Overview of recent correlation experiments at the proton drip line

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Correlations studies at the proton drip line

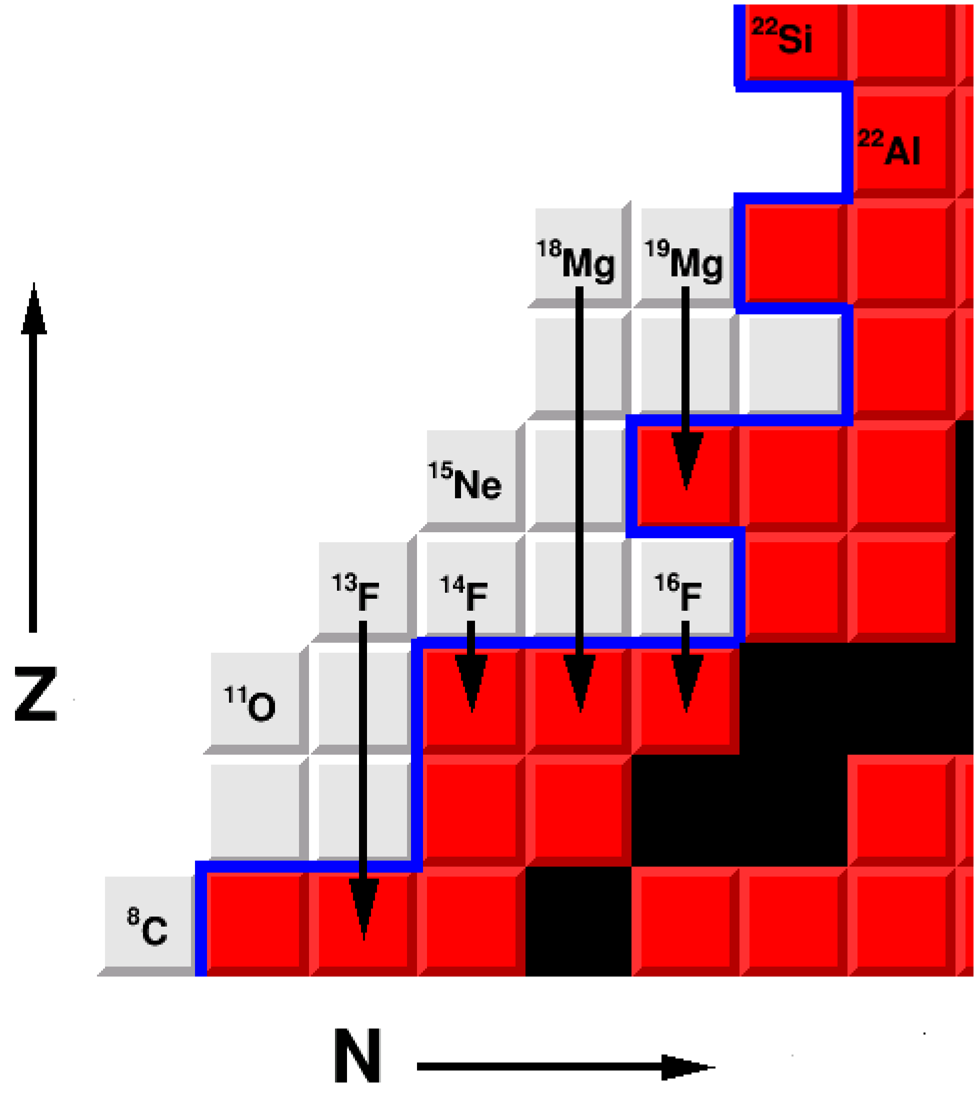
1) Differentiate prompt and sequential 2p decay.
2) Do they provide nuclear structure information?
3) Find decay path by finding intermediate states in 2p, 3p, 4p decays
4) Used to isolated rare decay modes.

Ground-state 2p decay ^{6}Be, ^{11,12}O, ^{15,16}Ne ^{19}Mg, ^{45}Ca, ^{48}Ni, ^{54}Zr, ^{67}Kr (even Z)

Ground-state 3p decay ^{13}F, ^{17}Na, ^{31}K (odd Z)

Ground-state 4p decay ^{8}C, ^{18}Mg (even Z)

And of course with more excitation, more protons can be emitted.



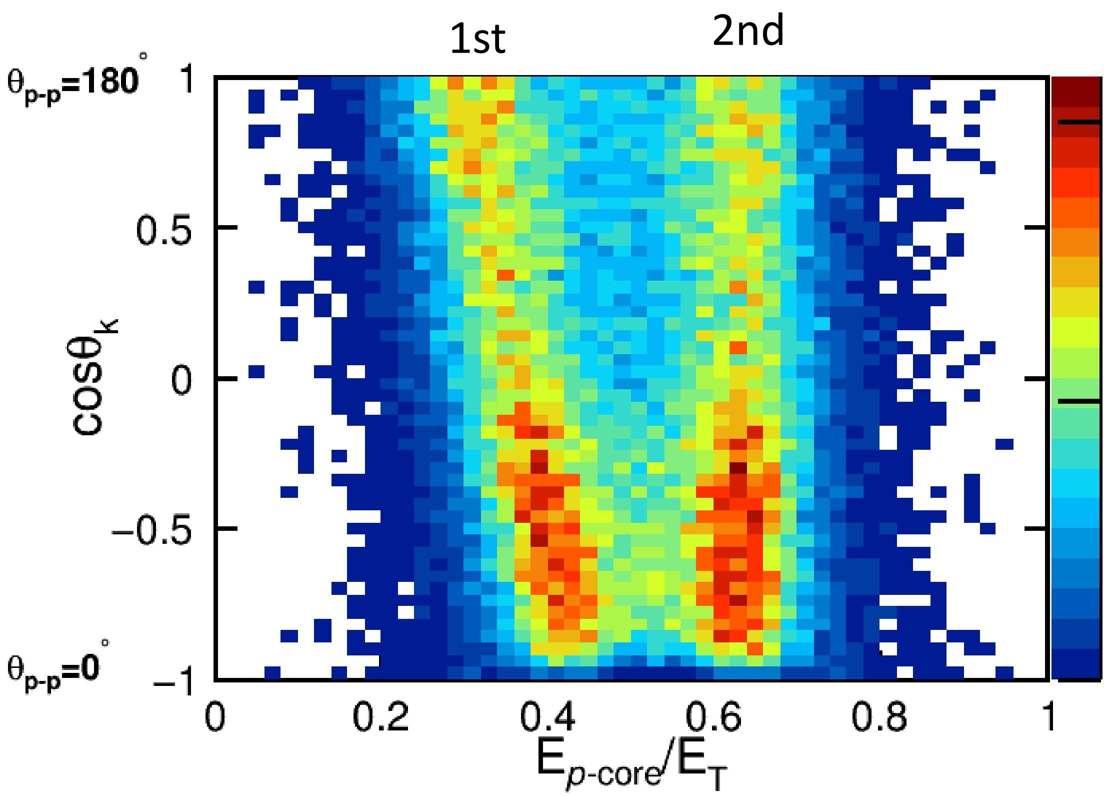
Momentum correlations in 3-body decay

With three momentum vectors = 9 degrees of freedom,
But with fixed decay energy and conservation of momentum - lose 4 of these
Also any arbitrary rotation of the three vectors are equivalent - lose 3 more associated the 3 Euler angles.

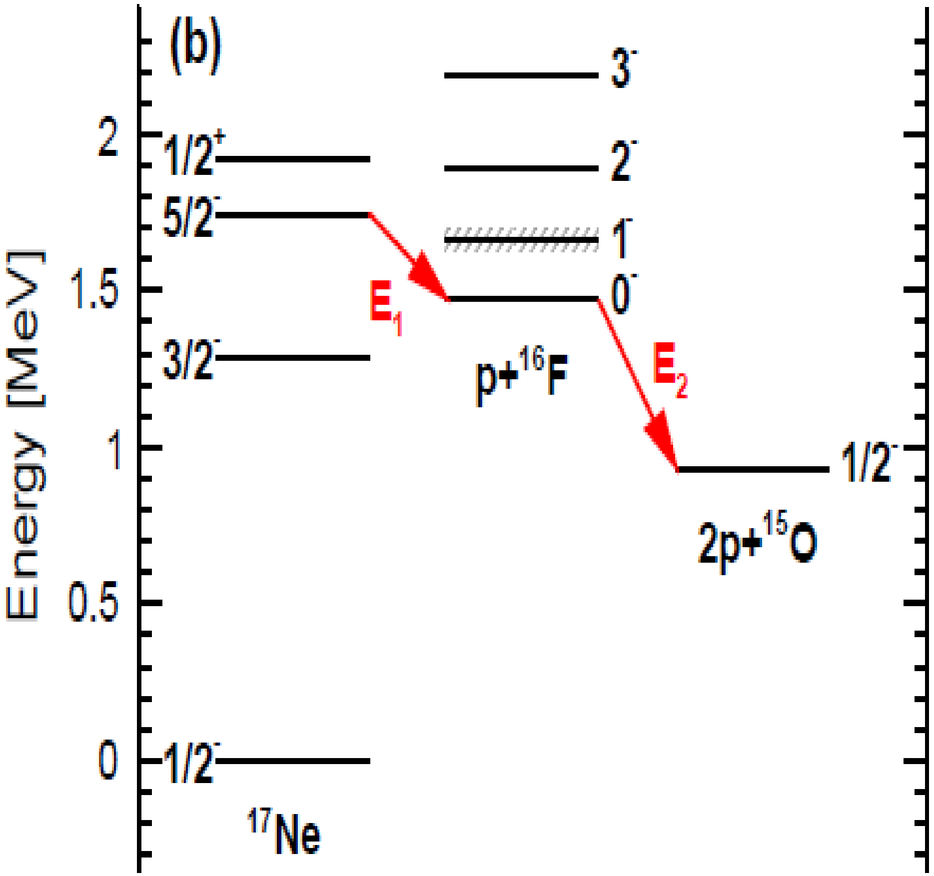
This leaves us with 2 degrees of freedom remaining.
The correlations can thus be described by a 2 dimensional distribution.

Two equivalent distributions are often used based on the Jacobi T and Jacobi Y coordinates. Another alternative are distributions based on Dalitz plots

4-body decay –> 5-dimensional distribution



Jacobi Y



Charity et al PRC 97 (2018) 054318

Jacobi Y correlation for sequential 2p decay of the $5/2^-$ state in ^{17}Ne.

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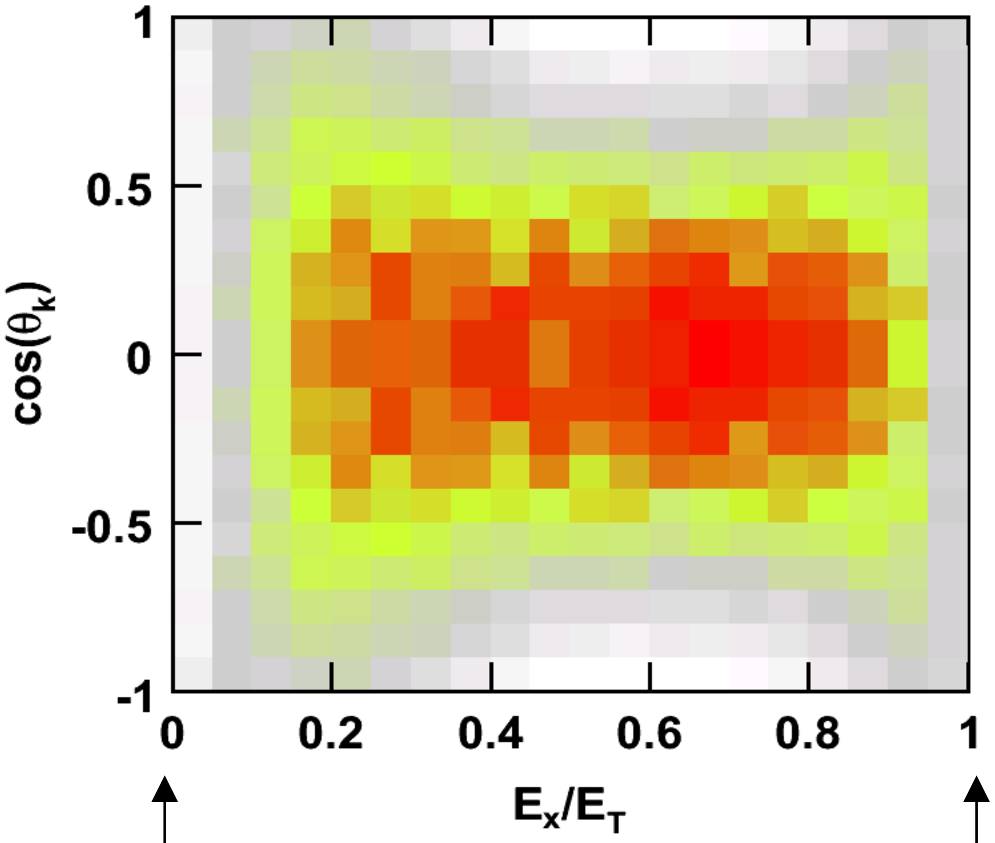
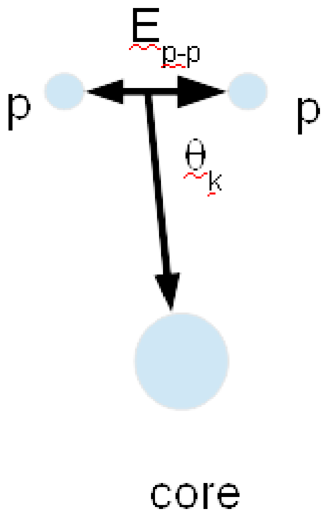
Jacobi T

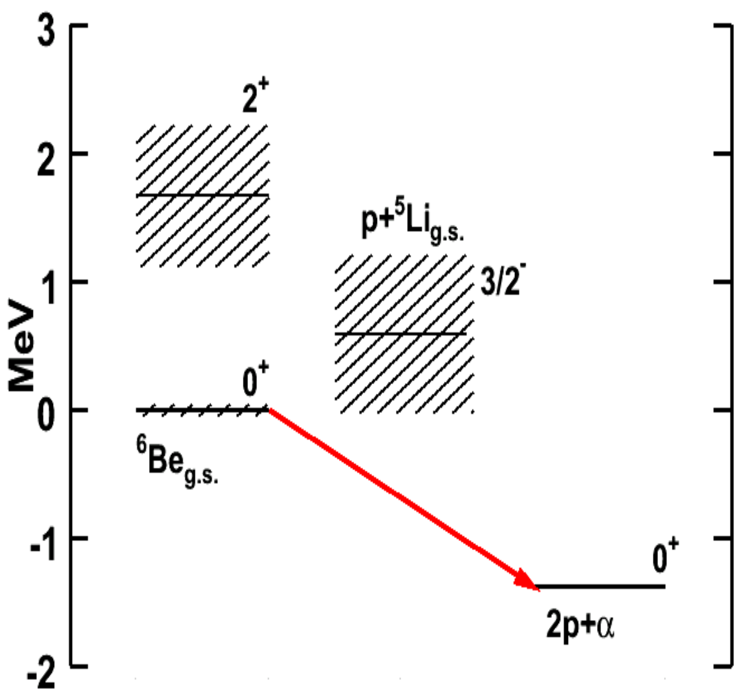


diproton

E_{pp}/E_T

Cigar (back-to-back)





Latest ground-state 2*p* correlations studies

	Nucleus	events	
	^{6}Be	64000	Egorova *et al.* PRL **109**, 202502 (2012)
	^{12}O	47000	Webb *et al.* PRC **100**, 024306 (2019)
E-ΔE arrays	^{16}Ne	32000	Brown *et al.* PRL **113**, 232501 (2014)
	^{19}Mg	5000	Jin *et al.,* unpublished (talk on Day 3)
	^{45}Fe	75	Miernik *et al.,* PRL **99**, 192501 (2007)
TPC's	^{48}Ni	4	Pomorski *et al.,* PRC **90** 014311 (2014)
	^{54}Zn	7	Ascher *et al.,* PRL **107** 102502 (2011)

For low statistics is best to compare the projections on the energy axes

Theoretical predictions of correlations – must propagate the protons out to very large distances due to the infinite range of the 3-body Coulomb force.

1) Three–body Model of Grigorenko et al

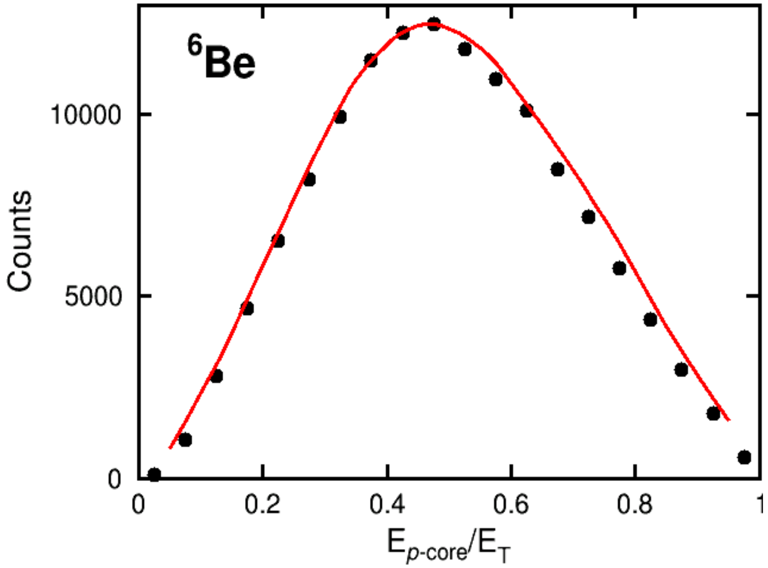
Applied to ^{6}Be, ^{16}Ne, ^{19}Mg, ^{45}Fe, ^{54}Zr ground states and some excited states

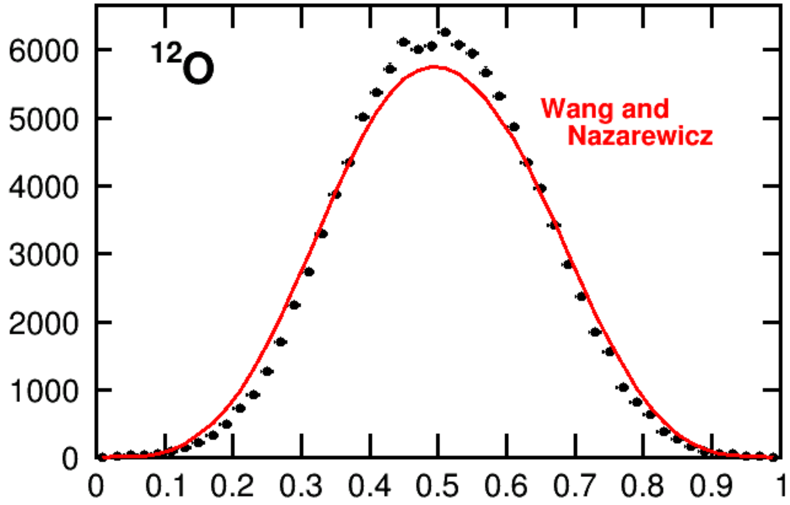
Egorova et al PRL 109 (2012) 202502
Brown et al PRL 113 (2014) 232501
Brown et al PRC 92 (2015) 034329
Miernik et al PRL 99 (2007) 192501
Ascher et al PRL 107 (2011) 102502

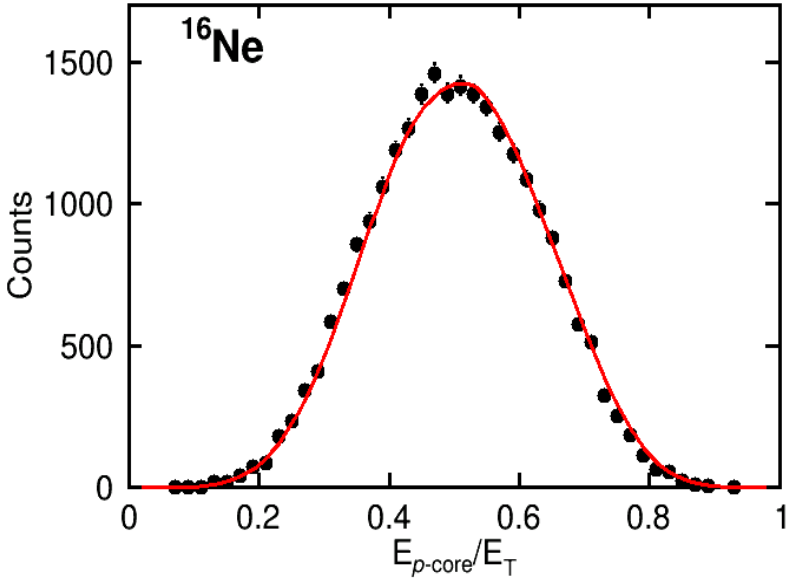
2) Time-dependent Model of Wang and Nazarewicz PRL 126(2021) 142501

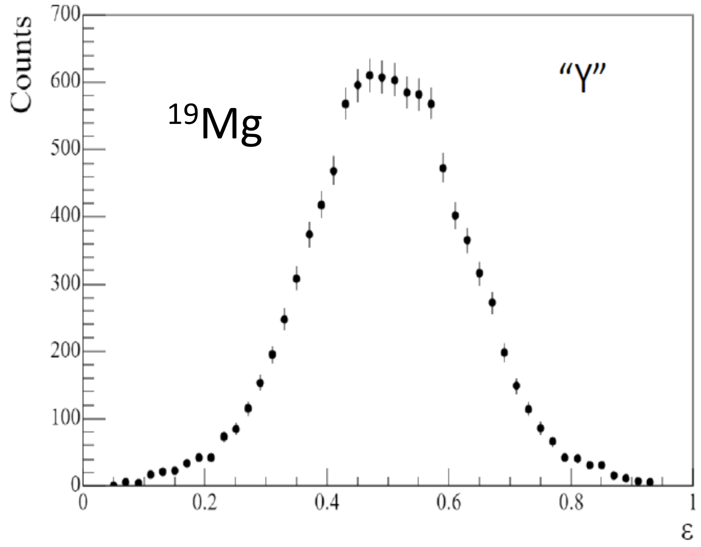
Predicts effects of the continuum on both the initial state configuration and the decay.
(Simin Wang's talk tomorrow)
Applied to ^{6}Be, ^{12}O

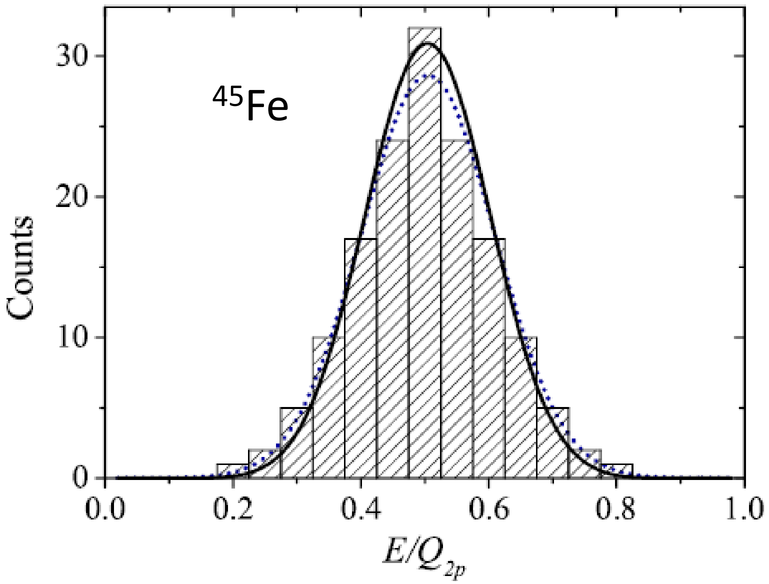
The two protons are emitted with equal as first predicted by Goldanski
Maximizes the product of the barrier penetration factors, well reproduced by theory
(Grigorenko et al   or Wang and Nazarewicz)

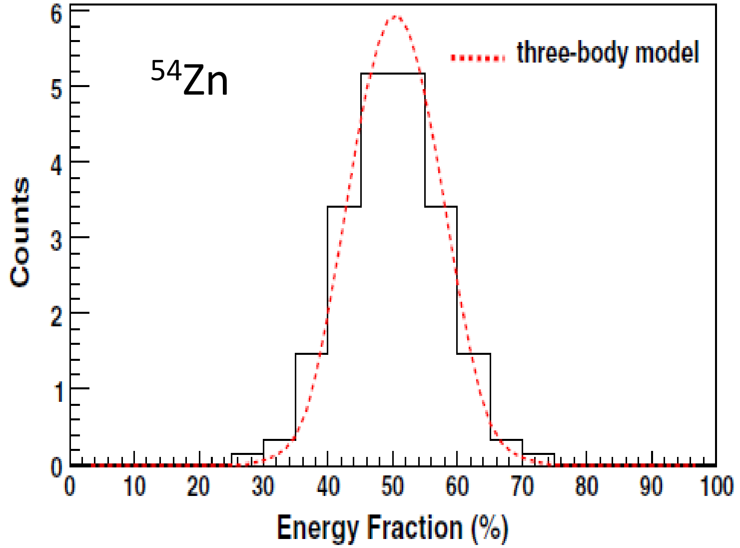








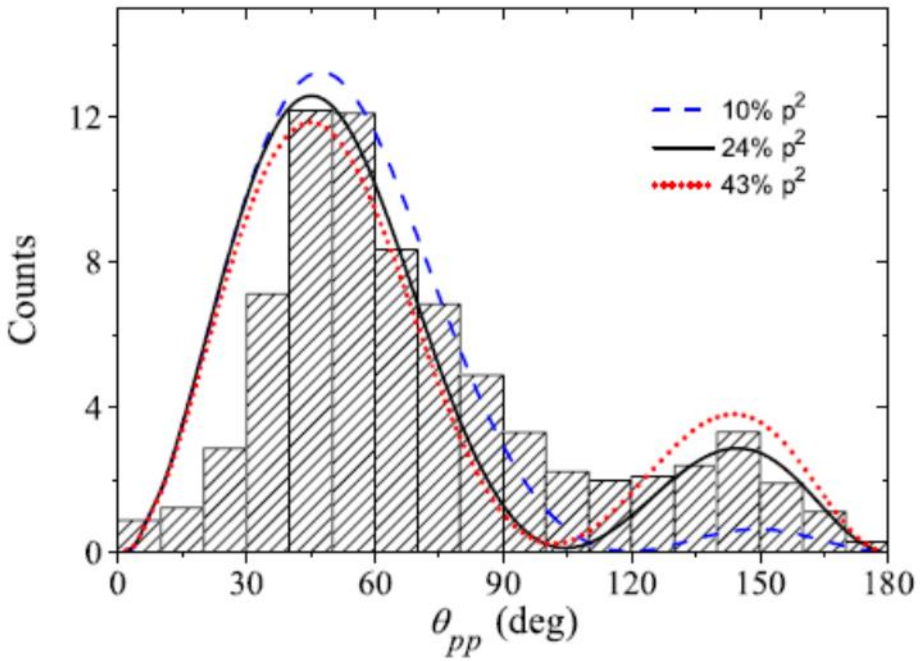




(Jacobi T) (Jacobi Y)

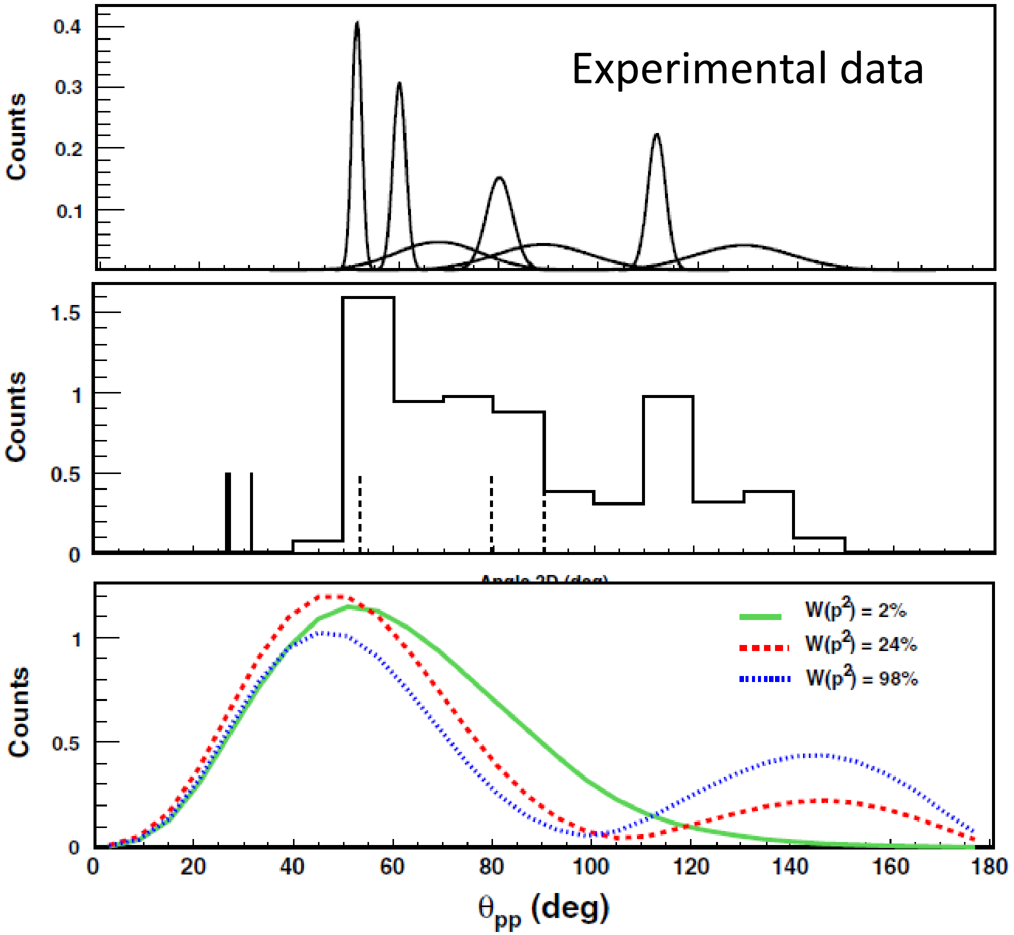
$E_{p\text{-}p}$ and $\theta_{p\text{-}p}$ distribution gives information on nuclear structure

^{45}Fe



Miernik et al PRL 99 (2007) 192501

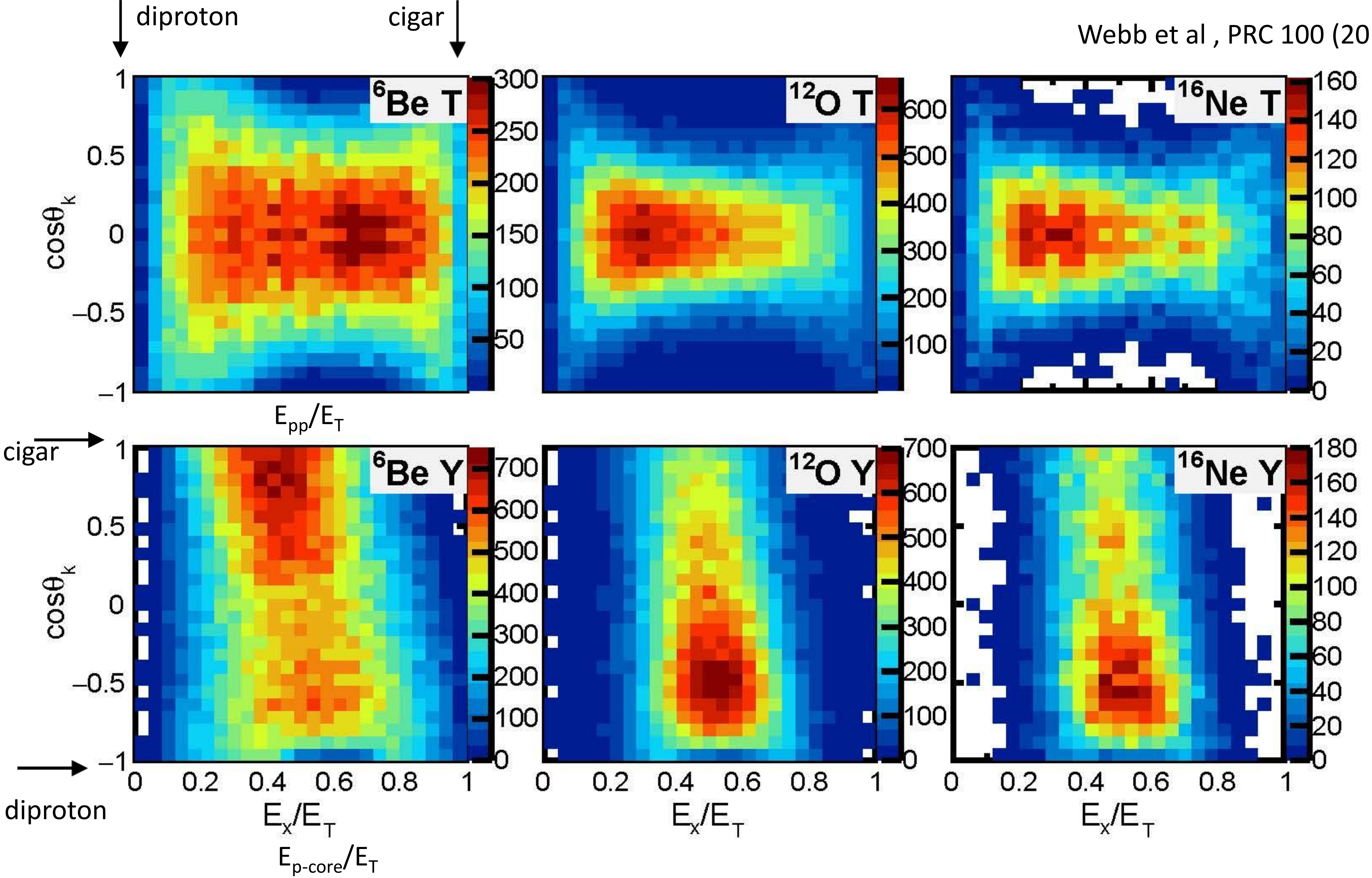
^{54}Zr

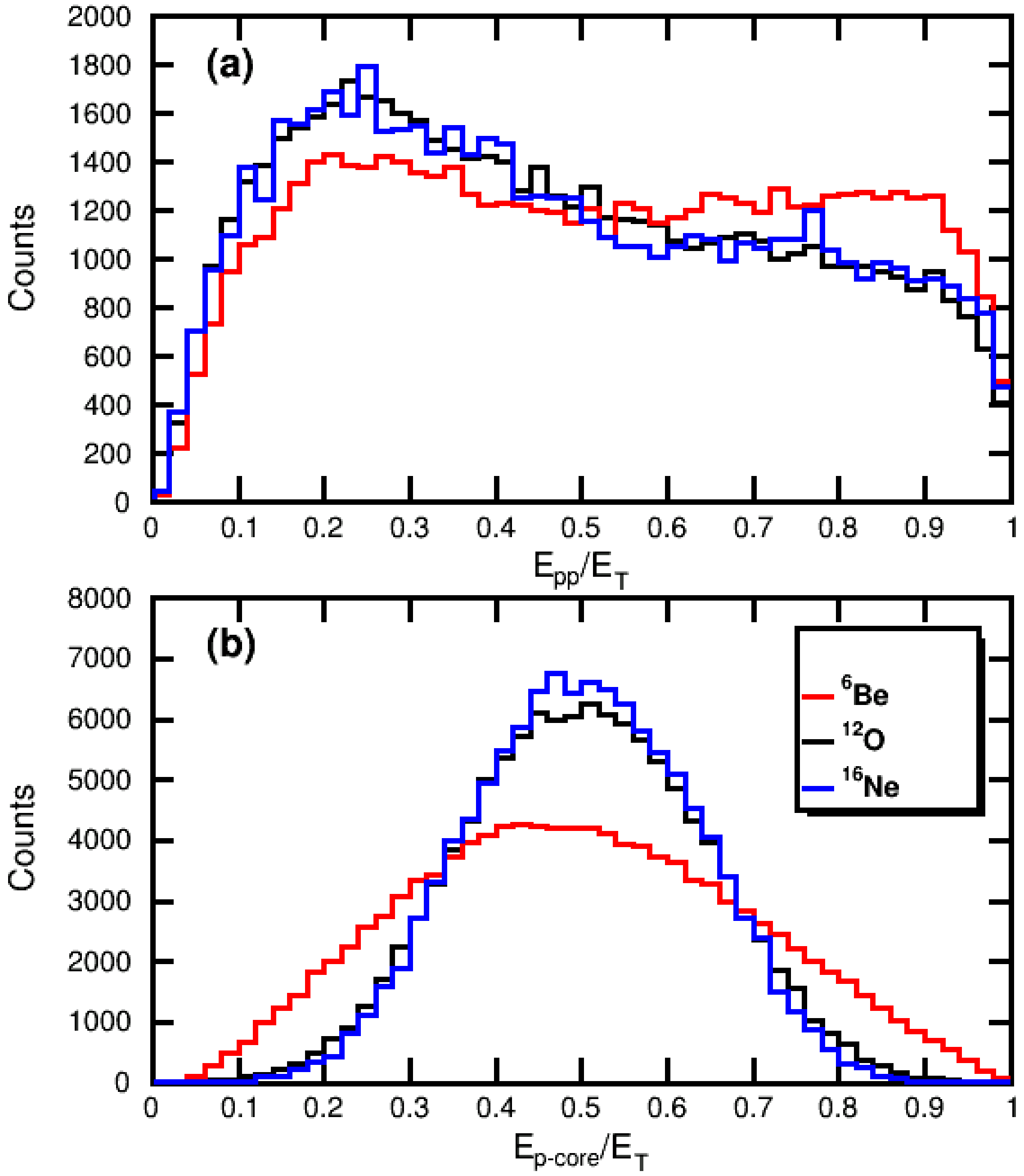


Ascher et al PRL 107 (2011) 102501

Calculations with the 3-body model of Grigorenko et al with initial f^2 and p^2 configurations

Webb et al , PRC 100 (2019) 024306





$E_{p\text{-}p}/E_T$ distributions quite similar for the lighter 2*p* emitters. The ^{12}O and ^{16}Ne decays have almost identical correlations.

How do we understand this?

	Q_{2p} (MeV)
^{6}Be	1.37
^{12}O	1.42
^{16}Ne	1.76

Webb et al, PRC 100 (2019) 024306

Decay of $^{12}O_{gs}$ in time-dependent model of Wang and Nazarewicz
Initial wavefunction -> 36% $s_{1/2}^2$ 25% $p_{1/2}^2$ 14% $d_{5/2}^2$ 13% $s_{1/2},d_{5/2}$
After decay->73% $s_{1/2}^2$ -> barrier penetration favors $s_{1/2}^2$

$^{16}Ne_{gs}$ is expected to have significant $s_{1/2}^2$ component, ~50% by some estimates, with d^2 components comprising most of the remaining strength.
By similar barrier penetration argument, we expect the decay is also dominated by the $s_{1/2}^2$ component.

Thus both ^{12}O and ^{16}Ne decay predominately by $s_{1/2}^2$ emission, hence the similarity of their decay correlations is not surprising.

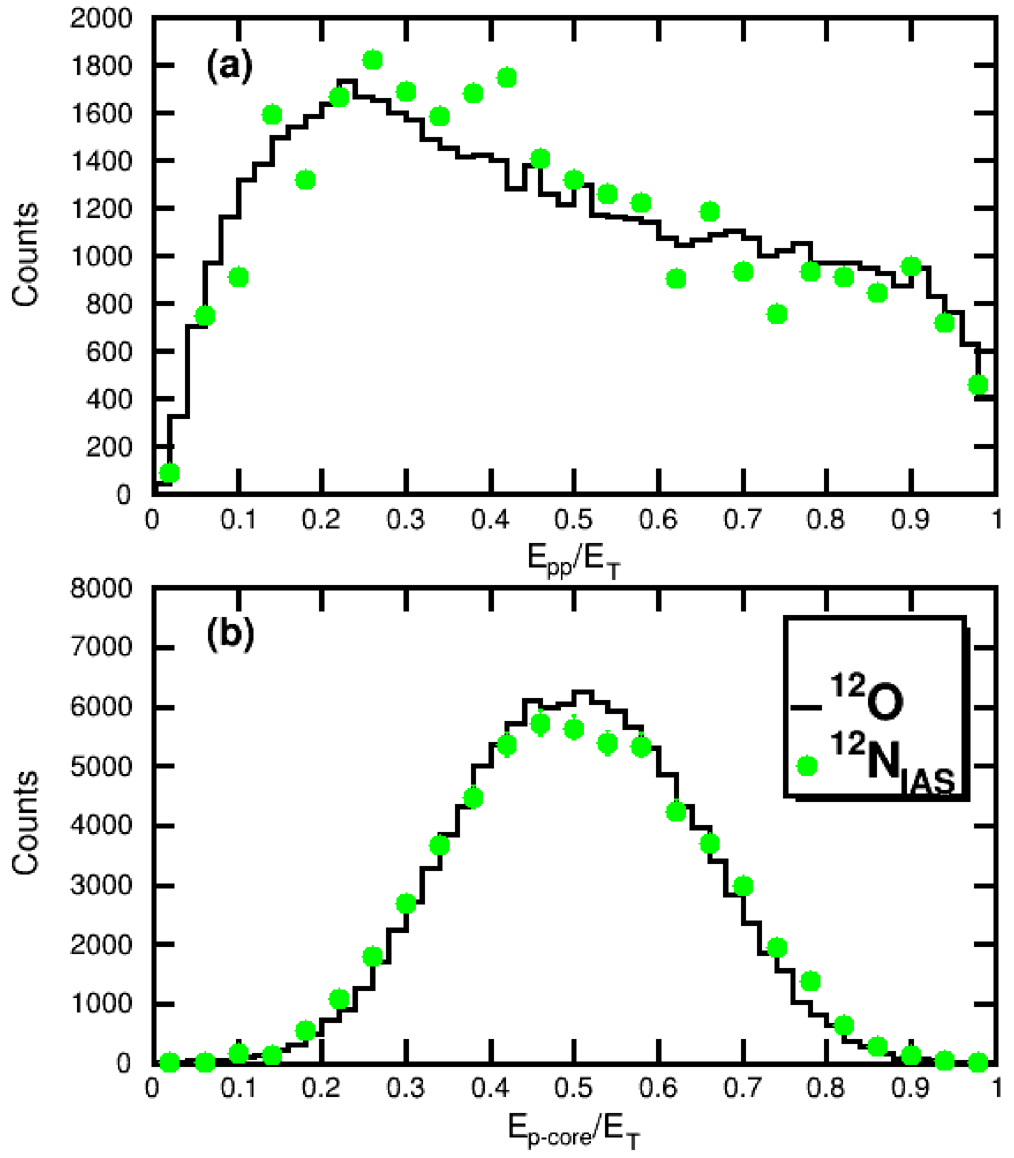
For the initial wavefunction of $^{6}Be_{gs}$ is expected to be mostly $p_{3/2}^2$ configuration, but Wang and Nazarewicz predict a small non-resonant $s_{1/2}^2$ component (~8%).

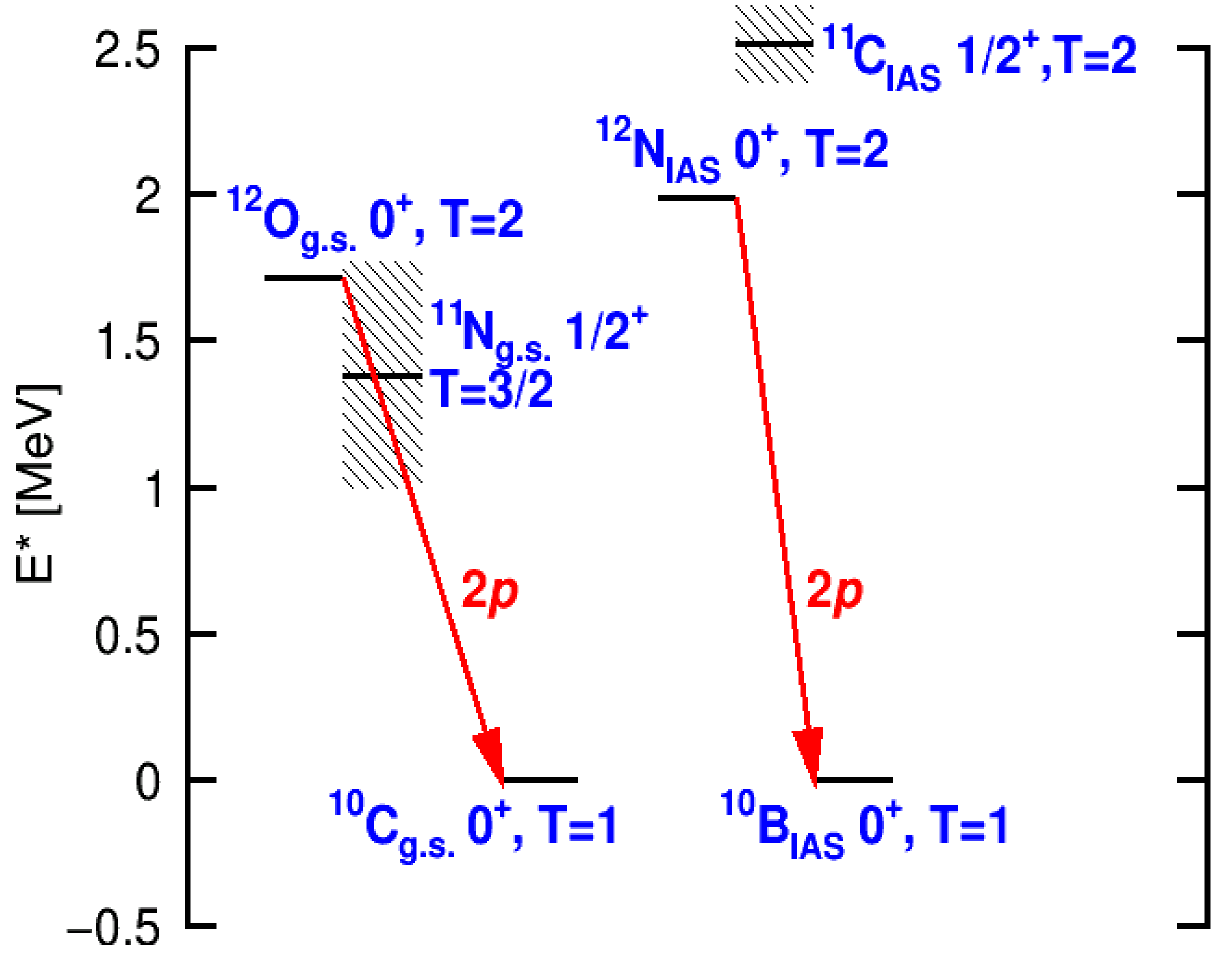
After decay, ~50% of the configuration is $s_{1/2}^2$, Similar numbers predicted by Grigorenko et al.

Webb, PRC 100 (2019) 024306

$^{12}N_{IAS}$ E* = 12.2 MeV

Isobaric analog of ground-state 2p emitter



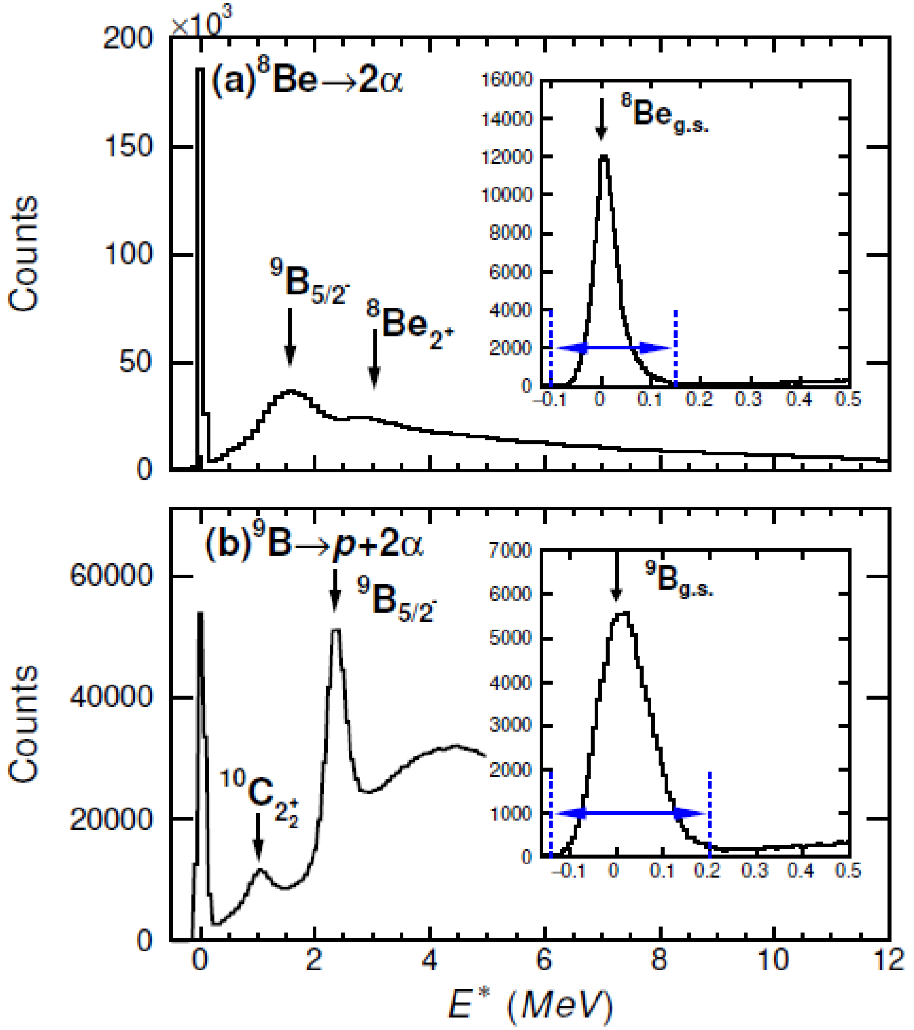


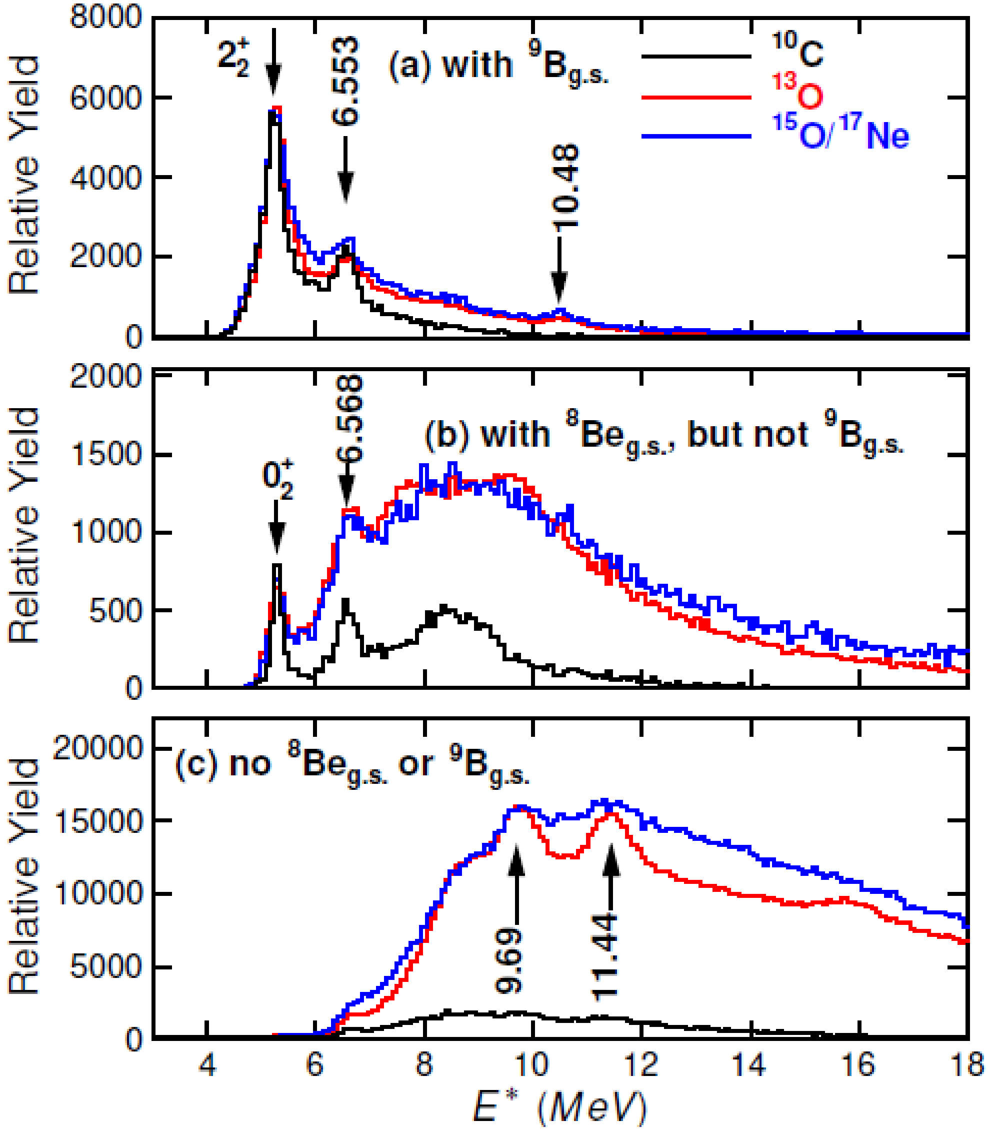
Democratic
2p decay

“true” 2p decay
a la Goldanski

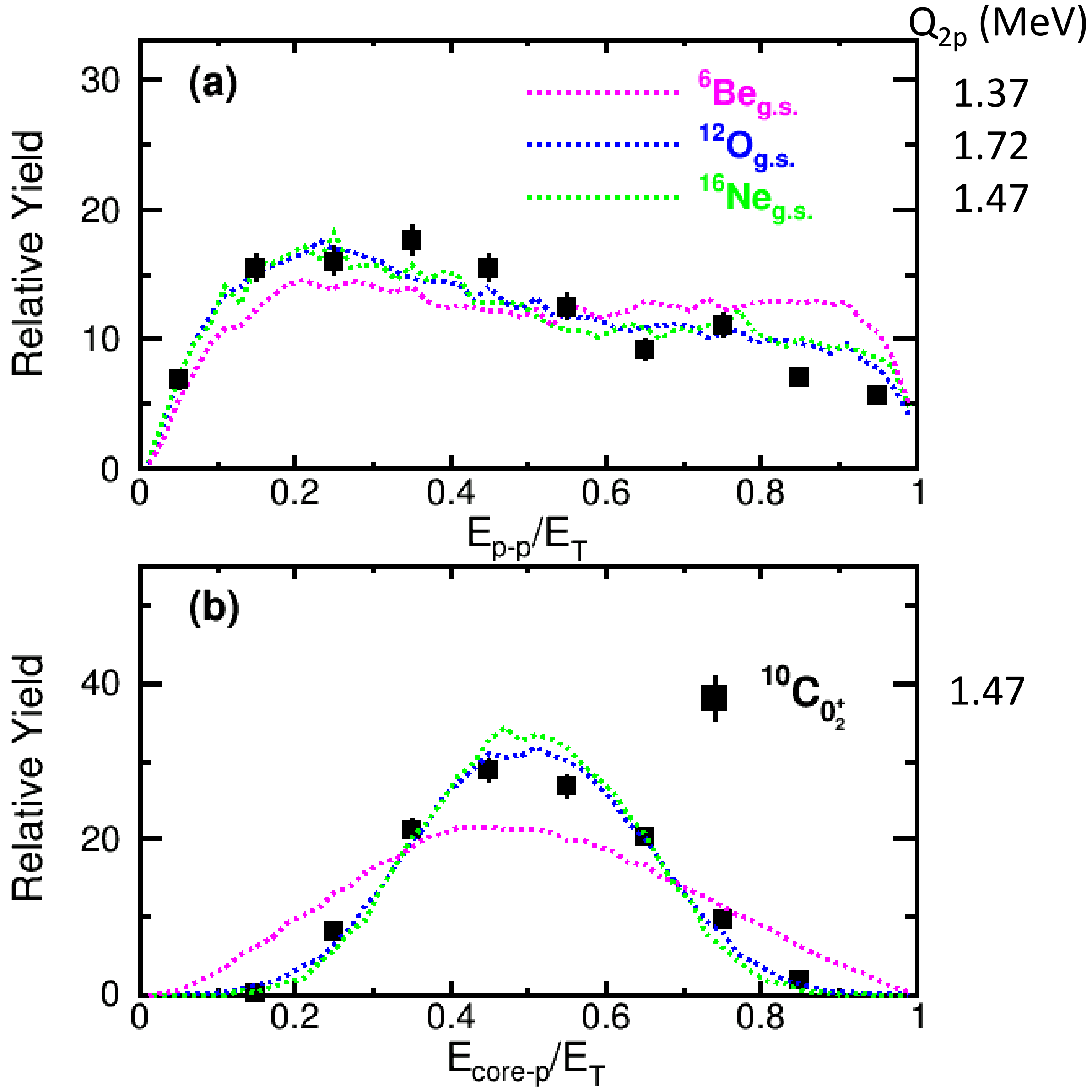
Location of the 1p daughter not important

2p decay in excited state of ^{10}C   analyze the 2p+2α exit channel

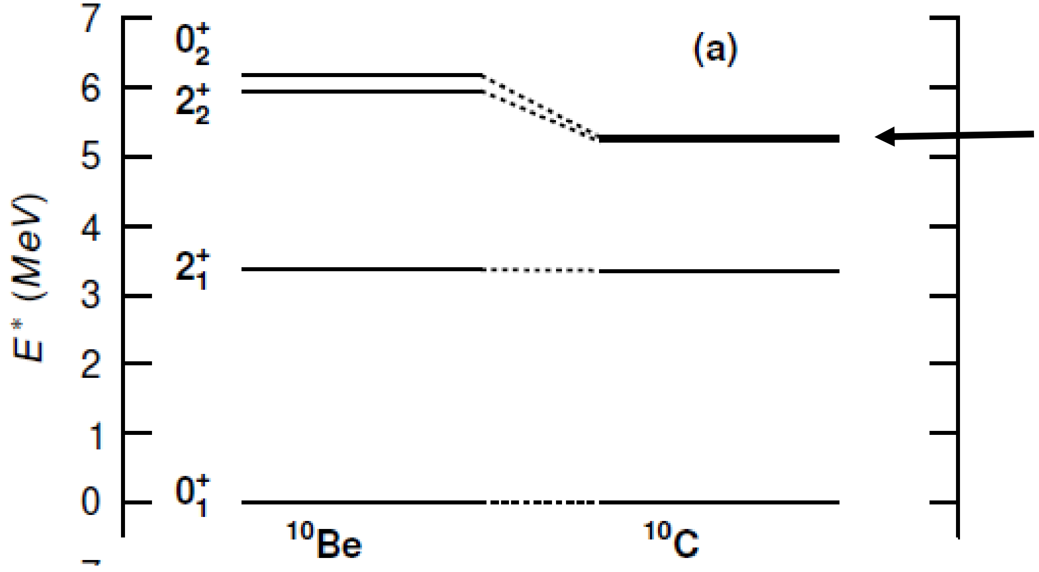




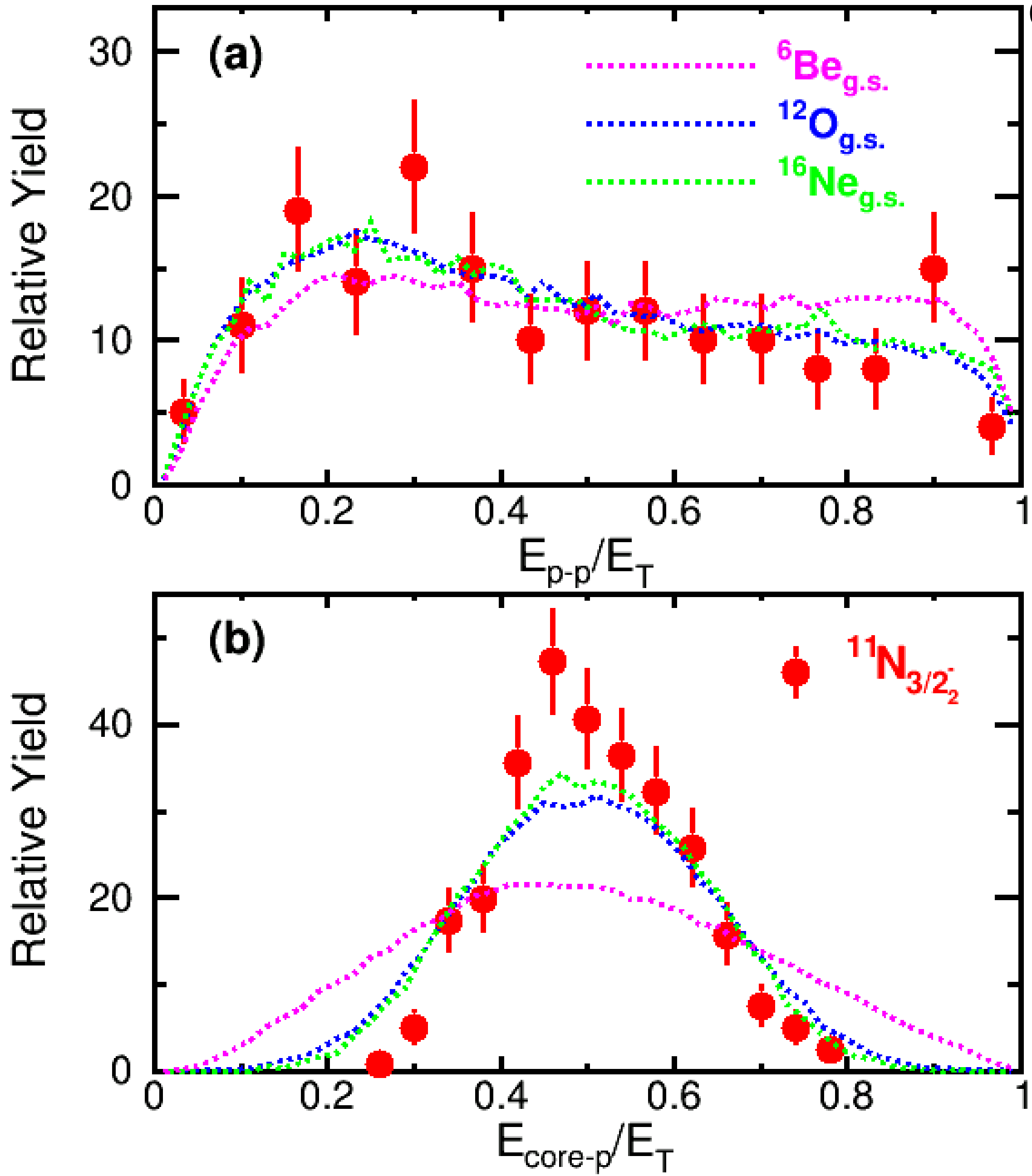
^{10}C (E^*=5.22 MeV) -> $2p$ + $^{8}Be_{g.s.}$ comparison to correlations from ground-state emitters (which similar Q_{2p} values)



Correlations the same as ^{12}O and ^{16}Ne ground state results which are dominated by the emission of two $s_{1/2}$ protons with total spin S=0. This state must be a 0^+ state. Thomas-Erhman shift confirms there is $s_{1/2}$ strength.



$^{11}N(E^*=3.93, 3/2^-) \rightarrow 2p+^{9}B_{g.s.}\ (3/2^-) \rightarrow 3p+2\alpha$ narrowest known state in ^{11}N (Γ=158 keV)



Q_{2p} (MeV)

1.37

1.72

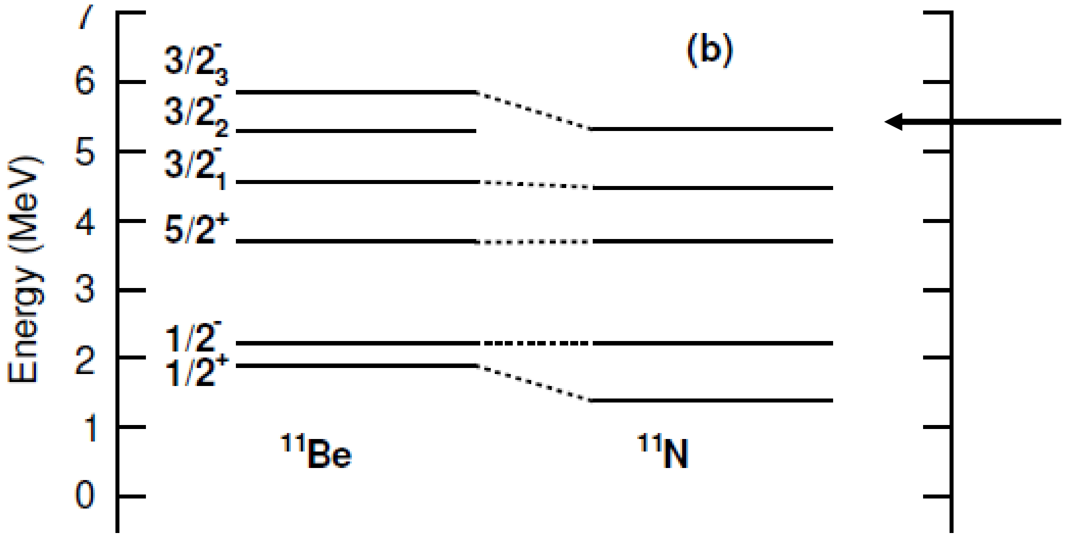
1.47

1.40

Correlation consistent with $0^+ \rightarrow 0^+$ ground state emitters.

The spin of this state must be 3/2-, which decays by two $s_{1/2}$ protons.

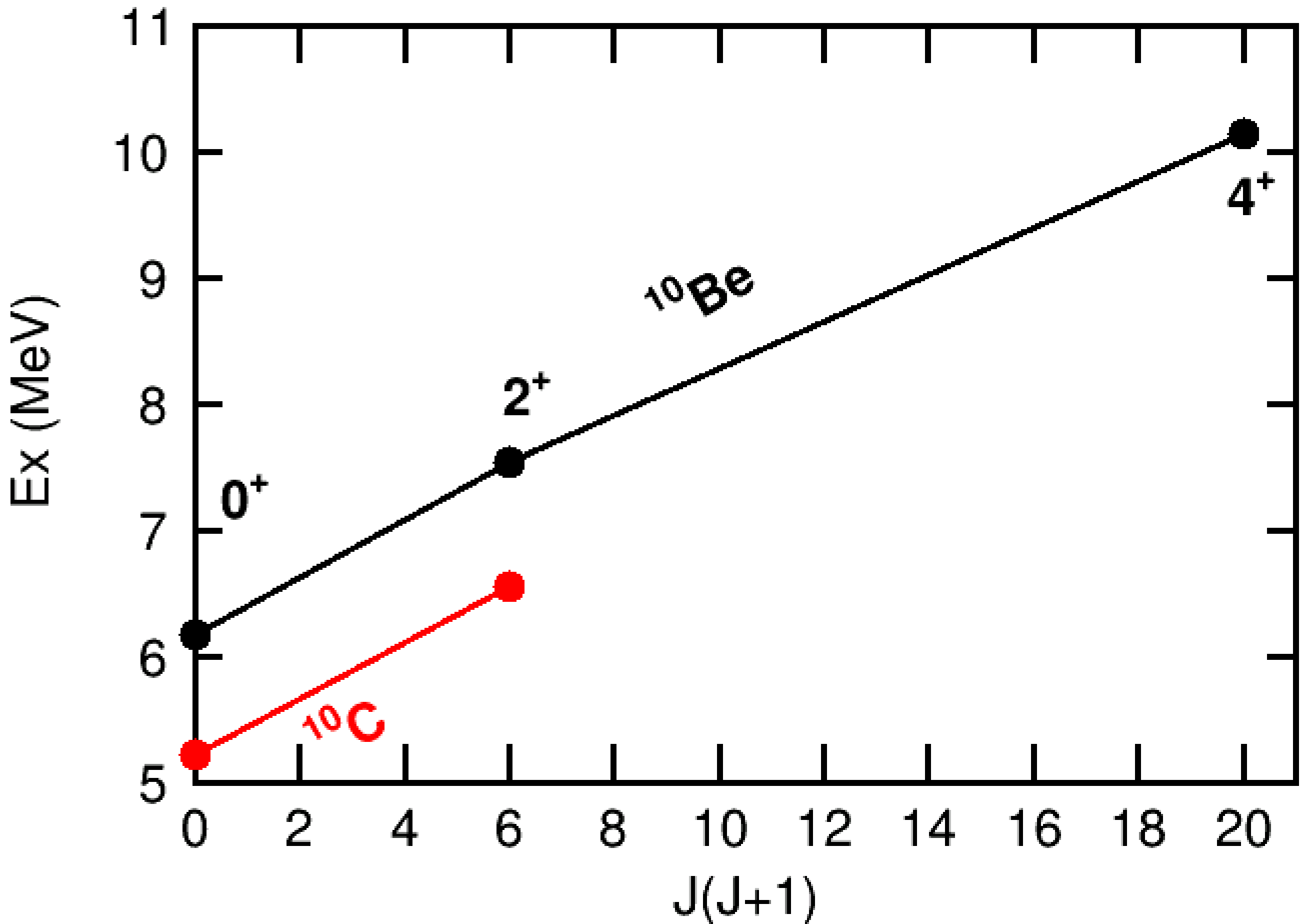
possible Thomas-Erhman shift.



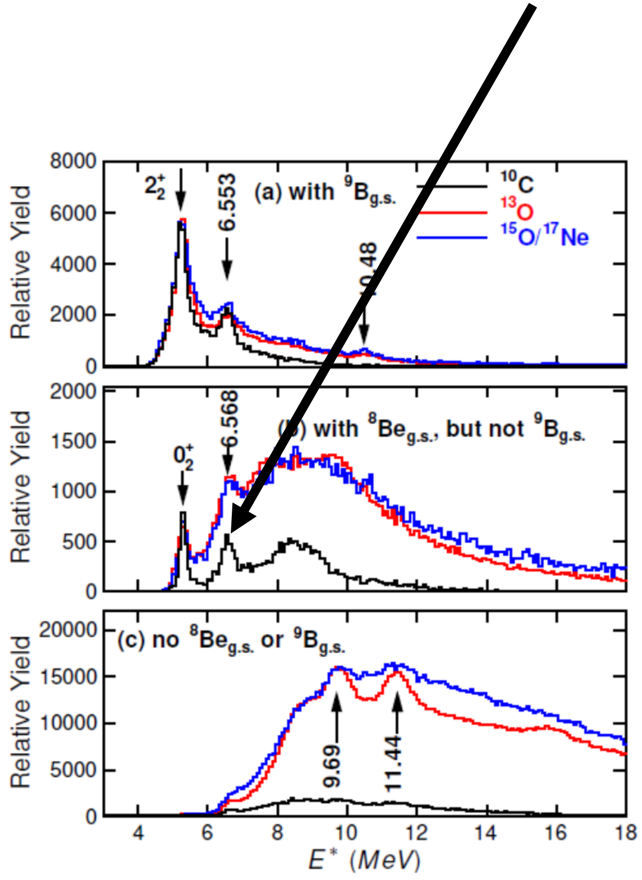
Both the ^{10}C and ^{11}N states discussed are cluster states, i.e. their cores (^{8}Be,^{9}B) are clustered and the mirror states in ^{10}Be and ^{13}B have been described as band heads for rotational bands.

Thus we see 2p decay from cluster states.

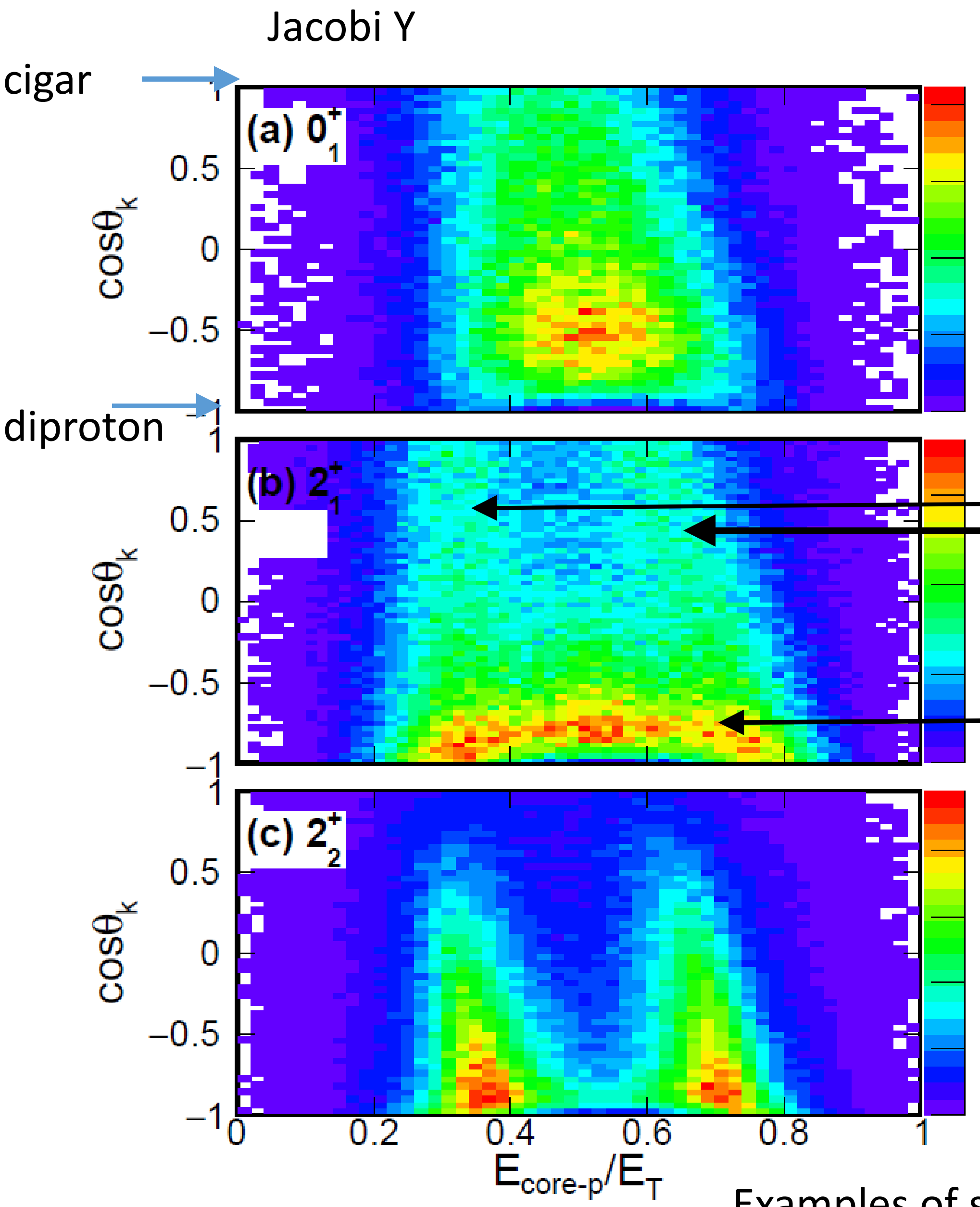
^{10}Be ->Freer et al PRL 96 042501 (2006)



2^{+} state?



Evolution from prompt towards sequential decay with excitation energy

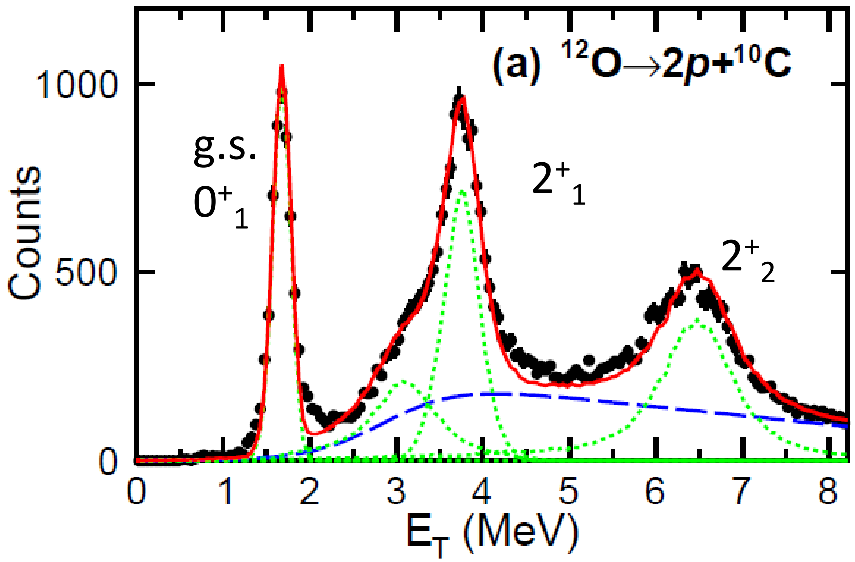


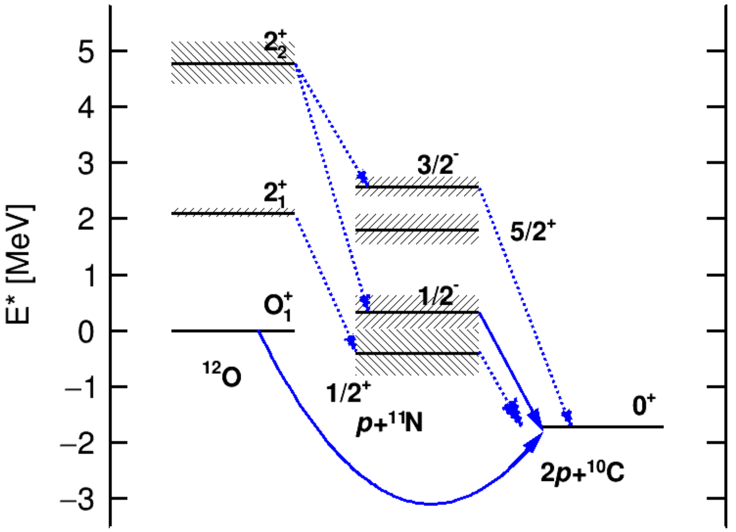
Ground state
Prompt decay

Sequential decay
ridges

Diproton arc

Two ridges, but most of the yield is still in diproton region





Examples of similar decay in other g.s. 2p emitters

Webb et al PRC 100 (2019) 024306

Conclusions

Momentum Correlations between the protons provide useful information.

Can differentiate prompt and sequential decay 2p decay.

Prompt 2p decay can give us some information in the initial wavefunction.
The same correlations as observed in the ground states can be found in excited states (isobaric analog states and cluster states)

The evolution of the correlations with excitation energy is complex and we see both sequential and prompt aspects in the decay correlations

Correlations will be used for 3p and 4p decays to understand their decay paths.