# Multiproton decay of resonances beyond the proton drip line


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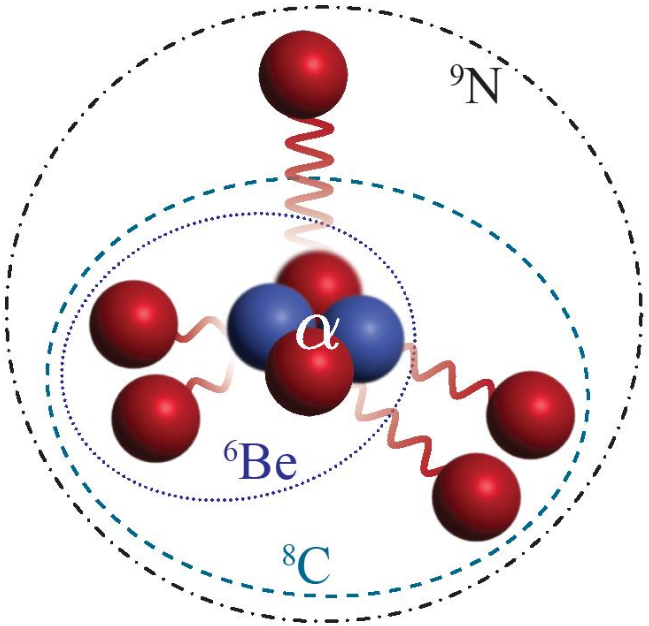
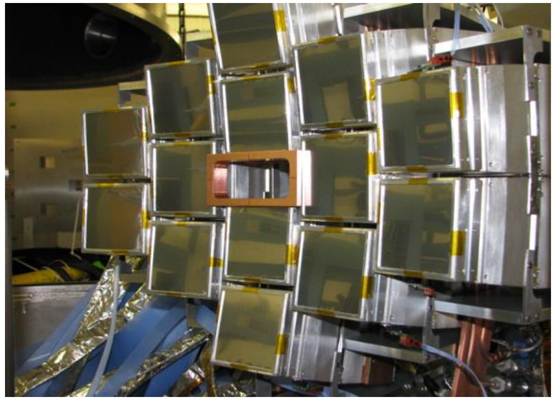


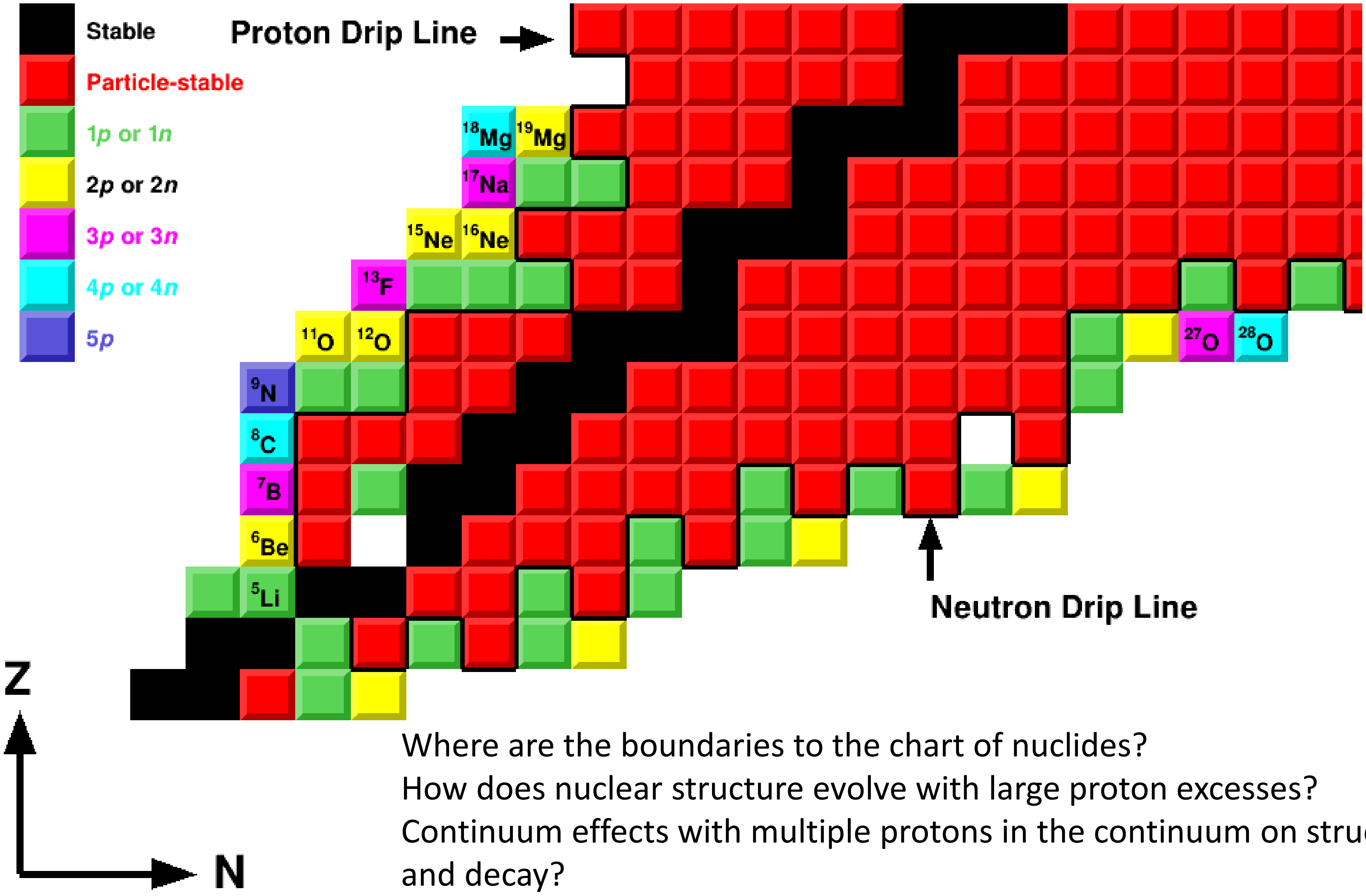


*HaloWeek'24 Gothenburg*



HiRA detector @ NSCL

Nuclei at the edge of existence well beyond the drip lines.




Where are the boundaries to the chart of nuclides?

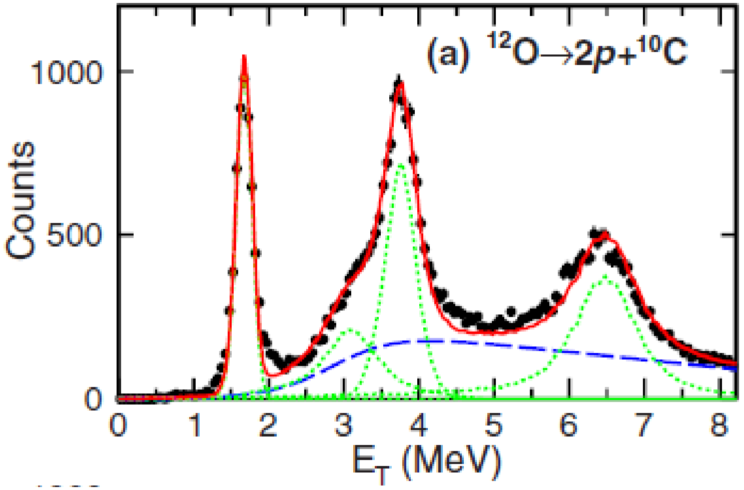
How does nuclear structure evolve with large proton excesses?

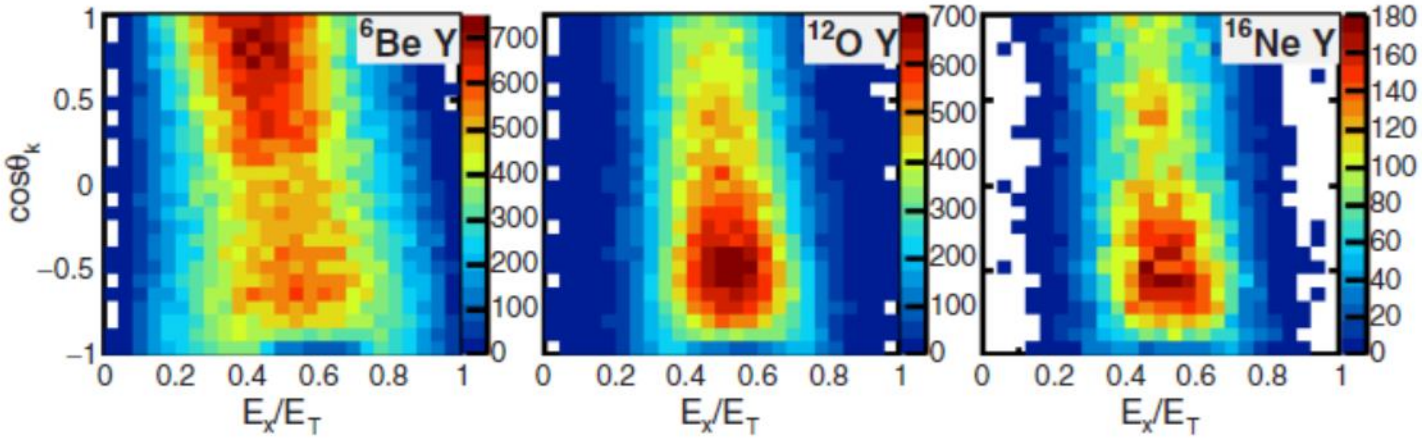
Continuum effects with multiple protons in the continuum on structure and decay?

A resonance like $^{9}$N can stress test nuclear-structure models that consider the continuum.

# Ground-state two-proton emitters

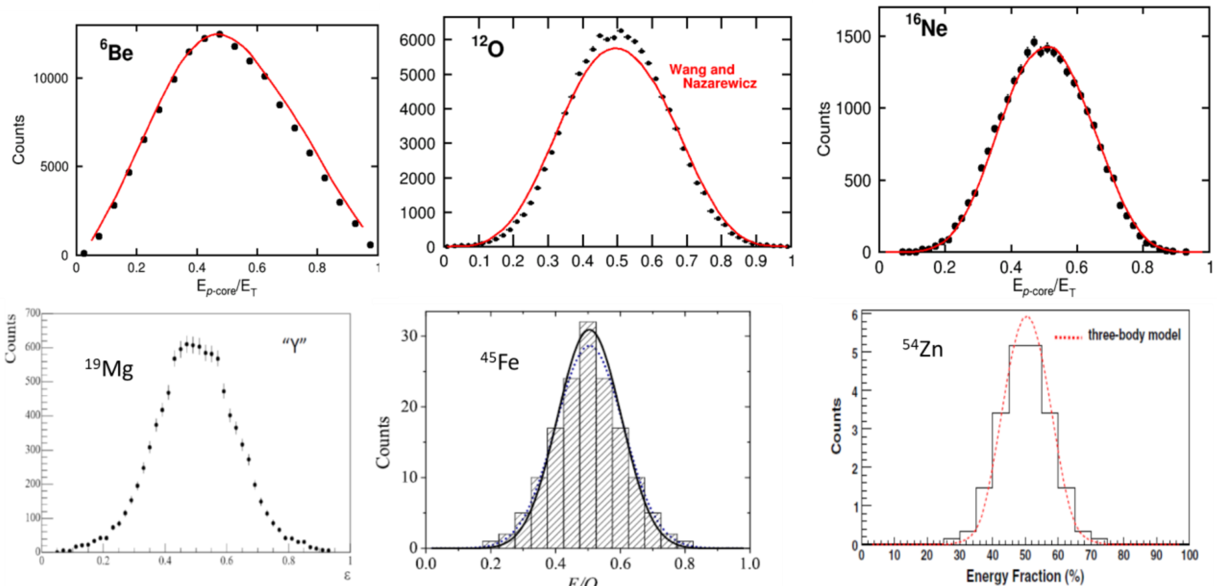
$^{6}$Be, $^{11,12}$O, $^{15,16}$Ne, $^{19}$Mg, $^{45}$Fe, $^{48}$Ni, $^{54}$Zn, $^{67}$Kr




Correlations in prompt emission of two protons

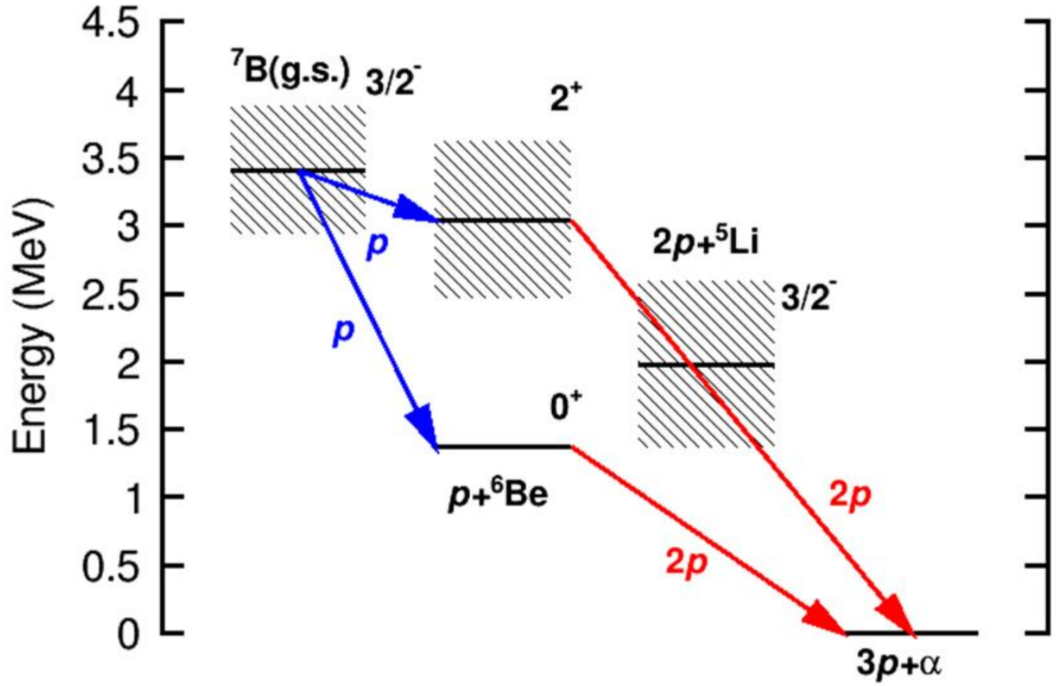
Webb et al, Phys Rev. C 100 (2019) 024306

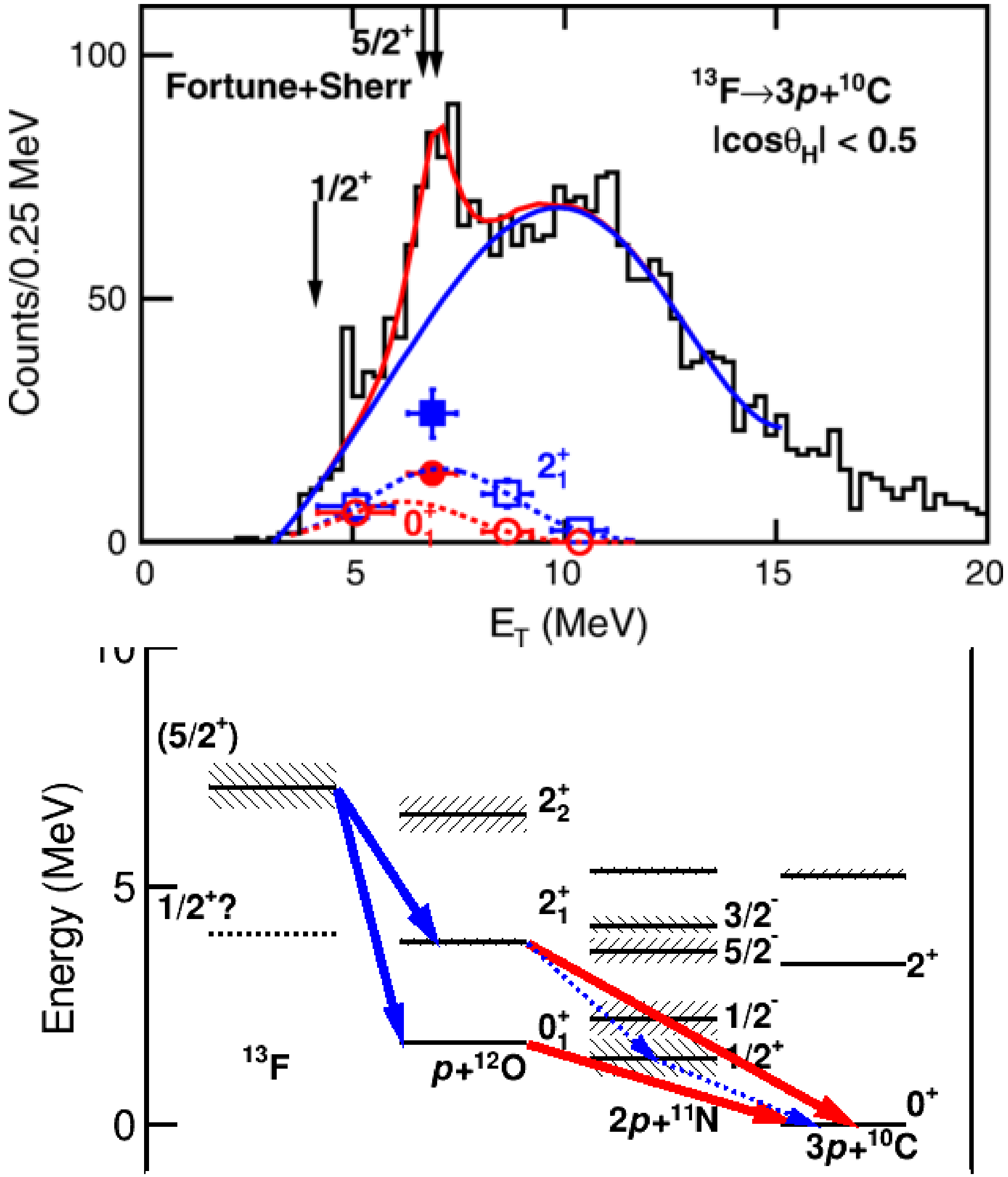



Two-protons like to have equal energies.

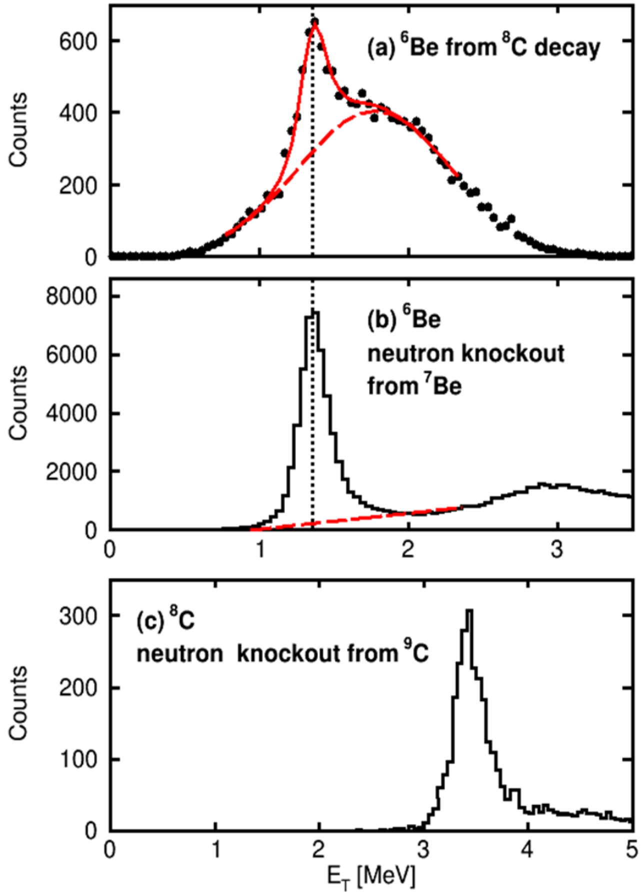
Charity et al , Phys. Rev. Lett. 126 (2021) 132501

# Three-proton emission $^{7}B$, $^{13}F$, $^{17}Na$, $^{31}K$




Three protons are emitted in steps –
First a single proton, then a pair of protons.




$^8$C lightest 4*p* emitter

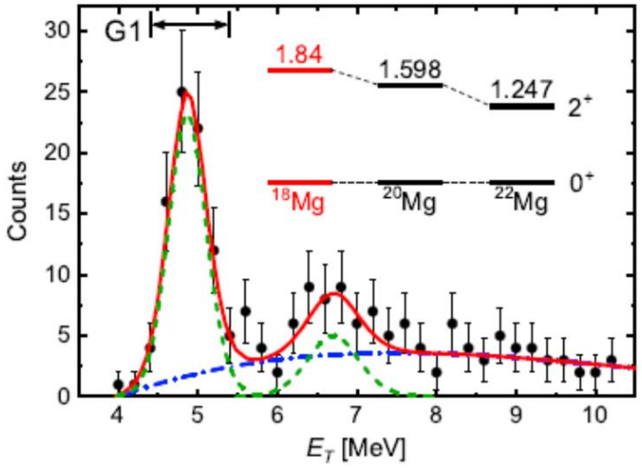
(neutron knockout from $^9$C)

92(5)% of events

2*p* decay to

the ground state of $^6$Be.

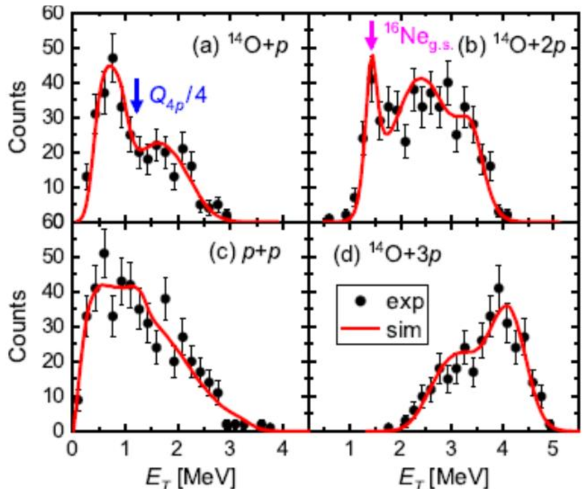
Charity et al. PRC 82, (2010) 041304(R)

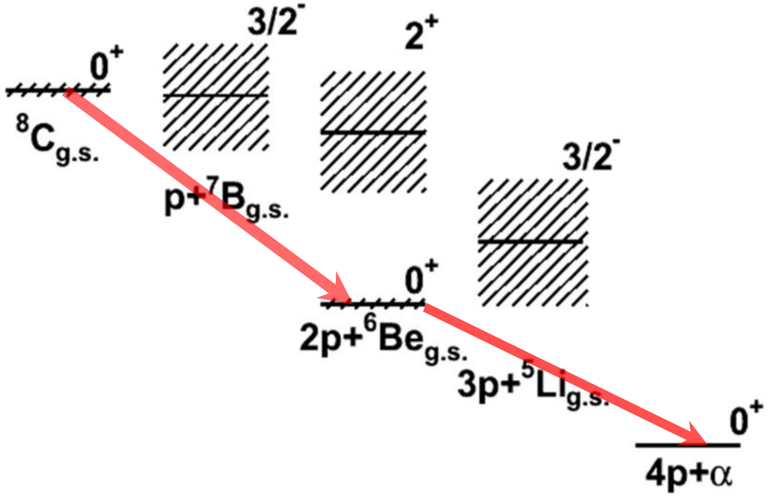



ansatz

Even Z: prompt 2p decay to next lowest even Z

Odd Z: single proton decay to next lowest even Z

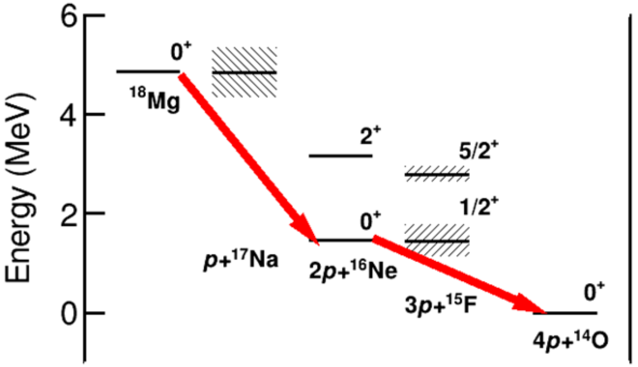



$^{18}$Mg->4*p*+$^{14}$O

( two-neutron knout from $^{20}$Mg)

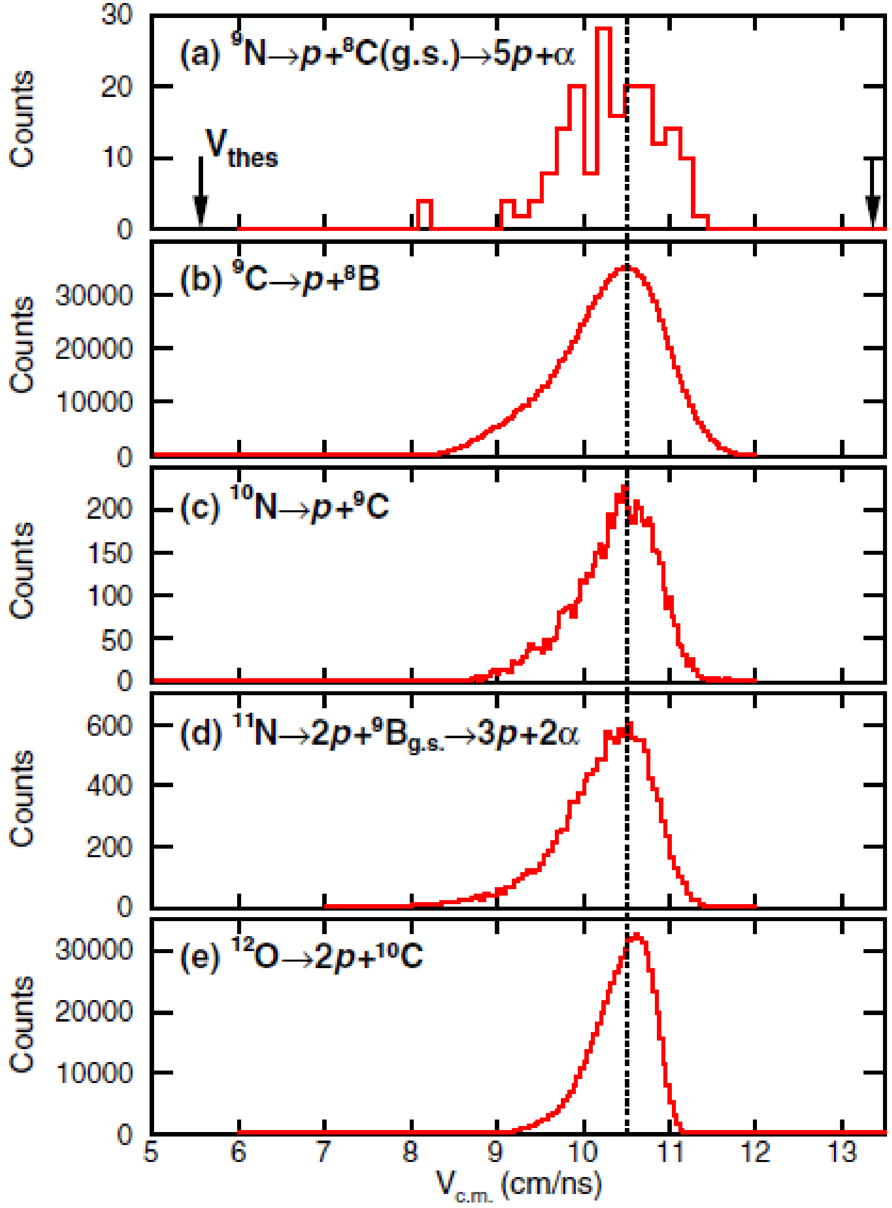
Jin et all, Phys. Rev. Lett. 127, 262502

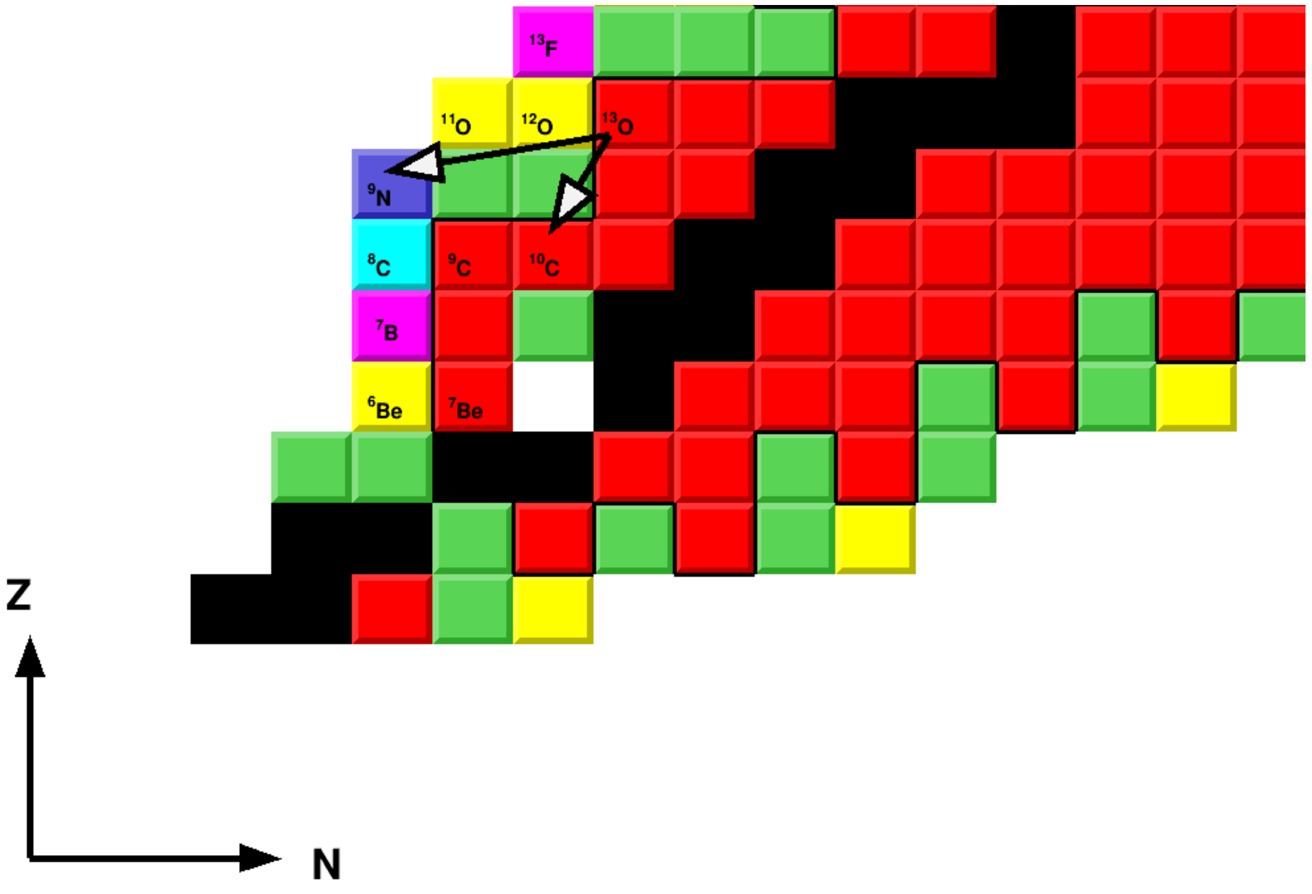


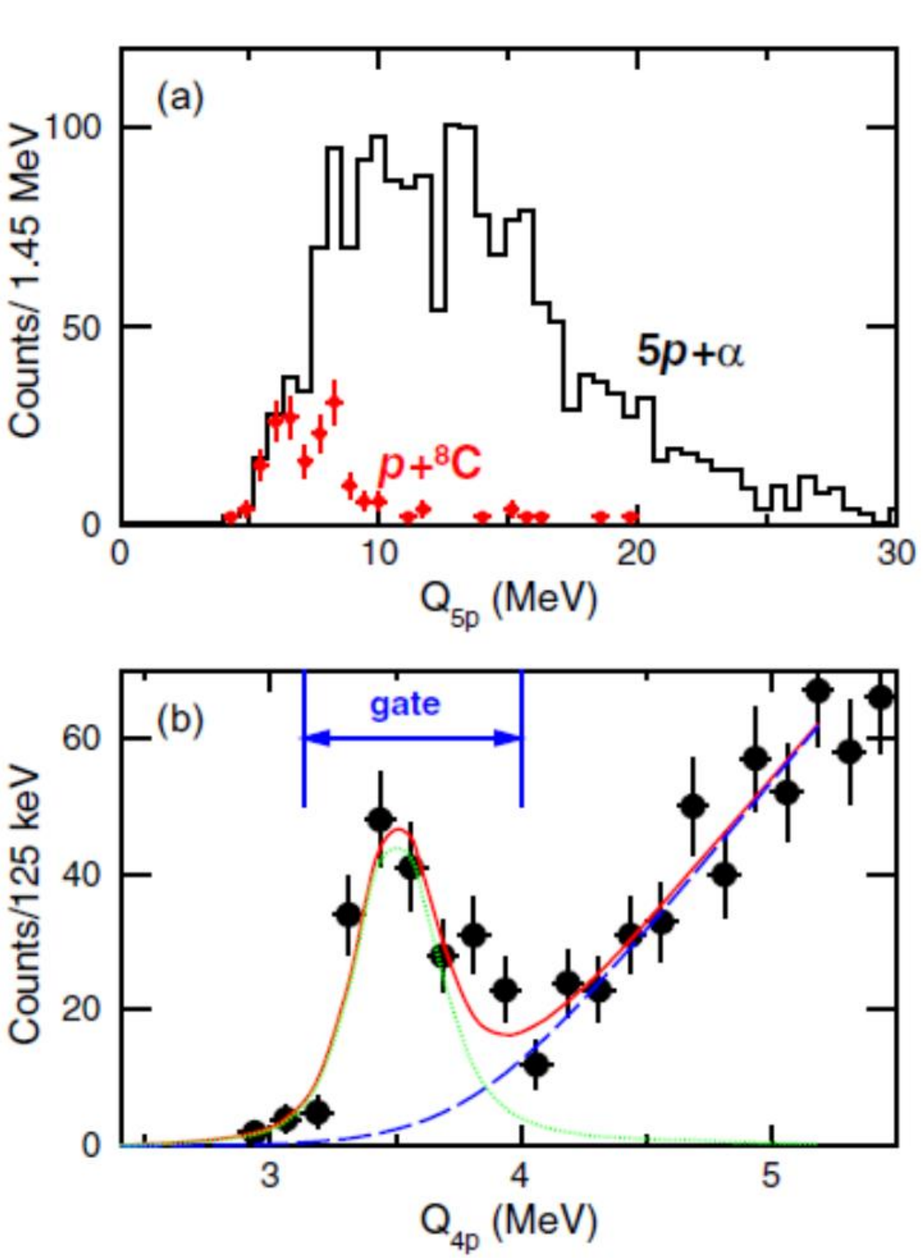
How to make $^{9}$N?

Projectile fragmentation from $^{13}$O beam (E/A = 65 MeV)

Be target



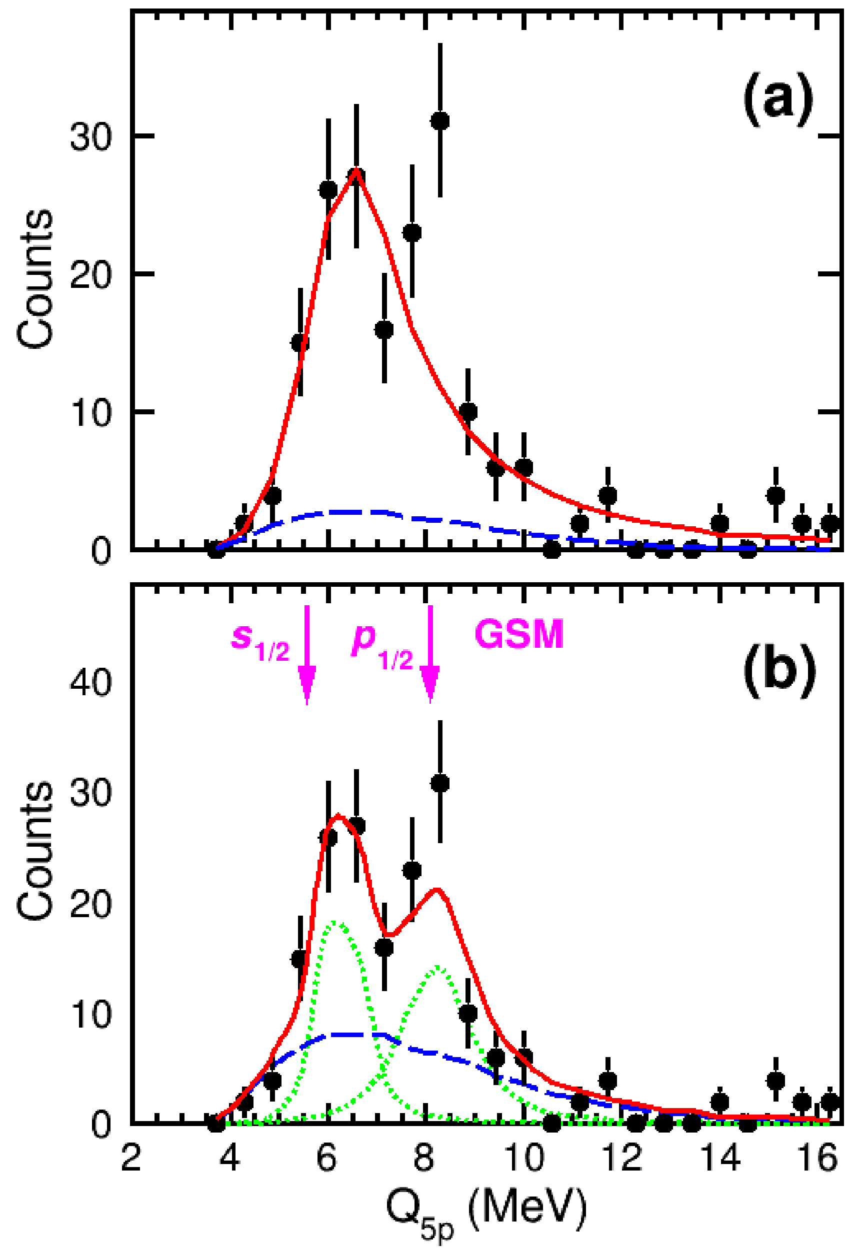



Charity et al, PRL 131 (2013) 172501

70 MeV/A $^{13}$O beam
Formation of $^{9}$N requires the removal of 1 proton and 3 neutrons from the projectile. These removed nucleons maybe free, or in bound in light clusters, or …

5$p$+$\alpha$ invariant-mass distribution is quite broad and no clear peaks with $\Gamma$ < 3.5 MeV

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




Can fit the invariant-mass spectrum as a singlet or doublet

Singlet: $\Gamma$~ 2.3 MeV ( less than 3.5 MeV)

Doublet: Consistent with predictions of the Gamow Shell model (Wiley, Wang, Nazarewicz)

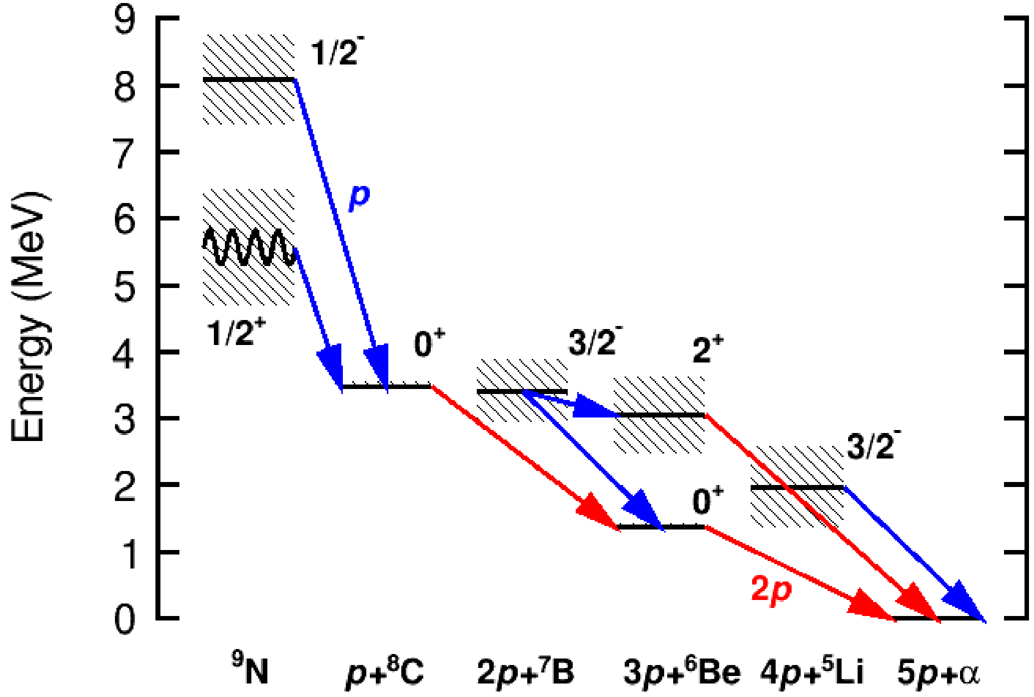
Ground state: $½^+$ $\Gamma$ = 1.74 MeV
First Exited: $½^-$ $\Gamma$ = 1.35 MeV

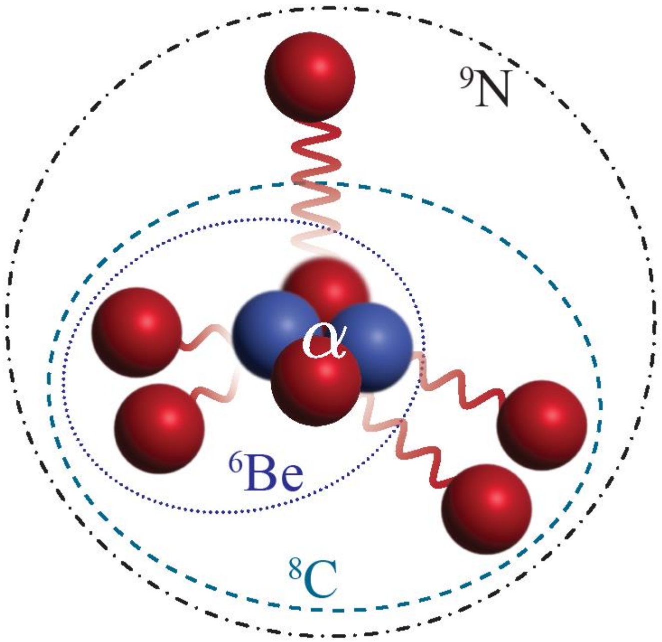
Based on of projectile fragmentation reactions, the fitted magnitude of the background is more reasonable for the doublet fits.

Need more statistics to differentiate between singlet or doublet, and for the latter to constrain the widths of the two resonances.
We cannot rule out that the lower peak is a subthreshold resonance. i.e. final-state interaction.

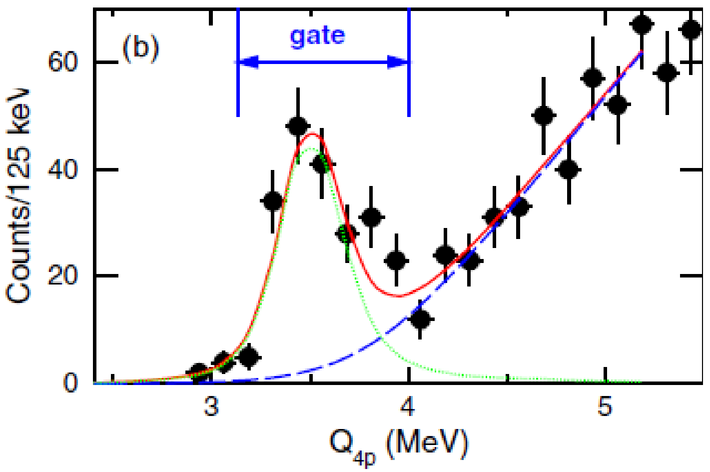
Charity et al, PRL 131 (2013) 172501

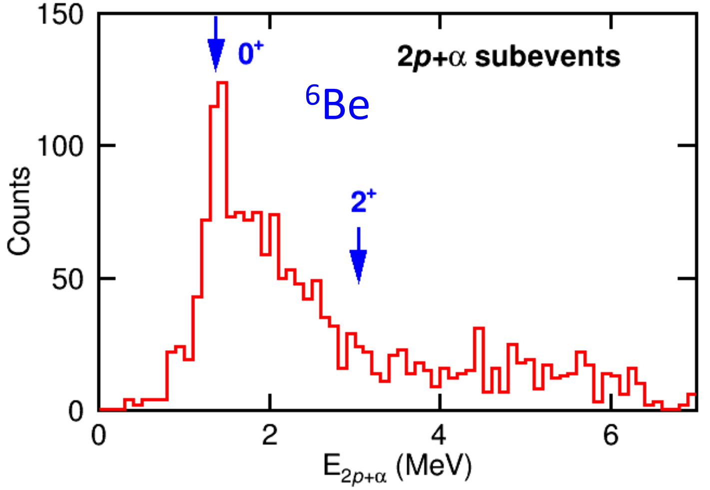
Decay schemes of the
N=2 isotopes



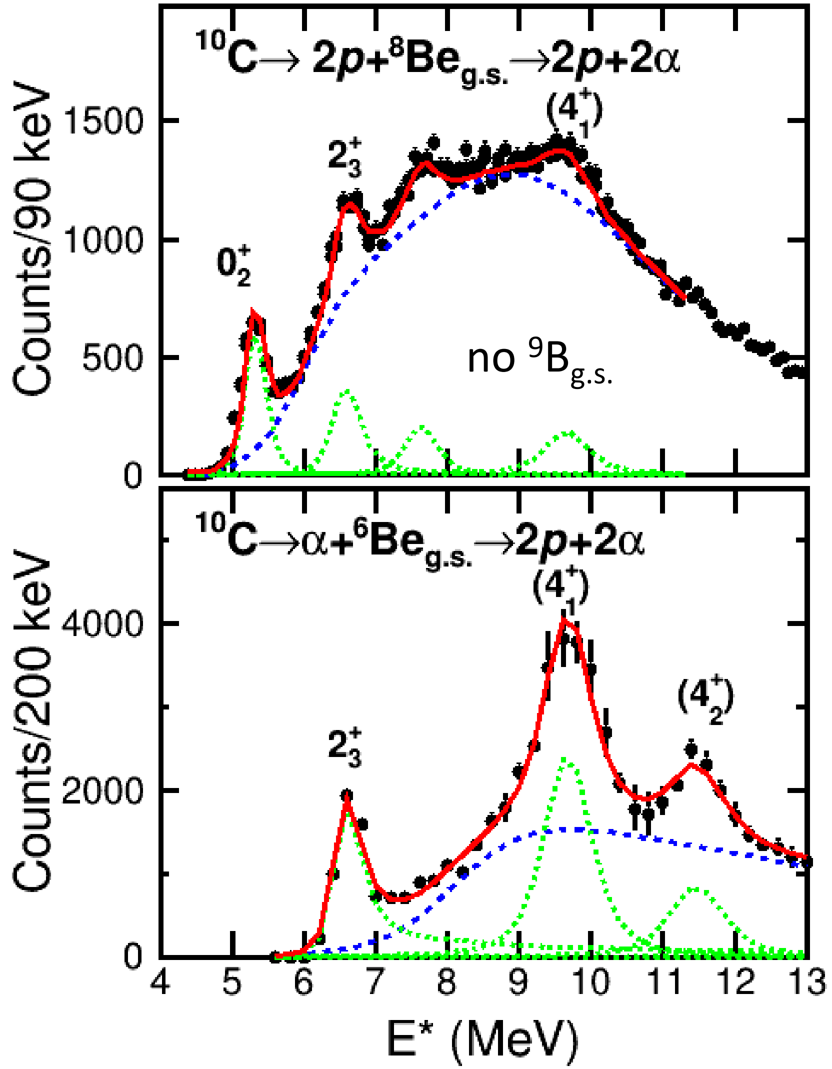

4p+α subevents



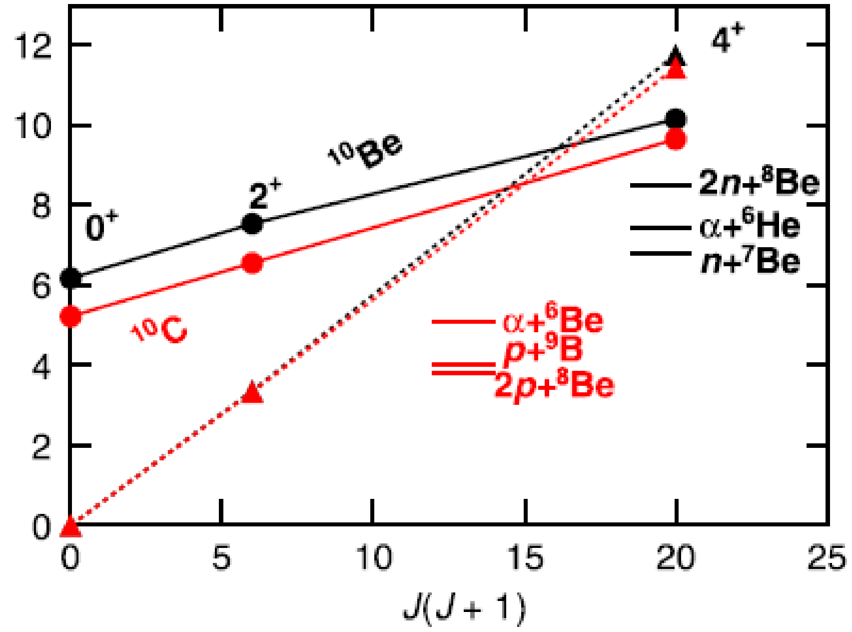
**Intruder states and prompt 2*p* emission** $^{10}C$ found with of $^{9}C$,$^{10}C$,$^{13}O$,$^{15}O$/$^{17}Ne$ beams

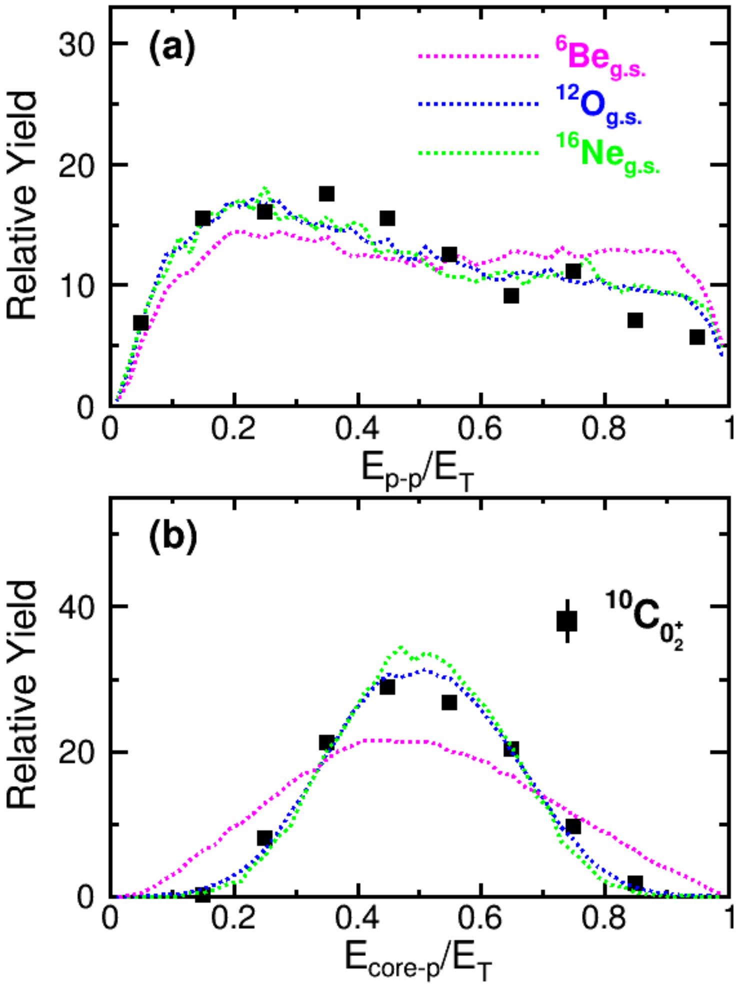
$Q_{2p}$ = 1.37 to 1.72 MeV




$^{13}O$ beam data

Thomas Ehrman shift = 0.892(15) MeV

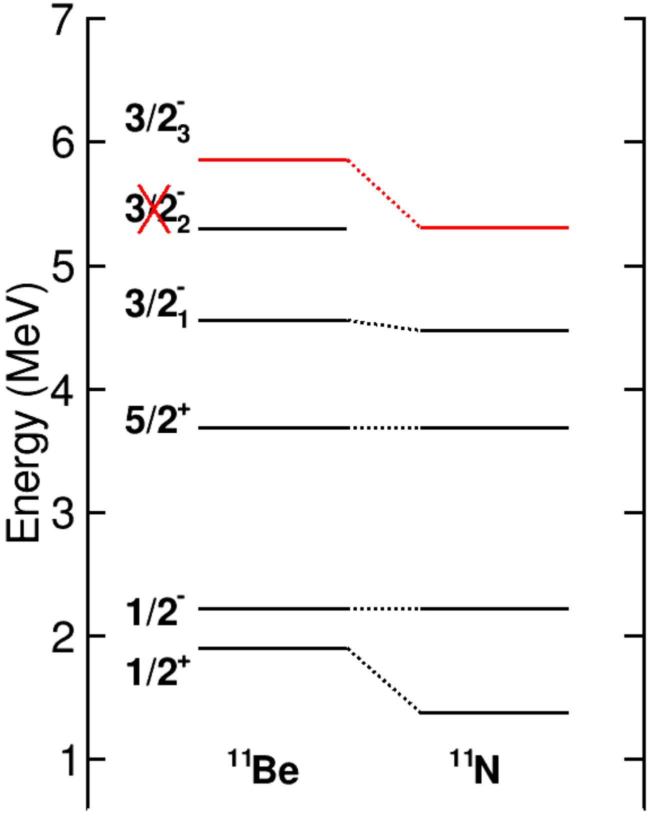


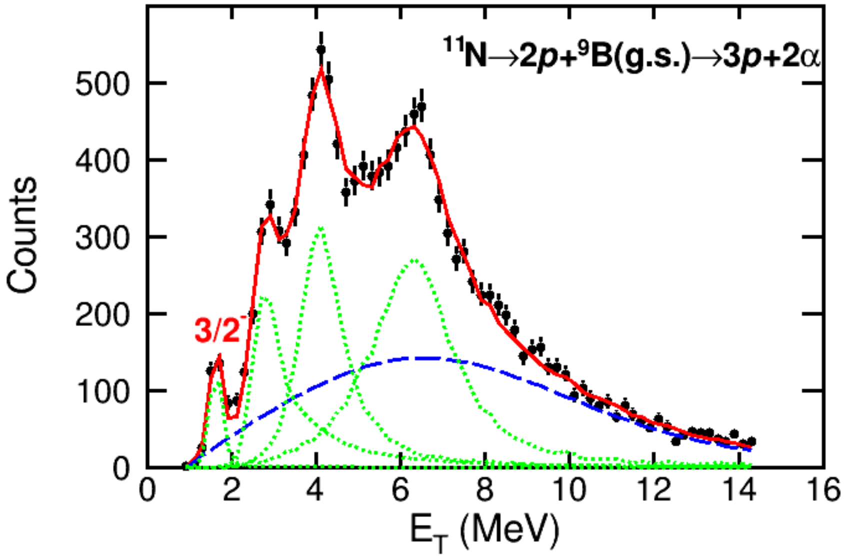



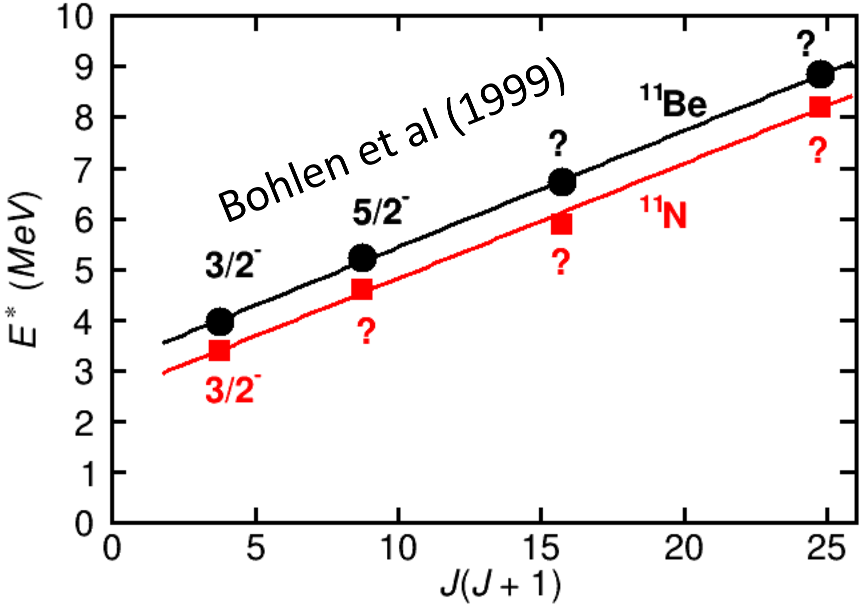

Correlations match up with $^{12}O$ and $^{16}Ne$ ground state 2*p* decay where the two protons are largely $(s_{1/2})^2$

Prompt $2p$ emission from intruder states in $^{11}N$ ($^{13}O$ beam)

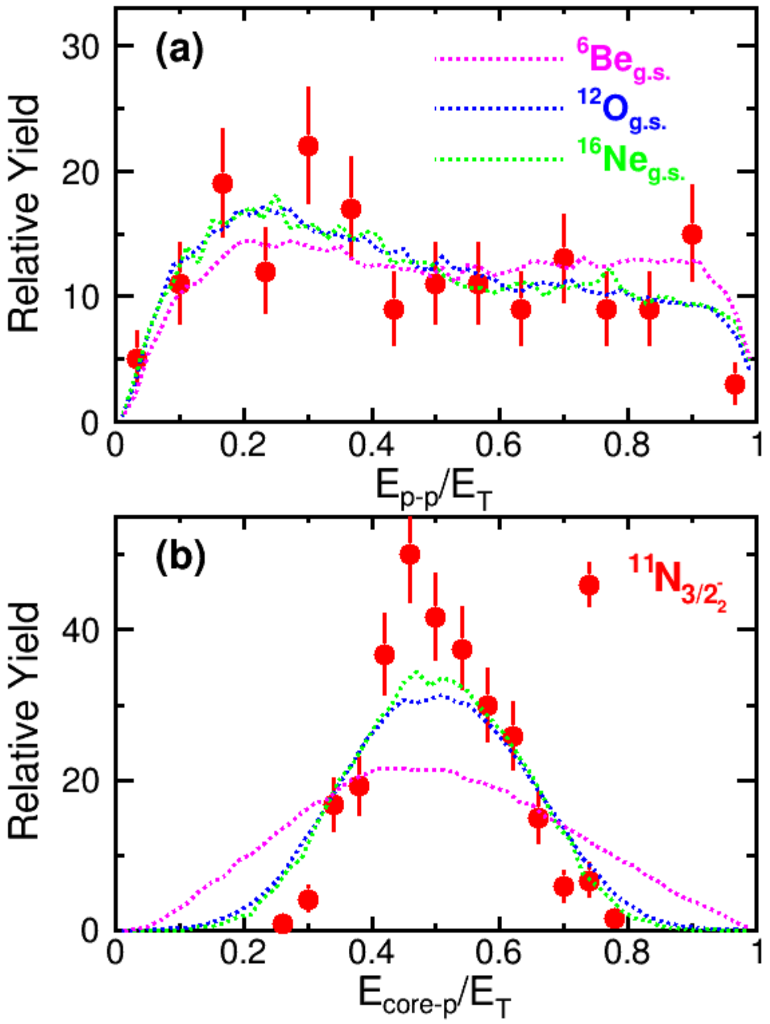
Thomas-Ehrman shift = 0.542(12) MeV




$Q_{2p}$ = 1.37 to 1.72 MeV



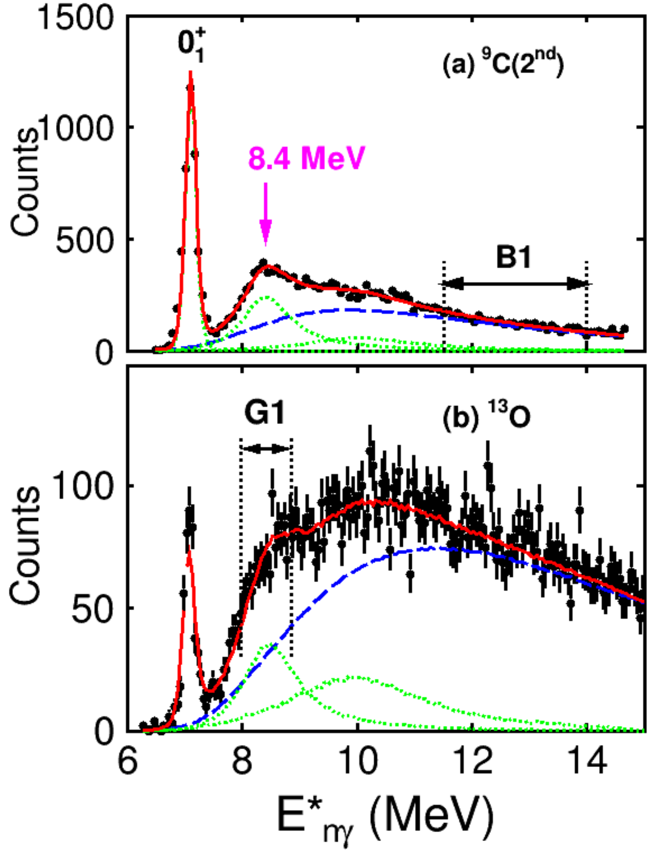
Prompt $2p$ emission in $^{8}$B

$^{8}B^{*} \to 2p + {}^{6}Li_{g.s.}$ or $^{8}B \to 2p + {}^{6}Li_{0+} \to 2p + {}^{6}Li + \gamma$

$Q_{2p}$ ($^{12}$O-$^{6}$Be(g.s.)) = 1.37-1.72 MeV

$Q_{2p}$ ($^{8}$B[8.4 MeV]) = 2.64 MeV

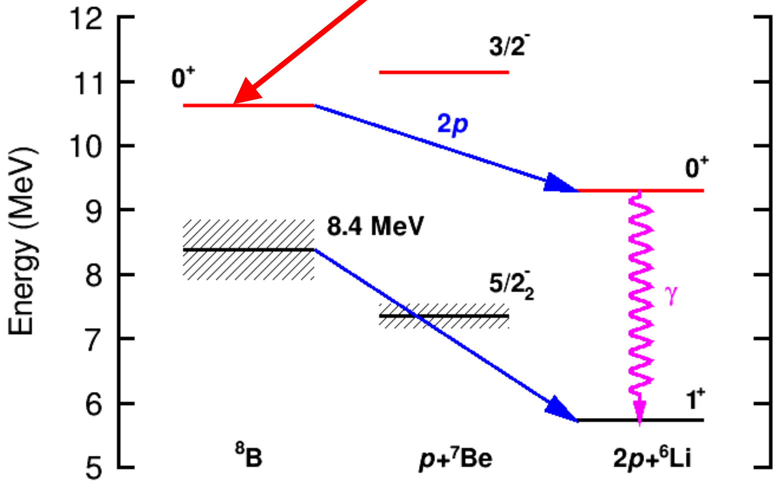
$Q_{2p}$[$^{6}$Be(2$^{+}$)] = 3.04 MeV

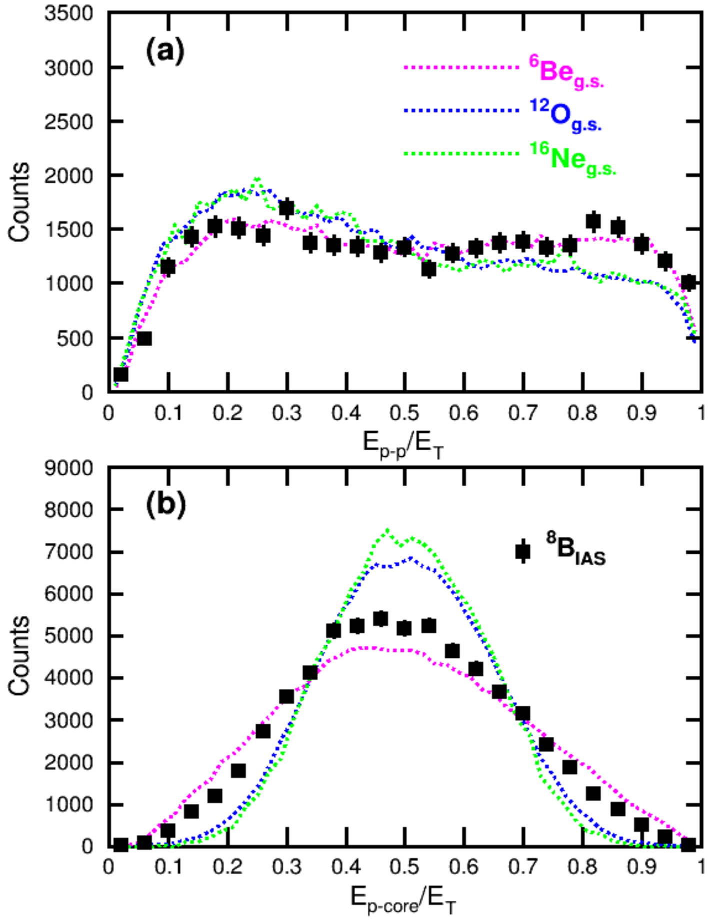


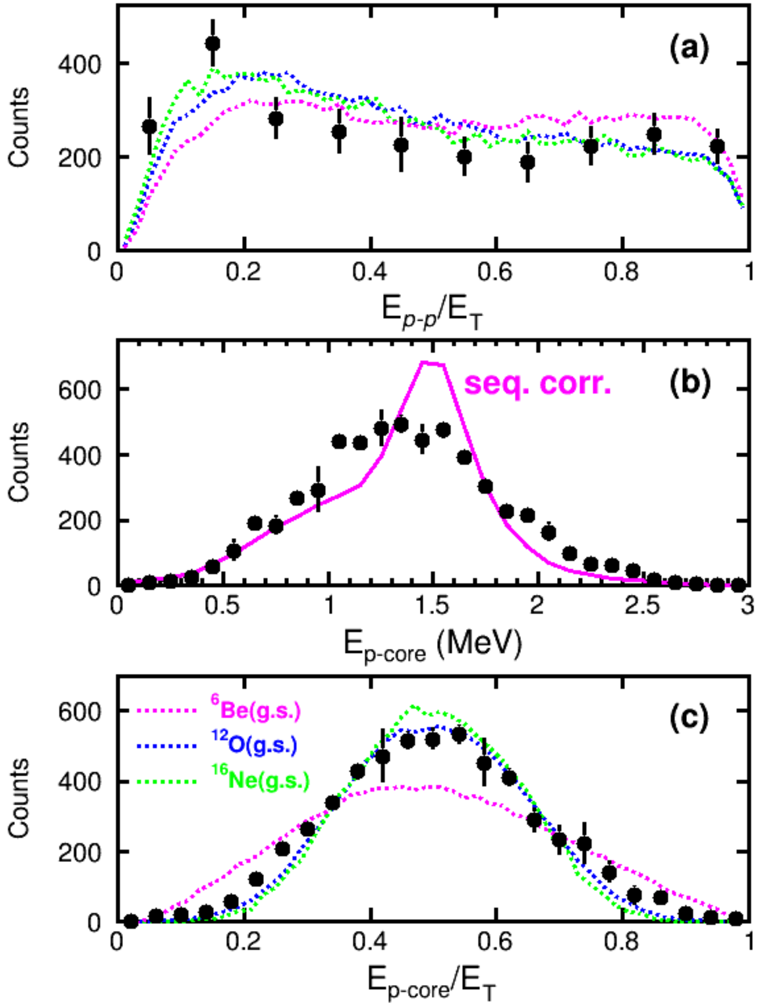

0$^{+}$ isobaric analog state.
Correlations very similar
to $^{6}$Be(g.s) with $(p_{3/2})^2$ structure
inside of the barrier

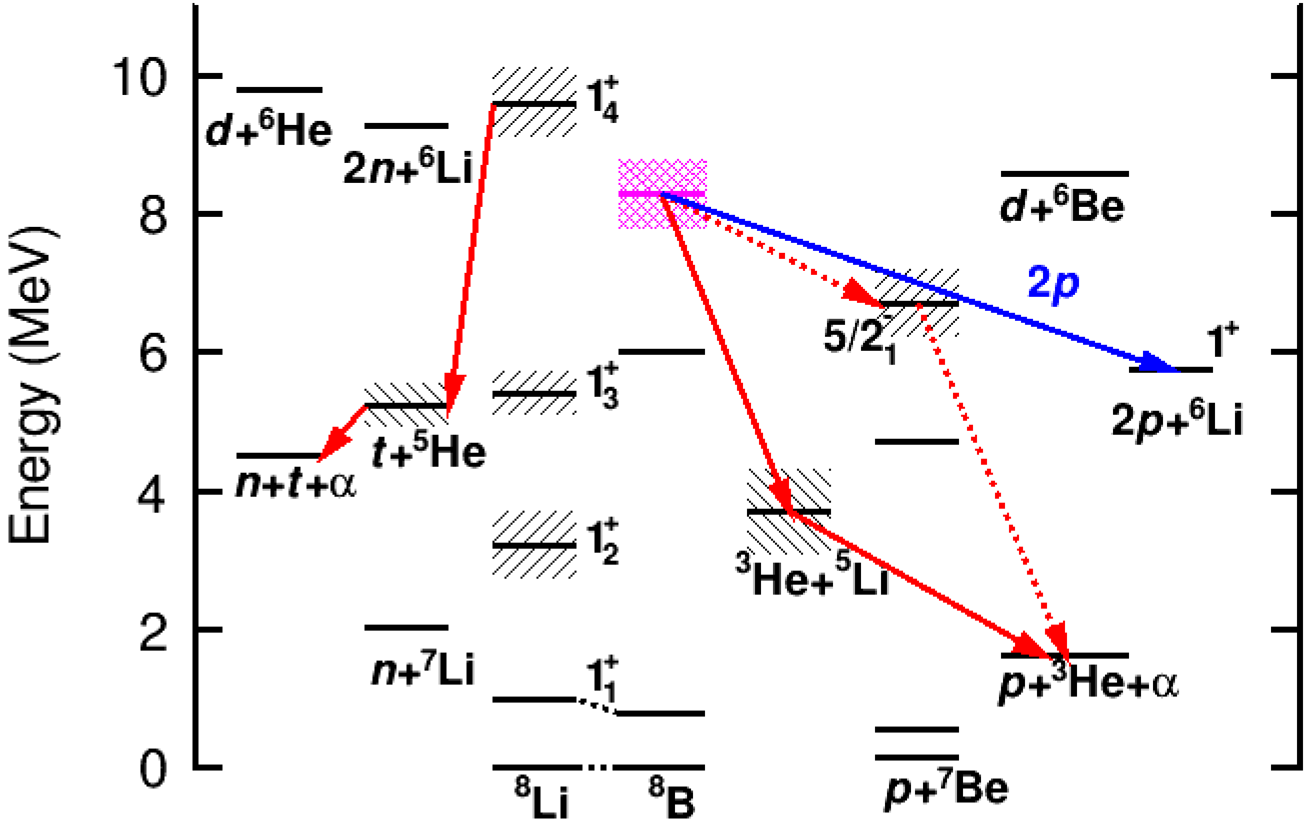
8.4-MeV state
Like $^{12}$O/$^{16}$Ne with $(s_{1/2})^2$ emission

Isobaric analog of $^{8}$C






If this new $2p$ emitter is a $1^+$ state?
Do we have a candidate for the mirror $1^+$ in $^8$Li?

The more likely would be the $4^{th}$ $1^+$ state in $^8$Li observed in the β-delayed triton emission of $^8$He. This was described as a super-allowed Gamow-Teller transition. Implying a strong overlap with the $^8$He wavefunction.

1) Both $^8$B and $^8$Li states have mirror cluster decay modes. $^3$He+$^5$Li and $^3$H+$^5$He
2) Both states are near their respective deuteron thresholds.
3) There is no phase-space for a $2n$ decay of the $^8$Li state.
4) The Thomas-Ehrman shift would be sizeable. ~1-1.6 MeV similar to that for the $0^+_2$ state in $^{10}$C-$^{10}$Be. Significant $s_{1/2}$ strength? What does this mean for $^8$He?
5) If the new $^8$B state is not $1^+$, there are no other known candidates for the mirror at this energy.

# SUMMARY

a) Multi-nucleon emissions beyond the drip lines proceed via sequential steps of single and two nucleon emissions.

b) Observation of the first ground-state five-proton emitter $^{9}N$

c) Prompt 2p decay of intruder states in $^{8}B$,$^{10}C$,$^{11}N$

PHYSICAL REVIEW LETTERS



## Strong Evidence for $^{9}N$ and the Limits of Existence of Atomic Nuclei

R. J. Charity, J. Wylie, S. M. Wang, T. B. Webb, K. W. Brown, G. Cerizza, Z. Chajecki, J. M. Elson, J. Estee, D. E. M. Hoff, S. A. Kuvin, W. G. Lynch, J. Manfredi, N. Michel, D. G. McNeel, P. Morfouace, W. Nazarewicz, C. D. Pruitt, C. Santamaria, S. Sweany, J. Smith, L. G. Sobotka, M. B. Tsang, and A. H. Wuosmaa

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