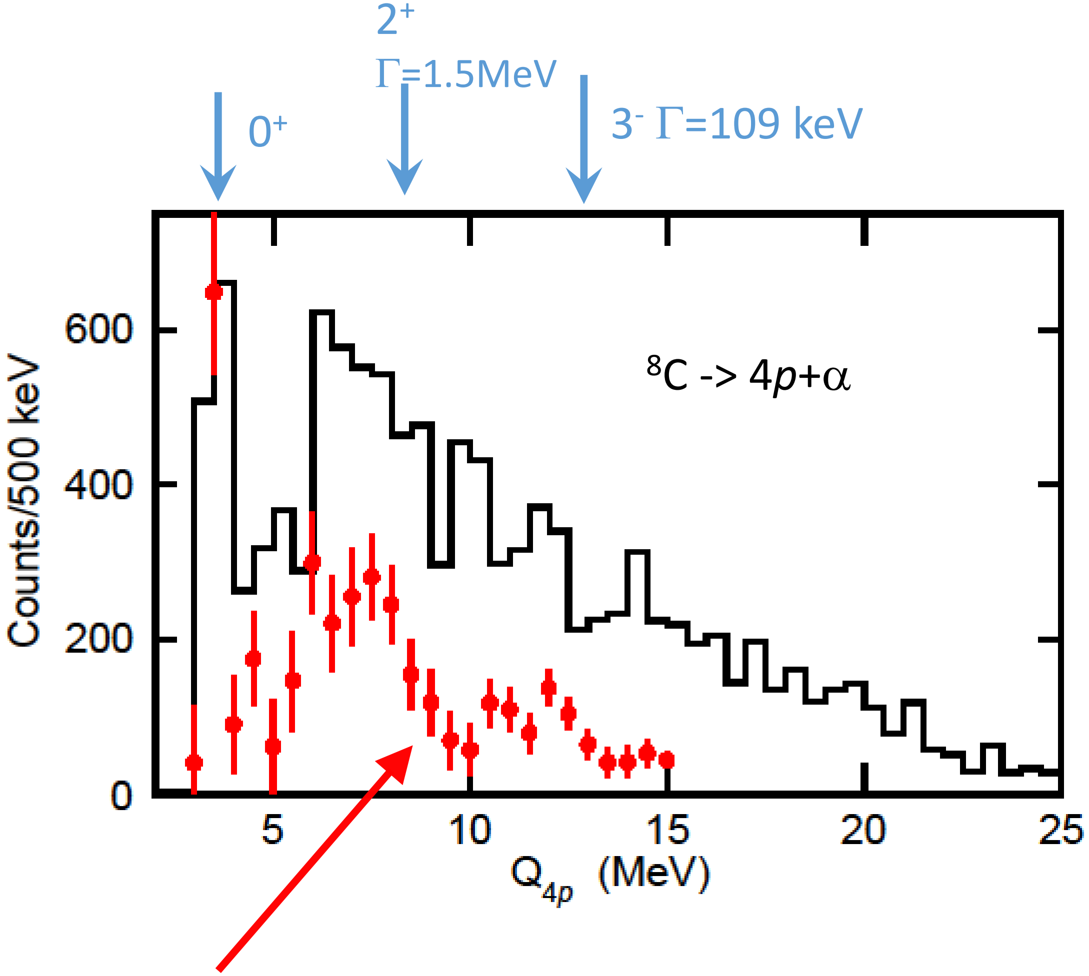
$4p+\alpha$ events from ^{9}C beam
following one neutron knockout



$^{8}C_{g.s.}$ decays by two sequential steps of prompt 2p decay.



^{8}C excited states?
5 nucleon knockout from a ^{13}O beam



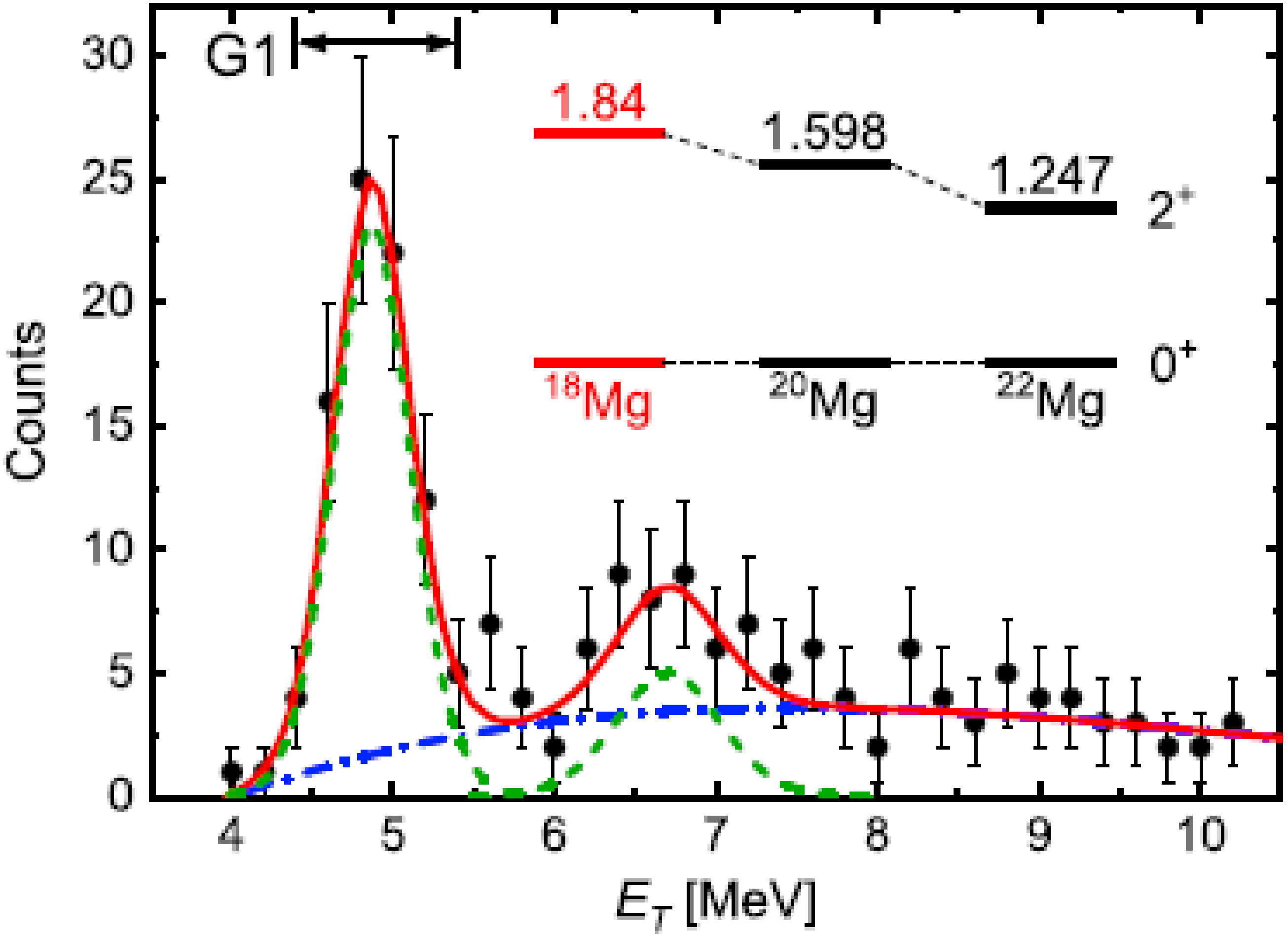
Yield with a ^{6}Be$_{g.s.}$

Background from ^{12}O -> 4p+2α subtracted

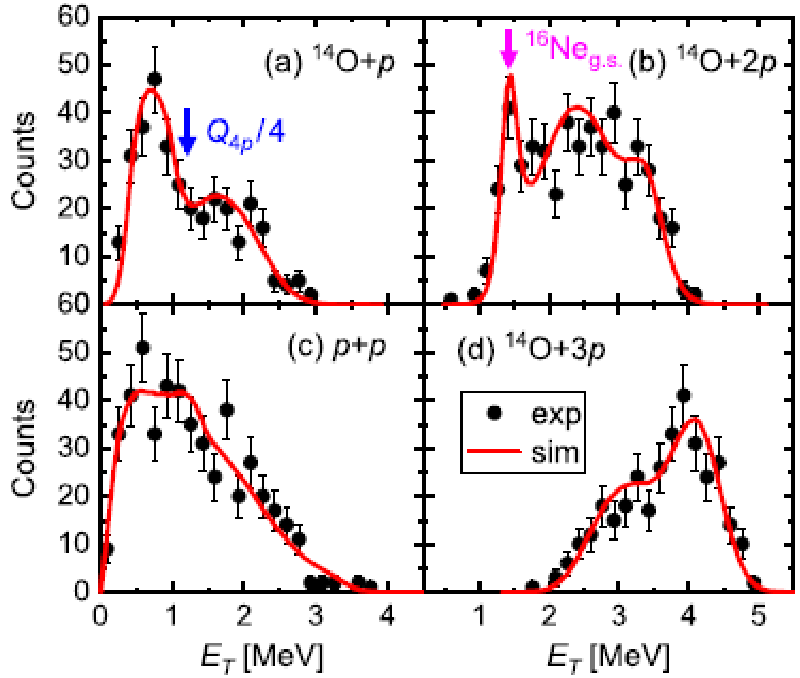
Gamow-Shell-Model predictions
J. Wylie, S Wang, W. Nazarewicz

2 protons plus a ^{6}Be core.

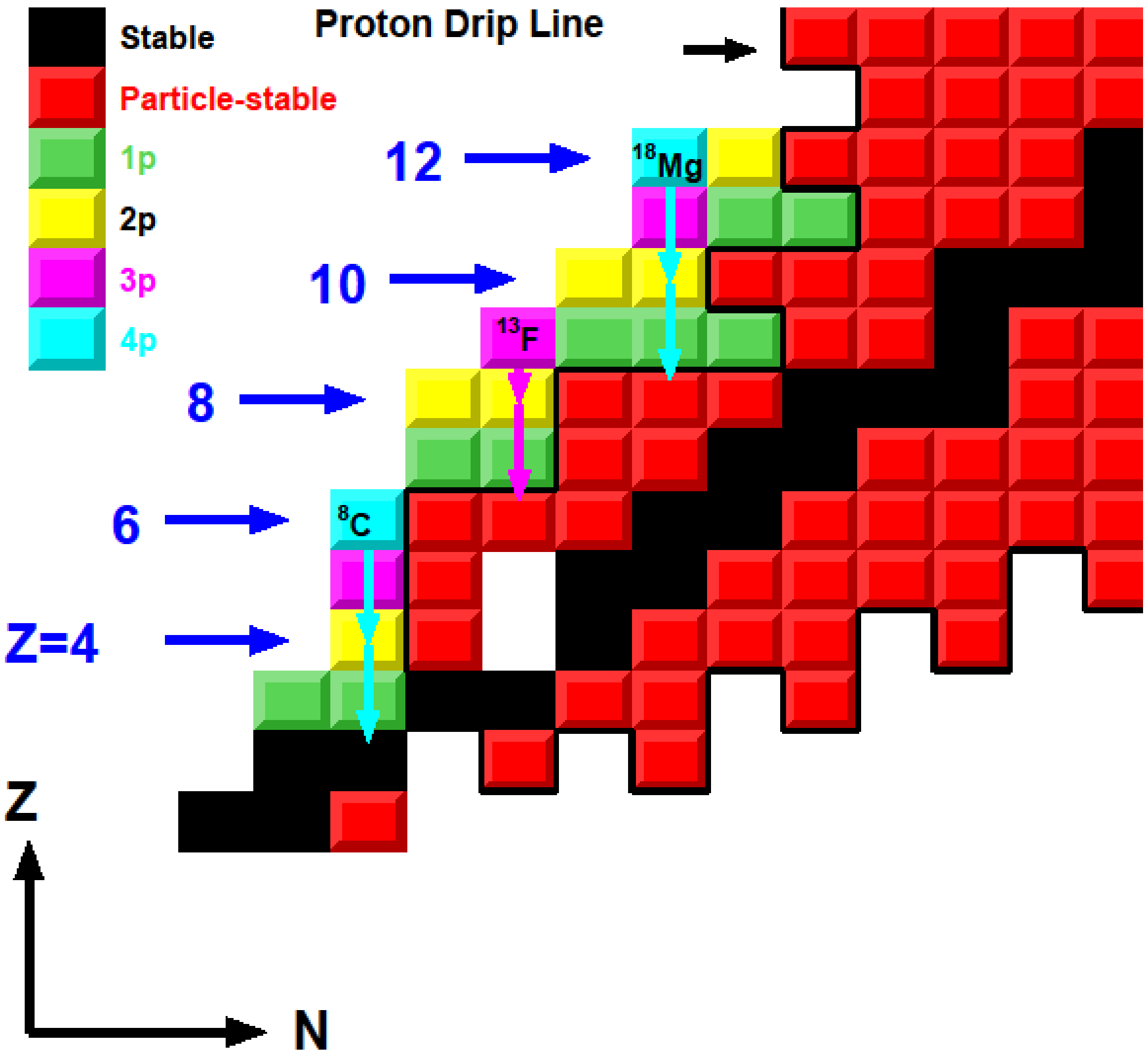
^{18}Mg formed following two-neutron knockout from a ^{20}Mg beam: NSCL PRL 127, 262502 (2021)
^{18}Mg->4p+^{14}O. ^{14}O fragment detected in the S800 spectrometer, protons detected in a Si-CsI(Tl) annular counter. Collaboration with Peking University.



Ground and 2$^+$ first excited state identified

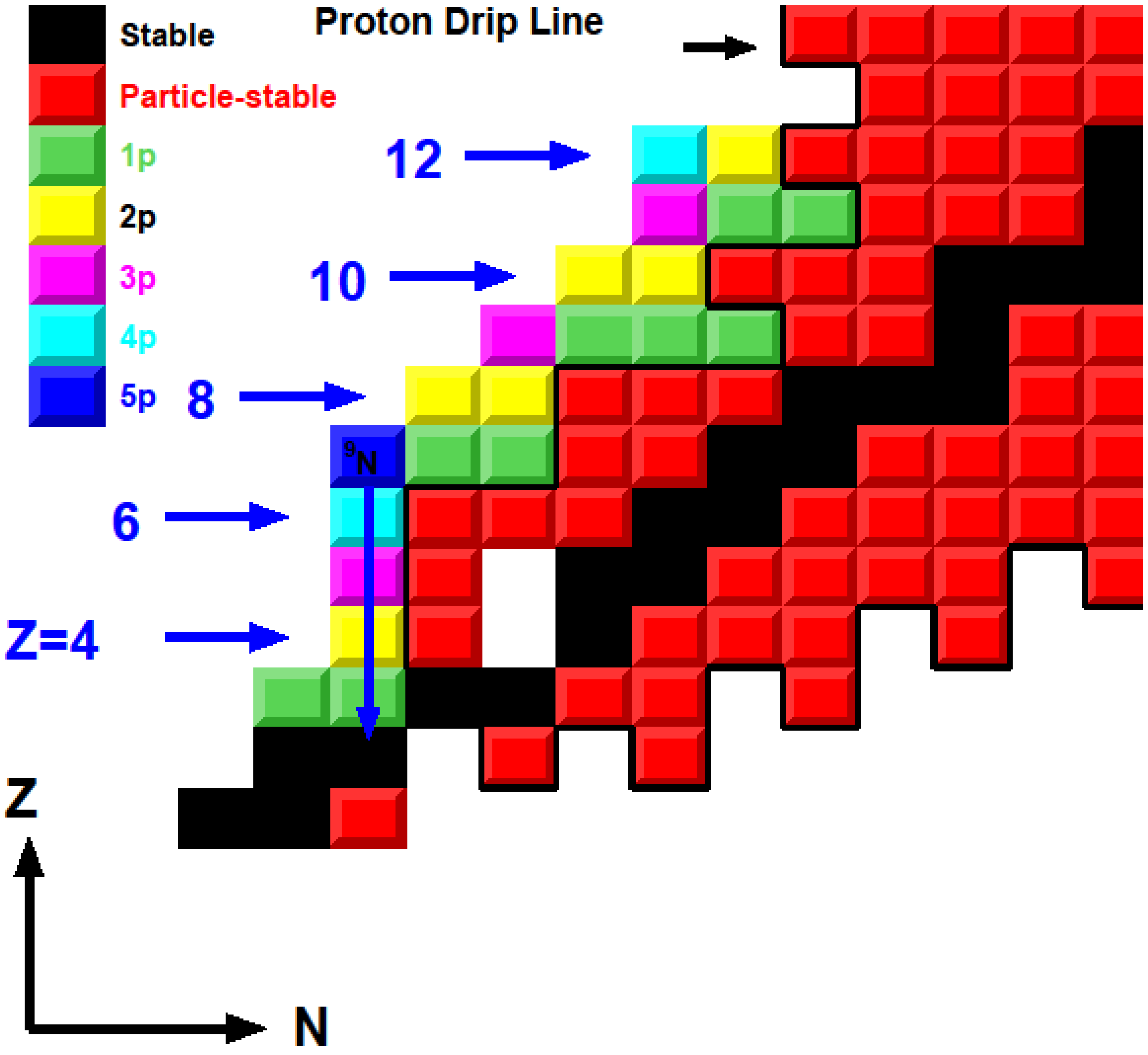


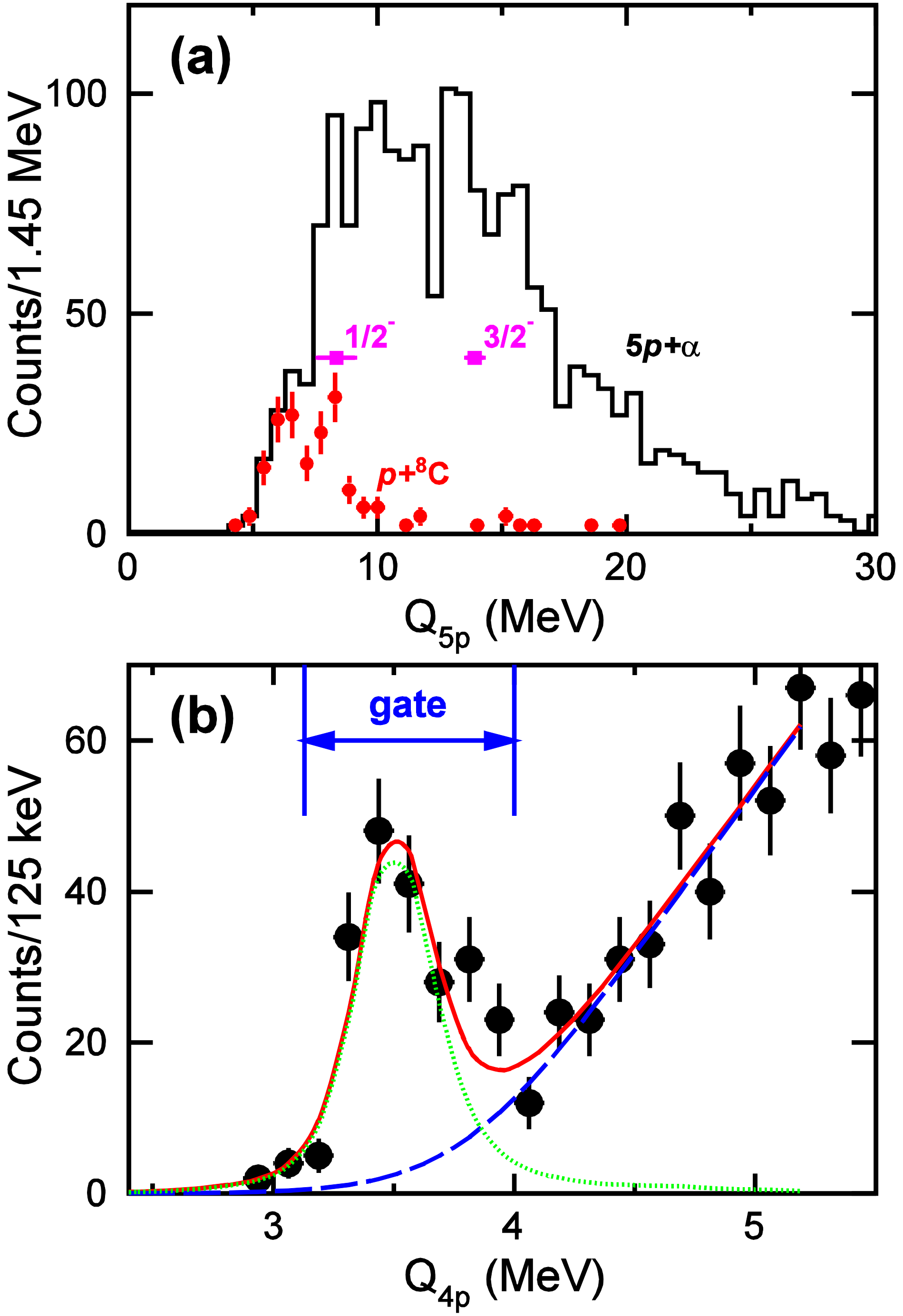
Ground-state subevents consistent with decay path consisting of two-steps of prompt 2p decay with a ^{16}Ne intermediate state.



3*p* and 4*p* emitters so far involve sequential steps of 1*p* and 2*p* decay. No evidence for prompt 3*p* and 4*p* emission.

5p emitters?

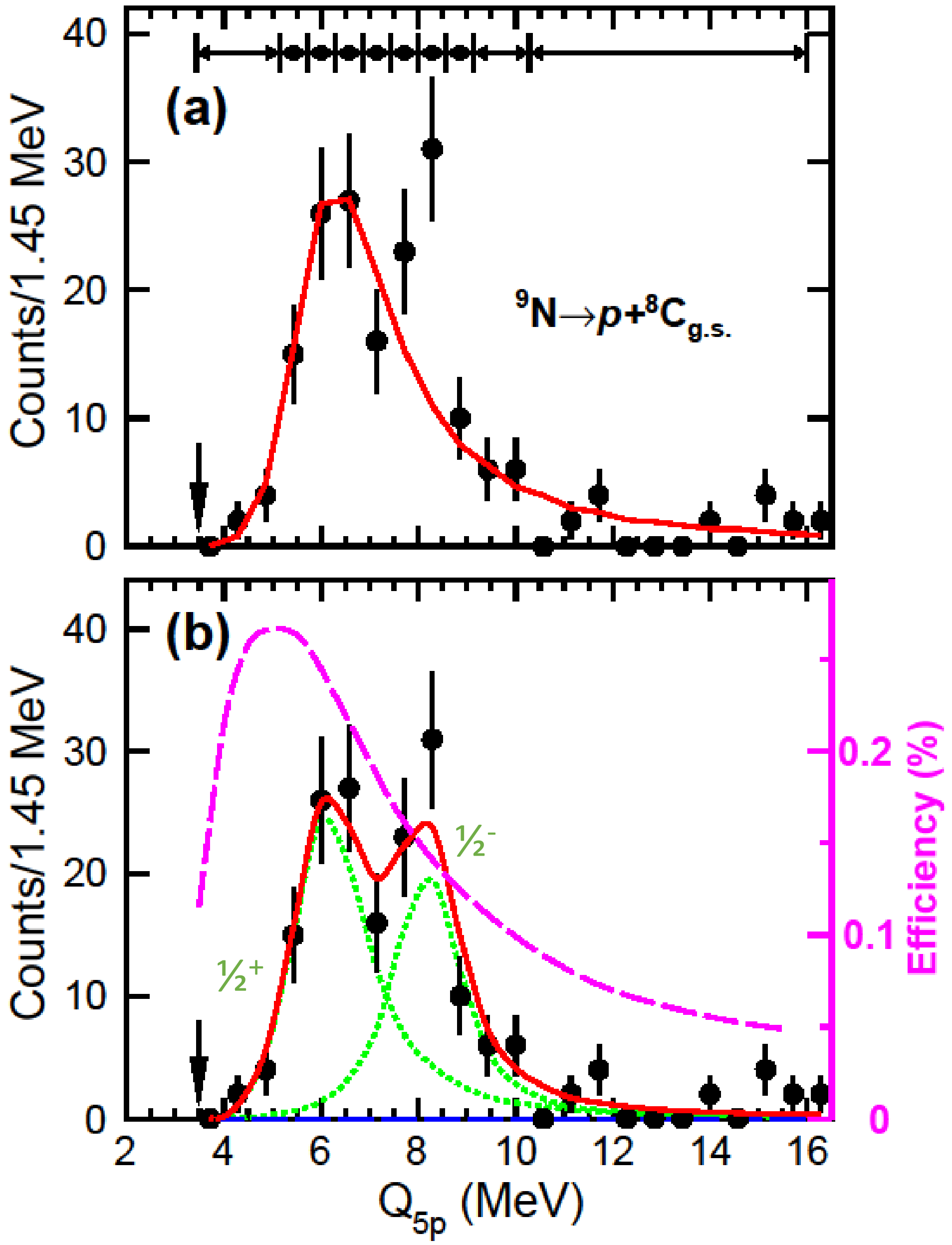

Stable
Particle-stable
1p
2p
3p
4p
5p
Proton Drip Line
12
10
8
6
Z=4
9N
Z
N



70 MeV/A ^{13}O beam – knockout 1 proton and 3 neutrons

$5p+\alpha$ invariant-mass distribution is quite broad and no clear peaks.

Look for events that $p+^8C_{g.s.}$ decay by gating on the invariant-mass of the $4p+\alpha$ subevents.
(Five subevents for each $5p+\alpha$ event)



Single peak fit.

Can only fit this as l=0 resonance using a R-matrix lineshape for p+^{8}C.

Q_{1p} = 1.22(6) MeV

Γ = 2.59(23) MeV

$\Gamma > 2\times Q_{5p}$ – subthreshold resonance (similar to diproton)

More of a final state effect.

Two-peak fit.

Upper peak is at energy of the ½$^-$ state predicted with Gamow Shell Model. (Wyle, Wang, Nazarewicz).

As for ^{11}Be, we expect an inversion of the ½$^+$ and ½$^-$ ground and first excited states as the $s_{1/2}$ orbital intrudes in the p-shell. Can the lower peak be the ½+ state?

In the mirror ^{9}He, a number of experimental studies report a ½$^+$ virtual state in the n+^{8}He system (final-state effect).

The Gamow Shell Model cannot find a real ½$^+$ resonance.

Within the statistical uncertainty we cannot determine if the ½+ peak is from a real resonance or a final-state effect.

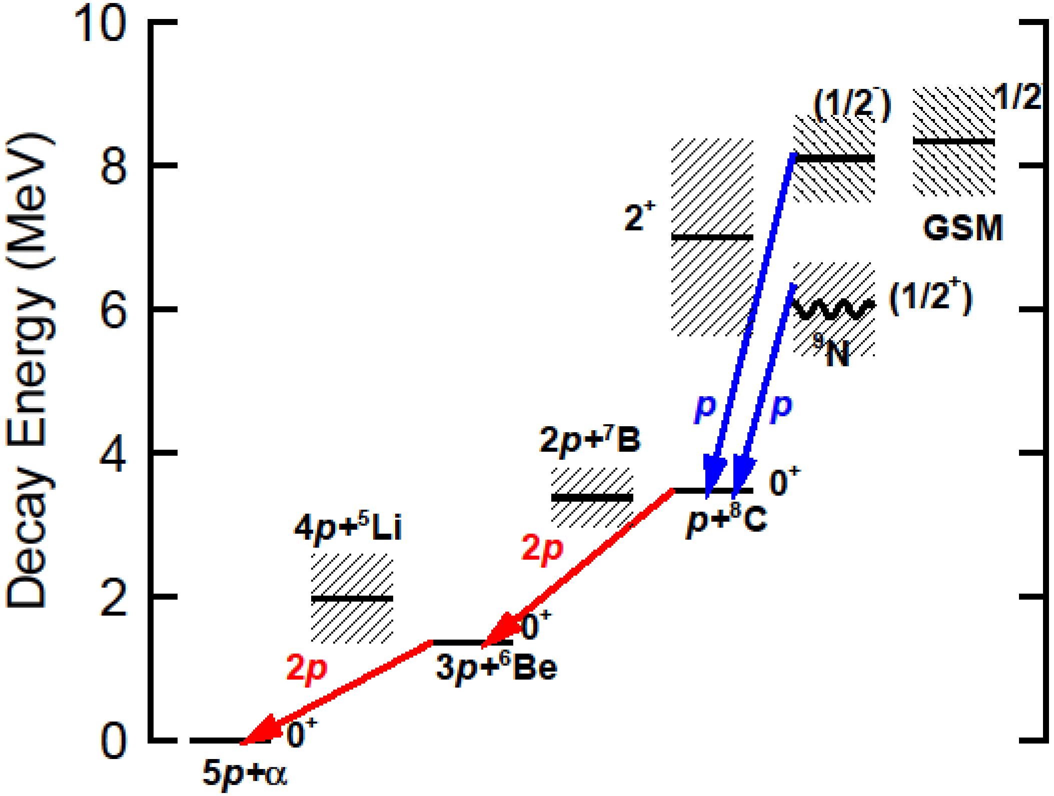
Do we see a ^{9}N state?

Option 1) one peak all associated with $s_{1/2}$ strength,
this strength is from a sub-threshold resonance, i.e., final-state interaction

Option 2) two peaks. Upper peak is the ½$^-$ state in ^{9}N. Within statistics we
cannot discriminate if lower peak in fit is from a real resonance or a final-state interaction.

Gamow Shell Model calculations (J. Wylie, S. Wang, W. Nazarewicz)

½$^-$ state Q_{5p} = 8.3 MeV Γ=1.4 MeV
Does not predict a 1/2$^+$ ground state



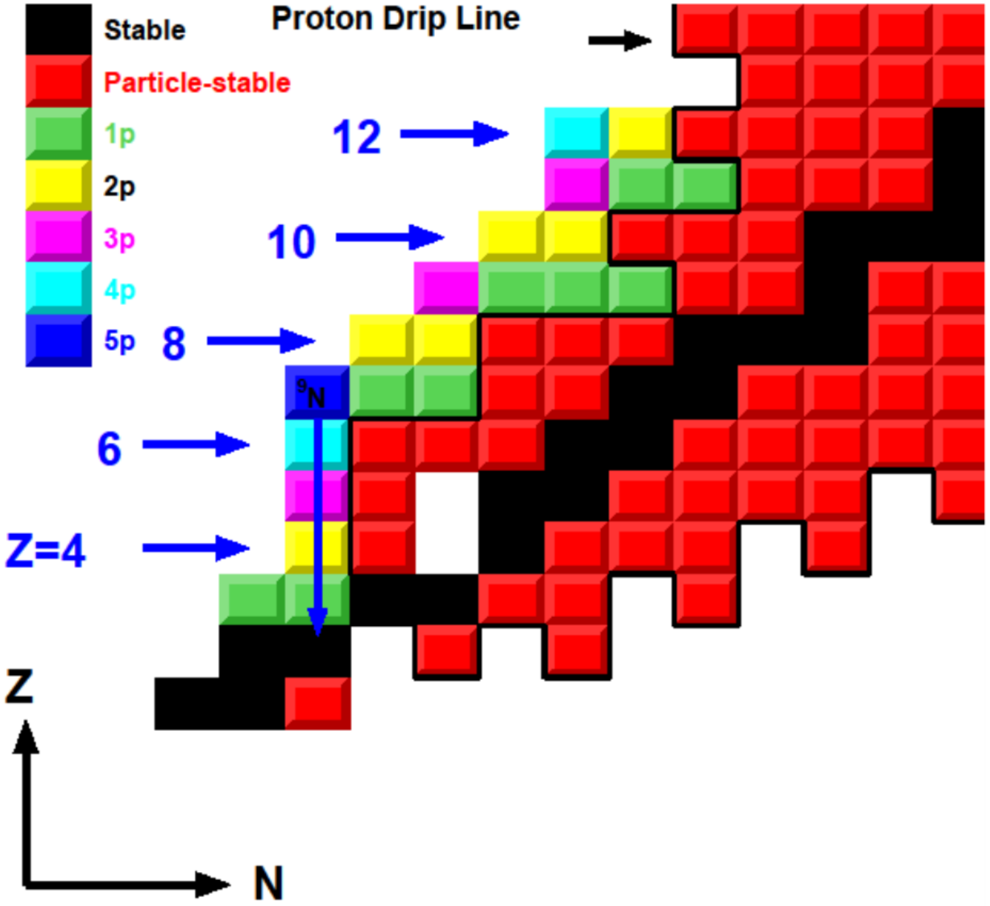
Decay scheme of ^{9}N states

Have we reached the edge yet?

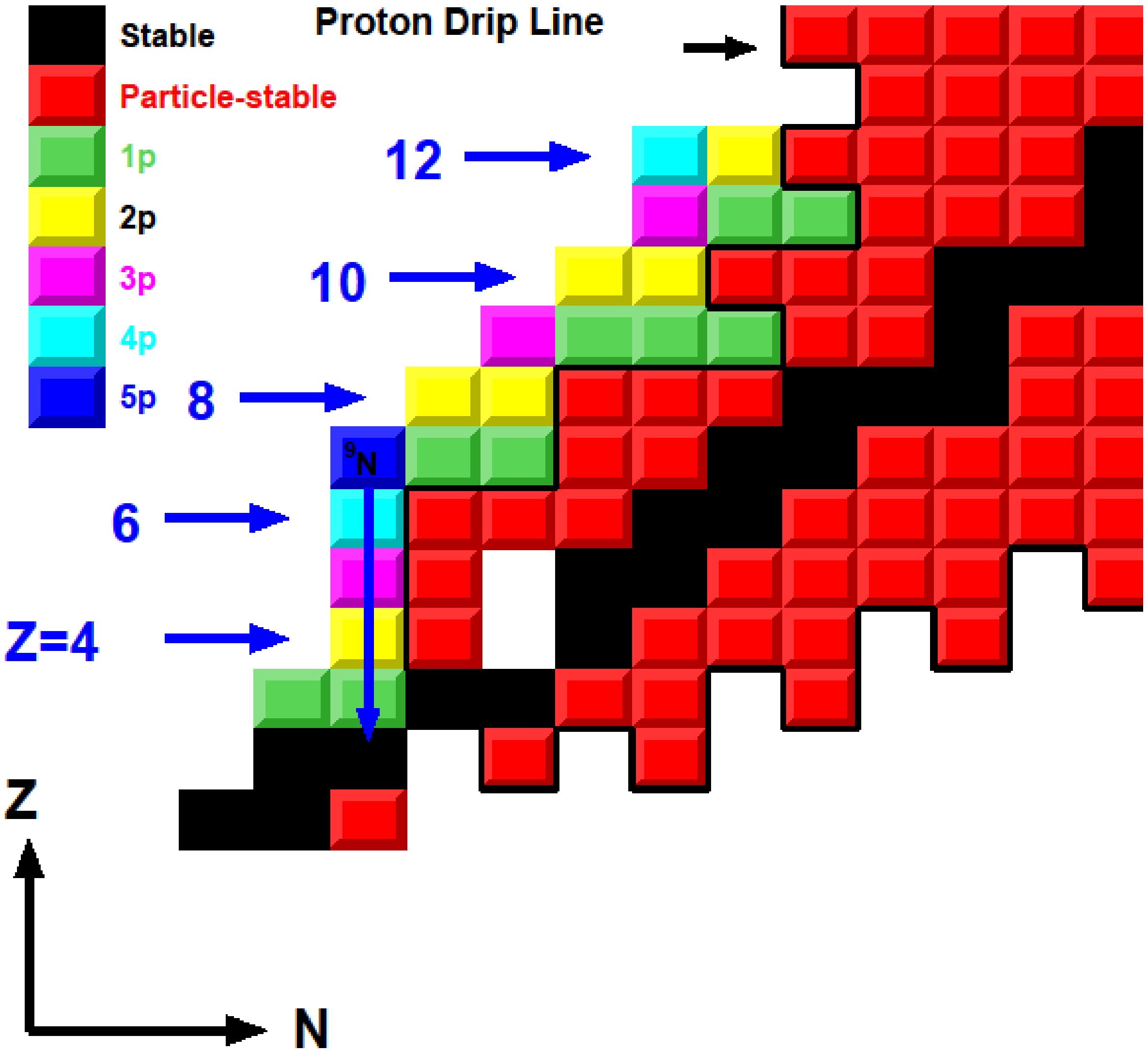
^{19}Mg Γ= 1x10^{-10} MeV (exp.)
^{18}Mg Γ=1.2x10^{-1} MeV (exp.)
Nine orders of magnitude change, extrapolating to ^{17}Mg would give us well over 10 MeV

^{16}Ne Γ = 0.8x10^{-3} MeV (prediction by Grigorenko et al.)
^{15}Ne Γ = 0.6 MeV (exp.)
Three orders of magnitude change

^{12}O Γ = 5x10^{-2} MeV (exp.)
^{11}O Γ = 1.3 MeV (exp + theory)
Two orders of magnitude change



Other 5*p* emitters, or even 6*p* emitters?



Summary

Exploration far beyond the proton drip line allows us to explore
the role of continuum in nuclear structure.

We have observed 3, 4, and 5-proton emitters at the extreme edge of Chart of Nuclides and more such emitters will be found in heavy isotopes.

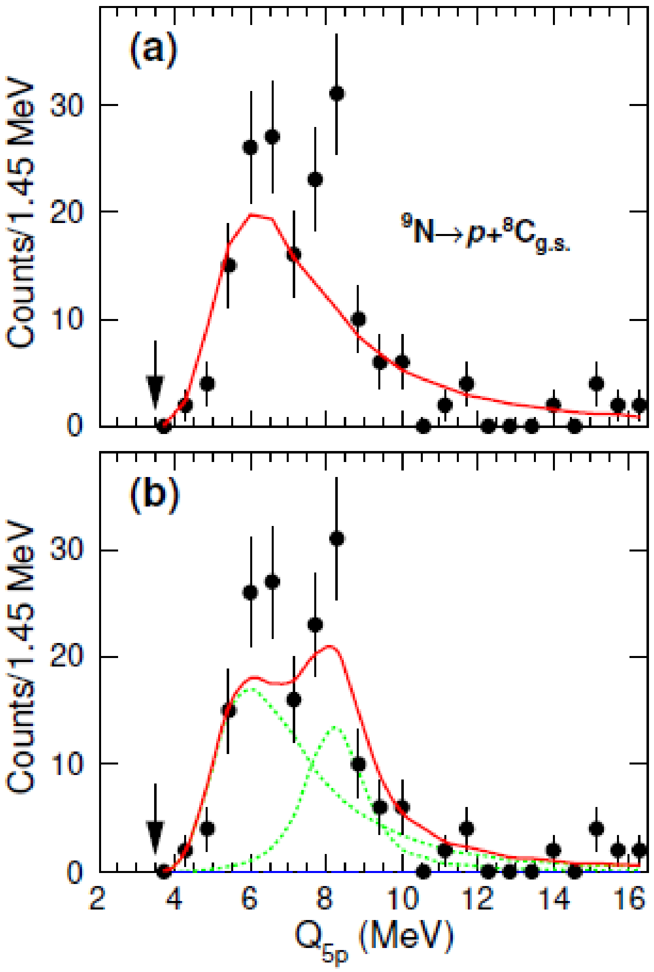
The extreme proton-rich edge of the chart of nuclides has been largely found in the region of light nuclei.

Collaborators
Washington University: Lee Sobotka
Kyle Brown (thesis)
Tyler Webb (thesis)
Dan Hoff
Cole Pruitt.

The Lynch/Tsang/Brown group at MSU
Simin Wang, Joshua Wylie, Witek Nazarewicz (Shanghai and FRIB)
Alan Wuosmaa group at U. of Connecticut

Peking University
Yu Jin (thesis), C.Y. Niu, Z. Li, H. Hua

Backup slides



Fits where ½$^+$ strength is from the Gamow Coupled Channels time-dependent calculations.