Changing decay mode with excitation energy for two-proton decay

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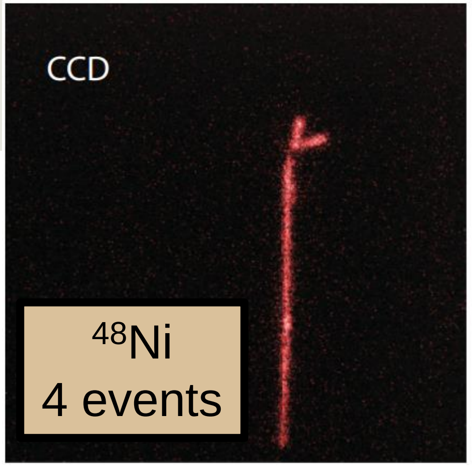
Particle physics has come a long way since the 1700s.

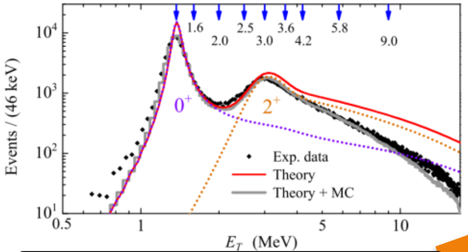
Smbc-comics.com

Outline

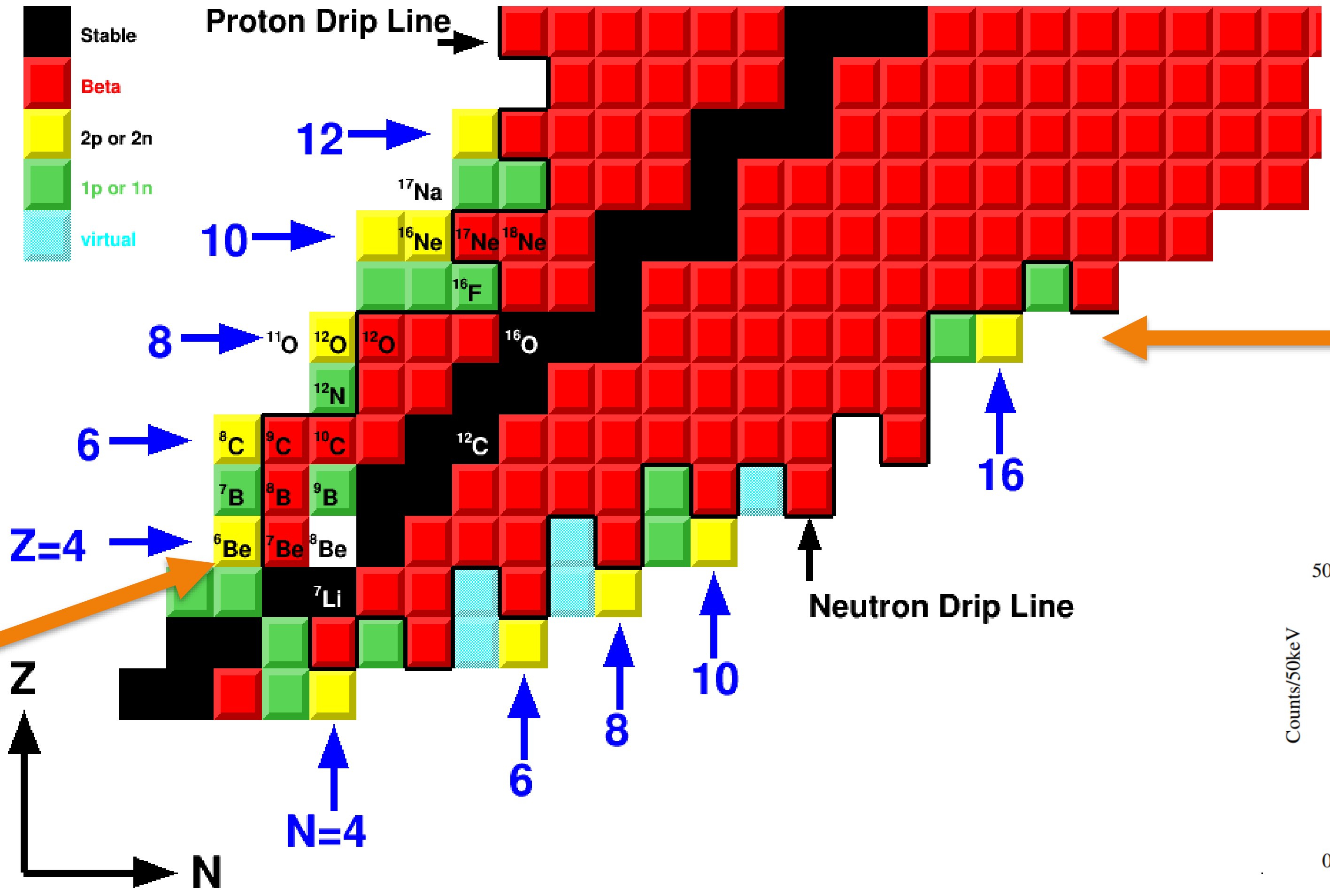
- Overview
  - Classifying types of 2p emitters
  - How can we distinguish them experimentally
- Experimental details
  - Invariant-Mass method
  - Getting beyond the drip lines
- Examples for interplay between the modes
  - ^{16}Ne
  - ^{12}O
  - ^{19}Mg

1 and 2 nucleon emitters

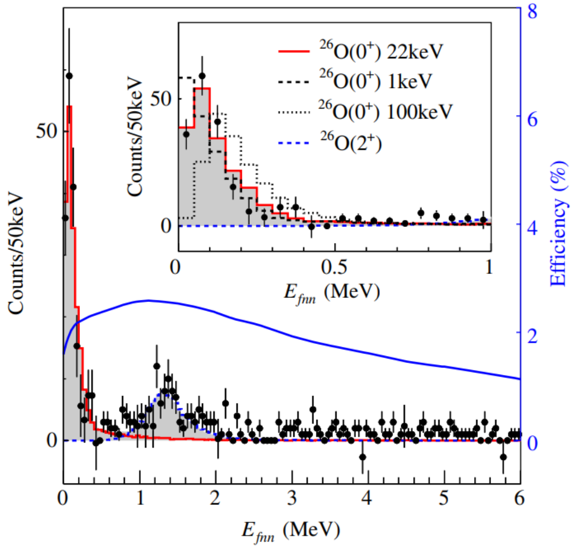




^{6}Be lightest known 2p emitter



^{26}O
2n emitter, 18 keV unbound



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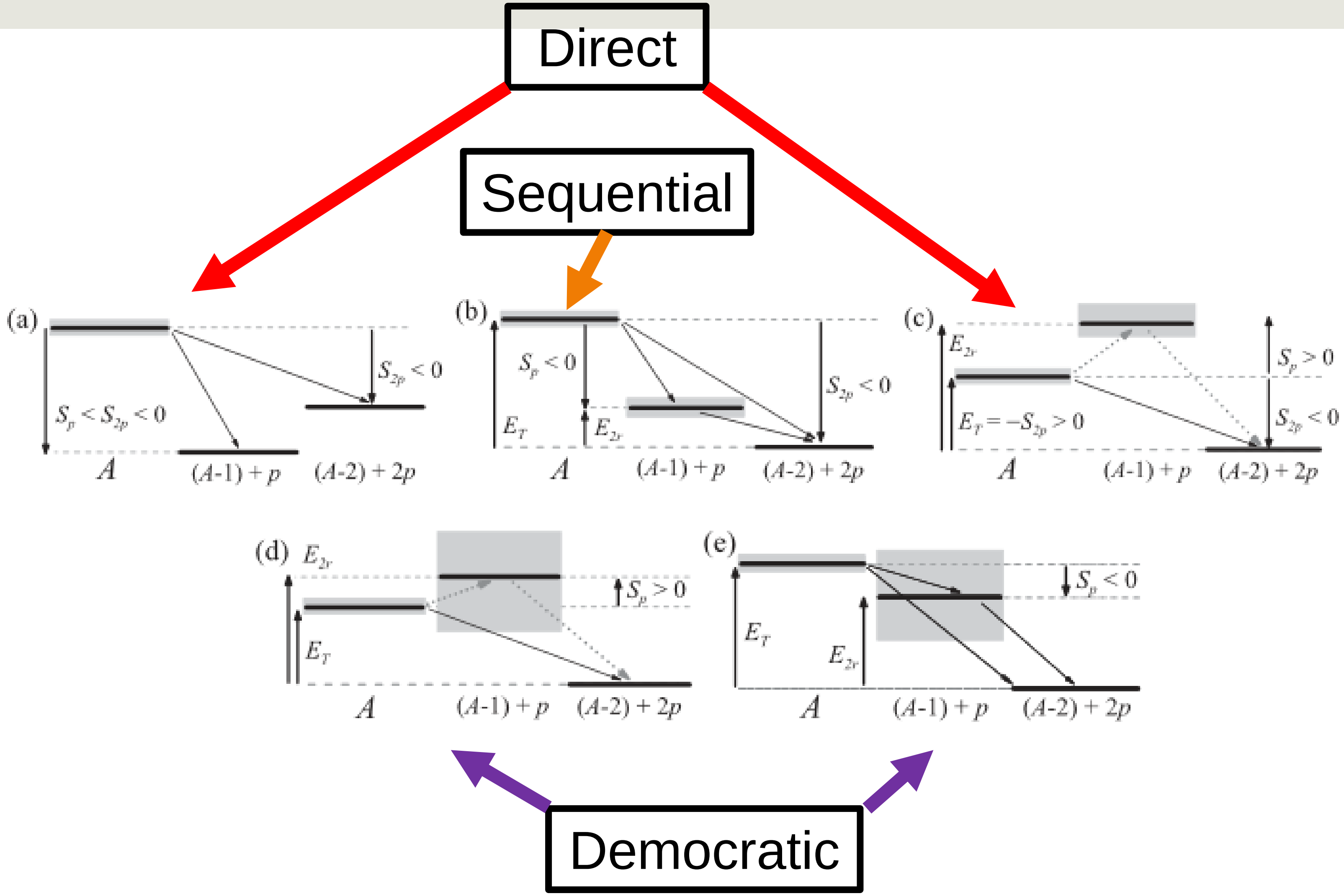
^{6}Be: I.A. Egorova *et al*. PRL **109**, 202502 (2012)
^{48}Ni: M. Pomorski *et al*. PRC **83**, 061303 (R) (2011)
^{26}O: Y. Kondo *et al*. PRL **116**, 102503 (2016)

Distinct types of 2p emitters

- Three classes of two-proton decay
  A. Sequential (b)
  B. Direct or “true” (a,c)
  C. Democratic (d,e)
- Classification is governed by energetics and nuclear structure
- Decay class revealed by the 3-body momentum correlations



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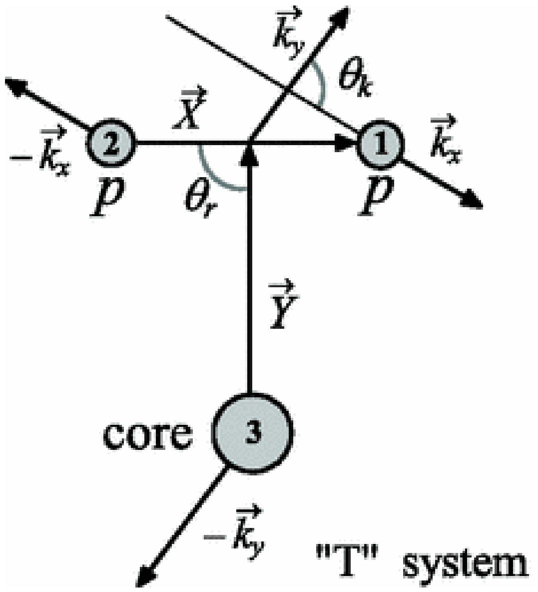
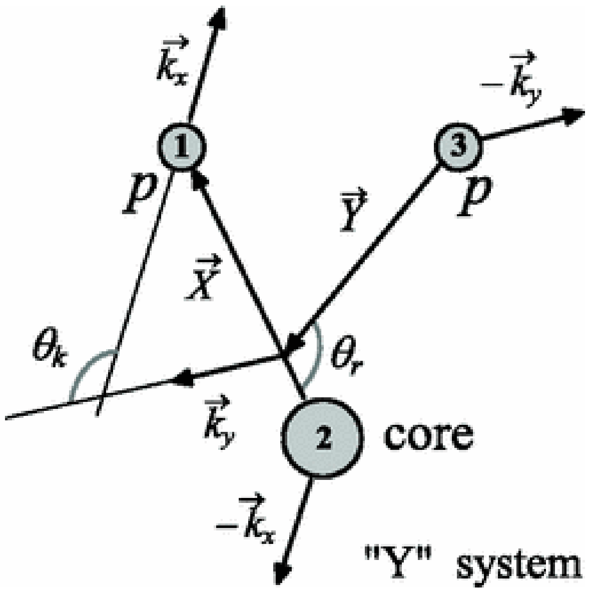
Pfützner *et al*. Rev. Mod. Phys. **84**, 567 (2012)

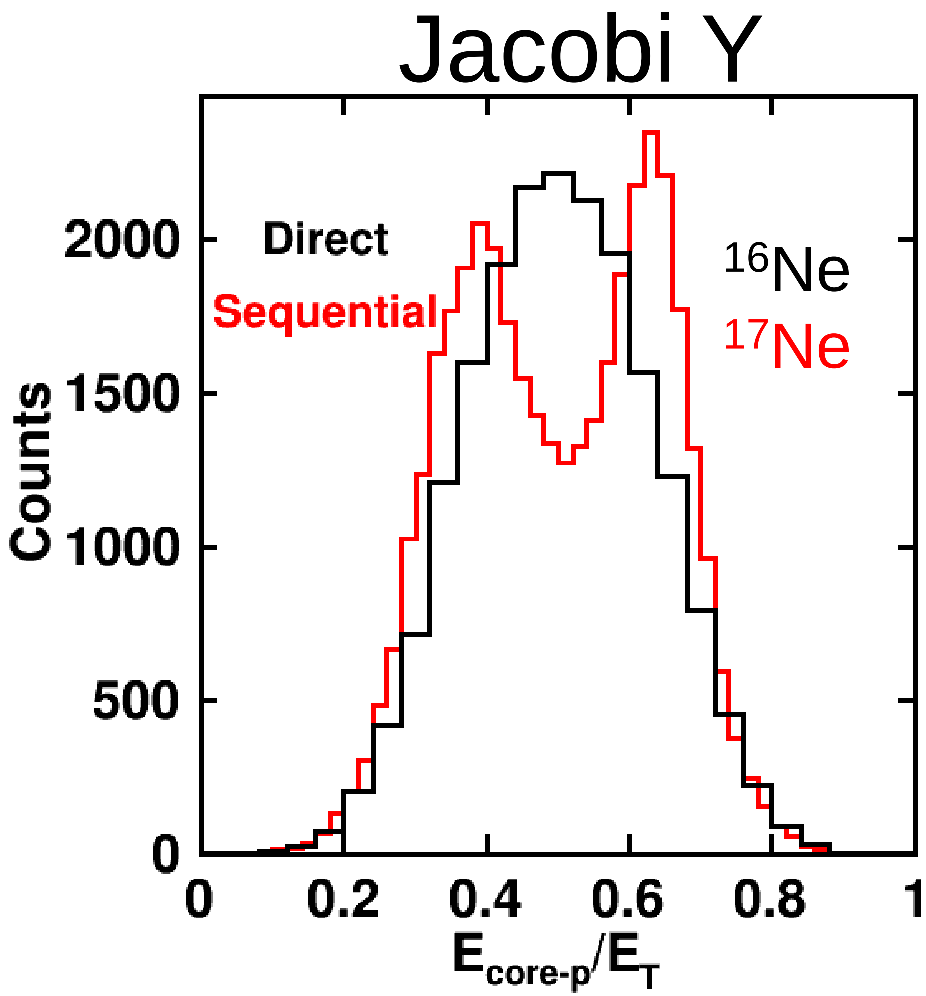
Distinguishing between direct and sequential

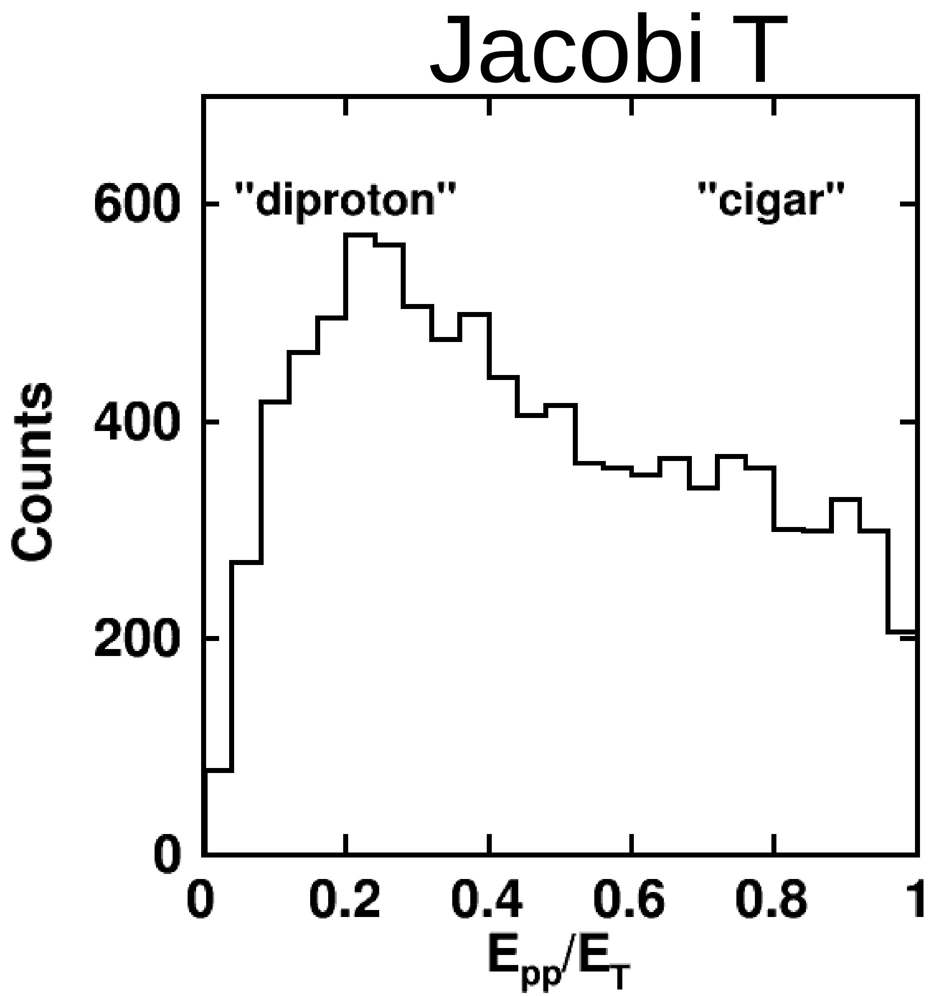




- 3-body decay-> 9 DoF - 3(COM motion) - 3(Euler rotation of decay plane) - 1 (fixed decay energy) = 2 DoF to describe system
- Jacobi T system -> E_{pp} vs θ_k: describes proton-proton relative motion
- Jacobi Y system -> $E_{Core\text{-}p}$ vs θ_k: describes core-proton relative motion → easiest way to tell direct vs sequential

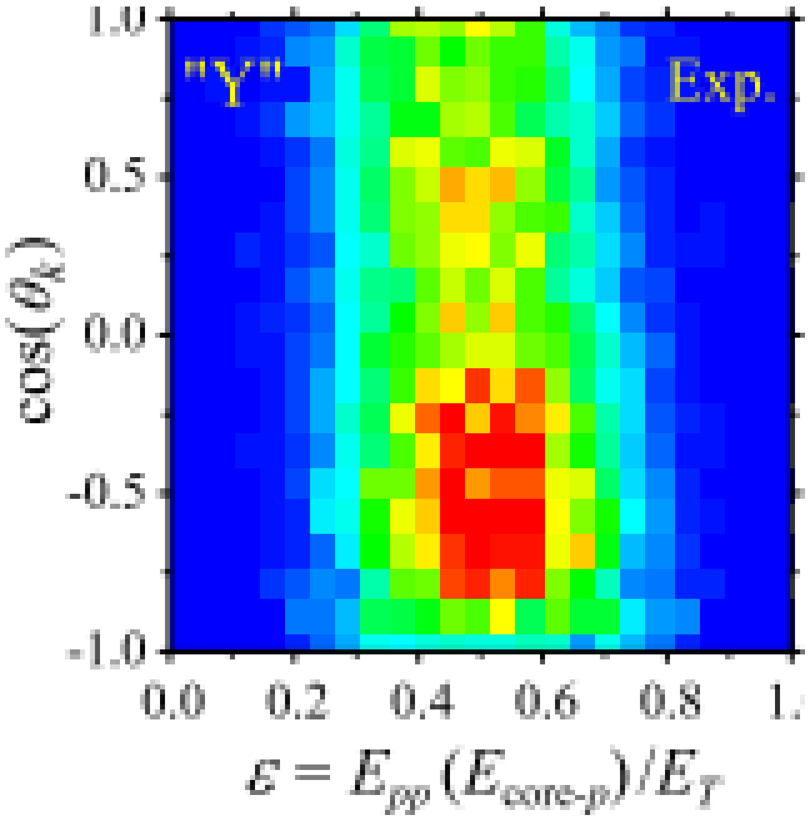
Distinguishing between direct and sequential



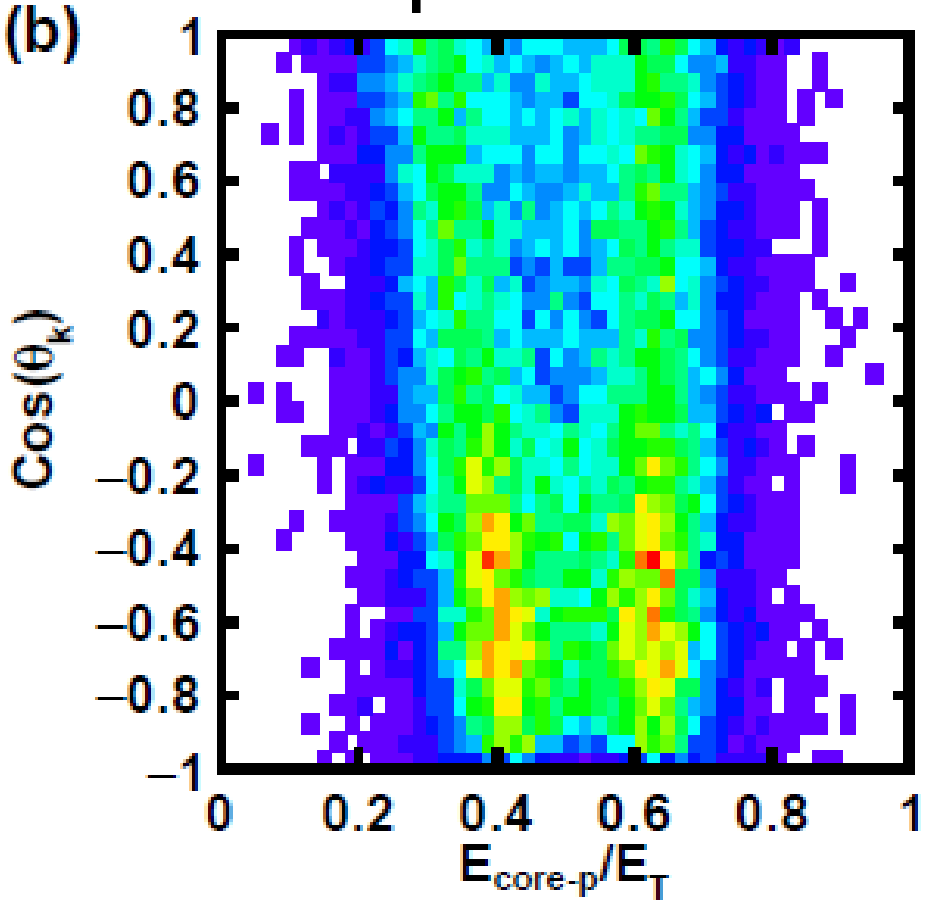


Distinguishing between direct and sequential

Direct

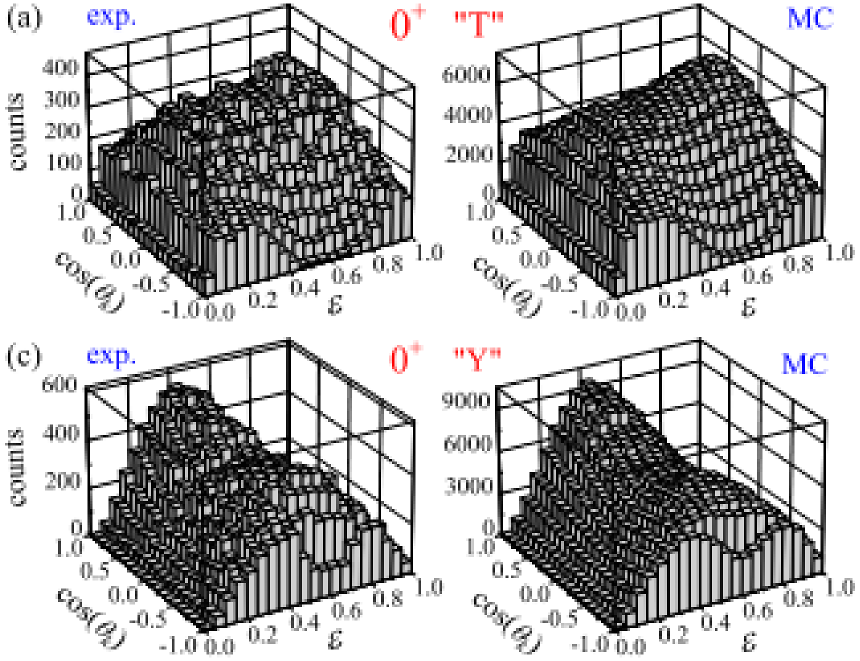


Sequential

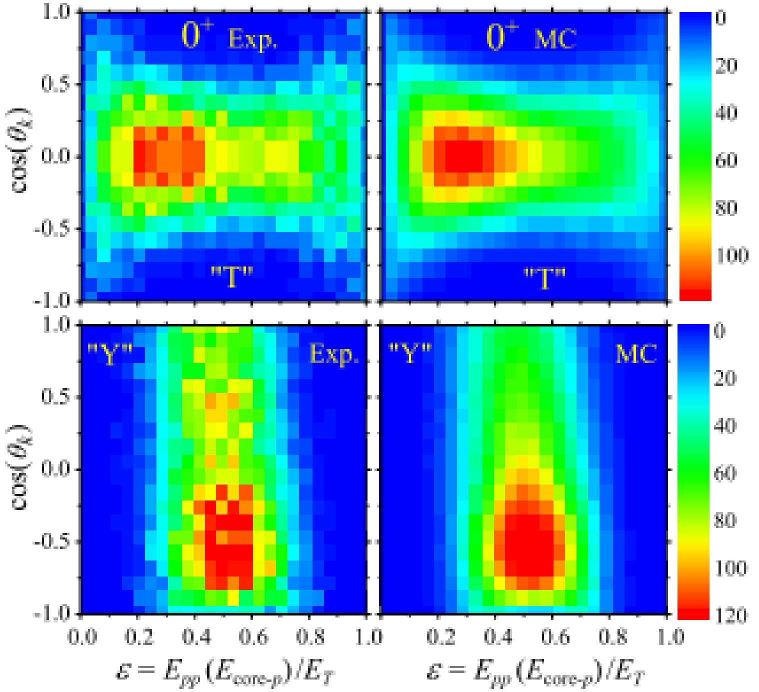


Measuring 2p Correlations

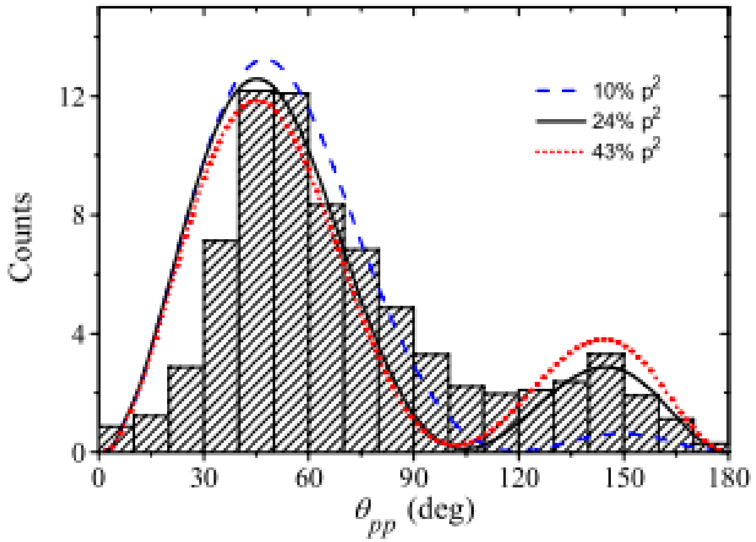
^{6}Be



^{16}Ne



^{45}Fe



NSCL
FRIB
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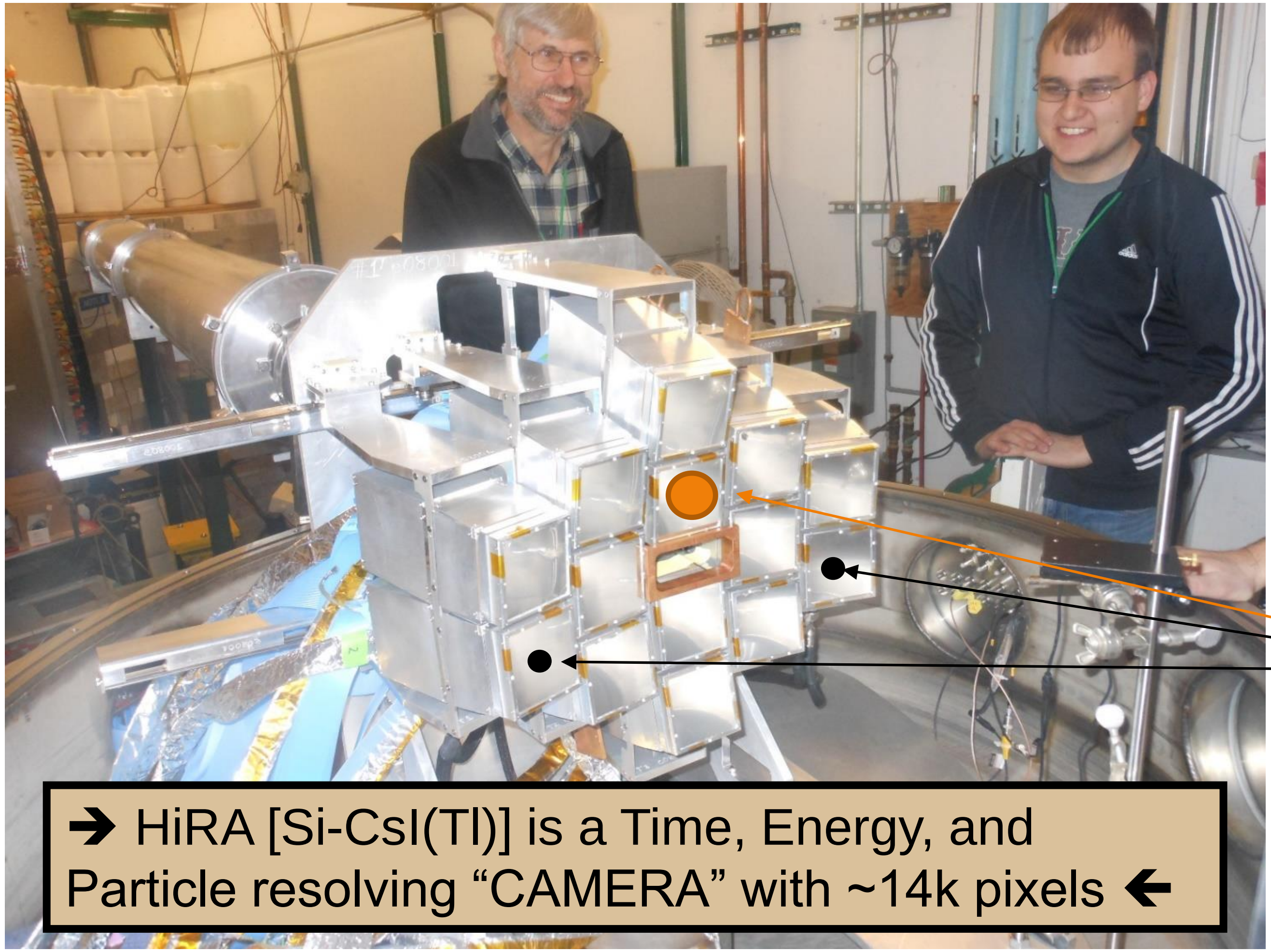
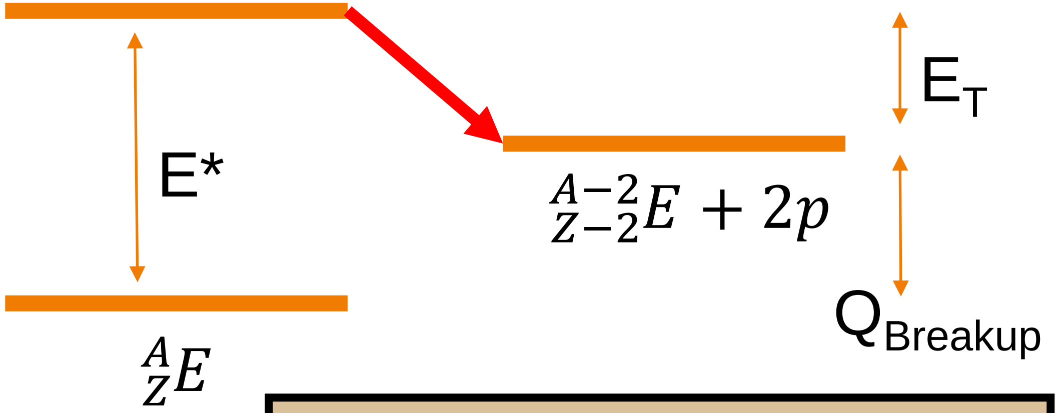
^{6}Be: I. A. Egorova, *et al.* PRL **109**, 202502 (2012)
^{16}Ne: KWB, *et al*. PRL **113**, 232501 (2014)
^{45}Fe: K. Miernik, *et al*. PRL **99**, 192501 (2007)

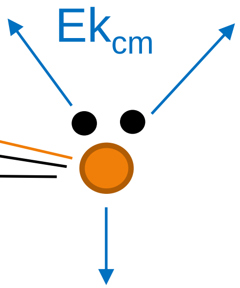
Experimental Technique: Invariant Mass



➔ HiRA [Si-CsI(Tl)] is a Time, Energy, and Particle resolving "CAMERA" with ~14k pixels ➔



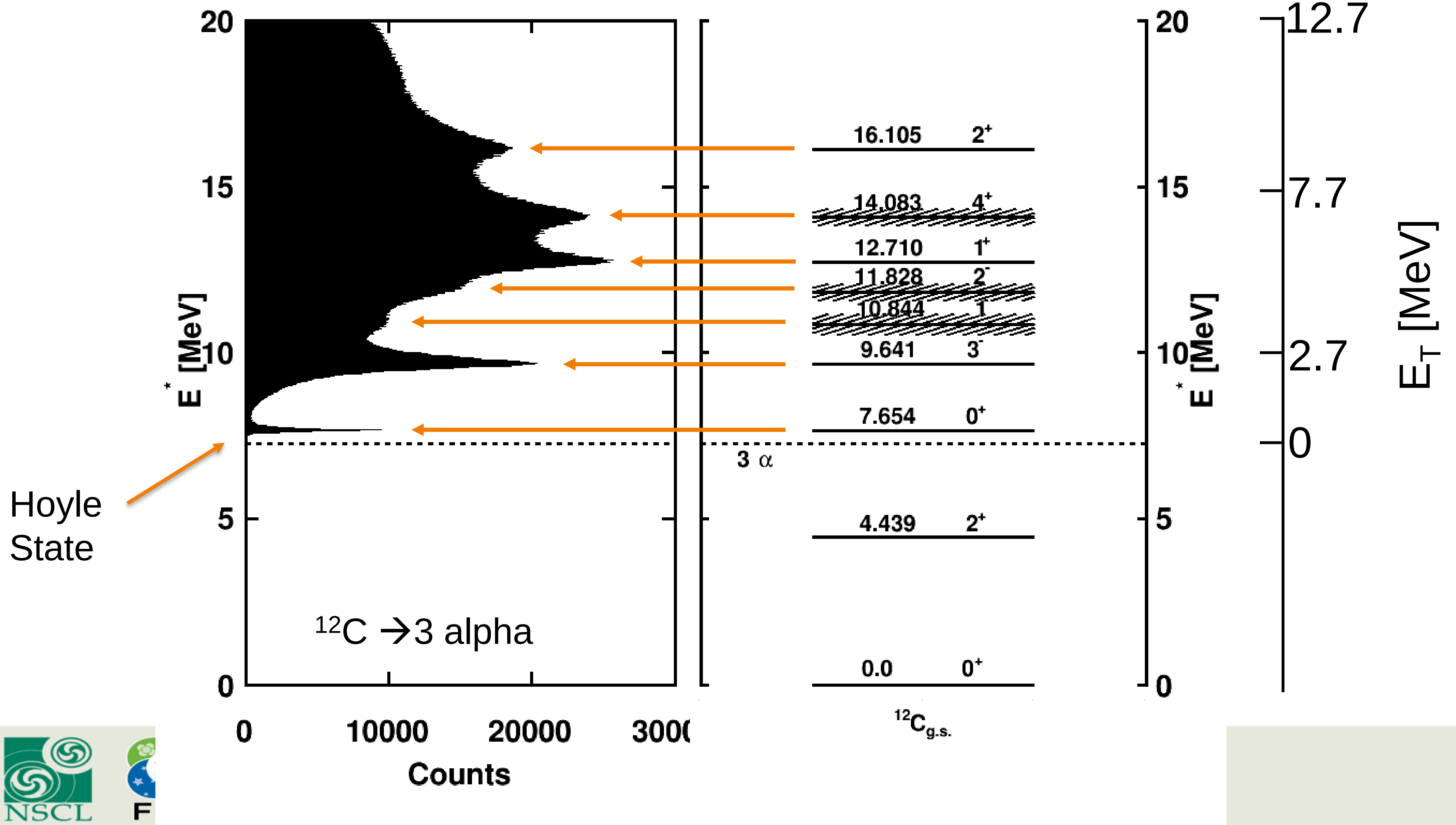
E* (parent) = "POP" - Δ mass



$$E_T = \sum_i Ek^i_{cm}$$

$$E^* = E_T - Q_{breakup}$$

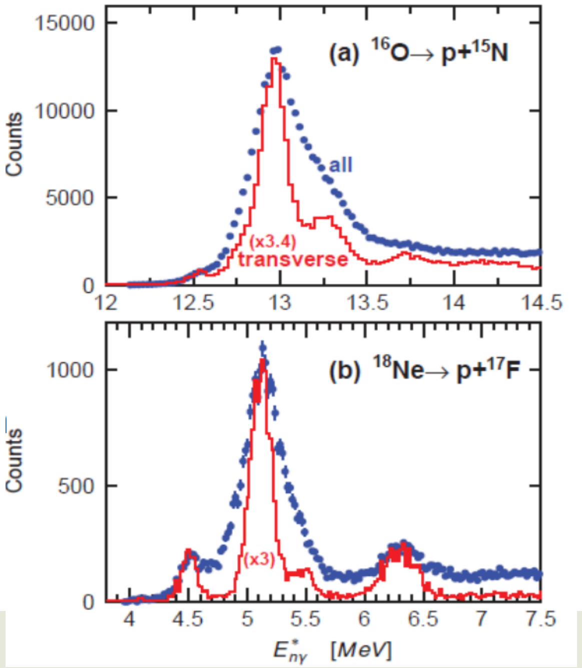
Invariant Mass in Action



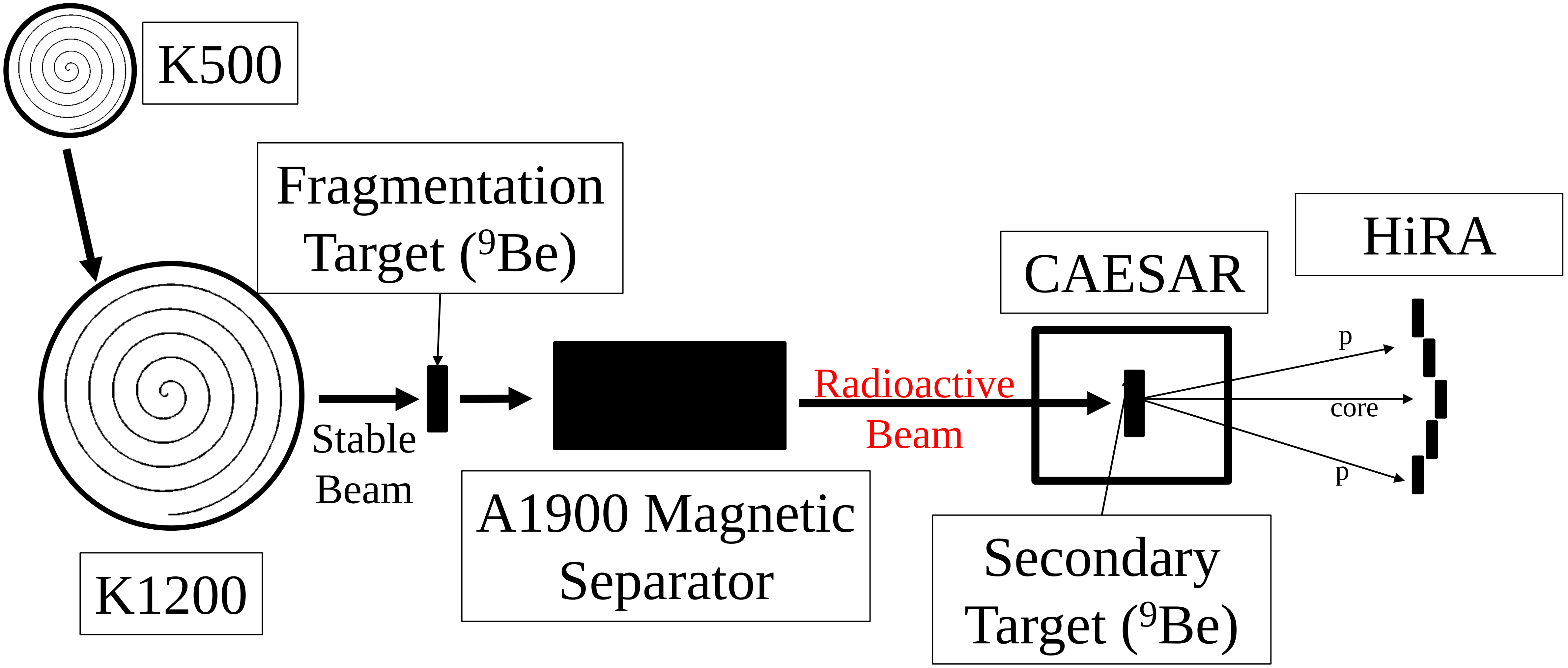
Pros and Cons

1. Insensitive to incoming beam spot size and trajectory – great for secondary beams produced in-flight by fragmentation (NSCL/FRIB, GSI, RIKEN, etc)
2. Begins to break down for long-lived states (τ ~ 1ns), need the decay to occur in or close to the target
3. Resolution is dominated by the differential energy loss in the target, heavy recoil loses more energy than the protons
4. Can trade statistics for resolution by selecting transverse decays
5. Charged-particle detectors should be paired with a gamma

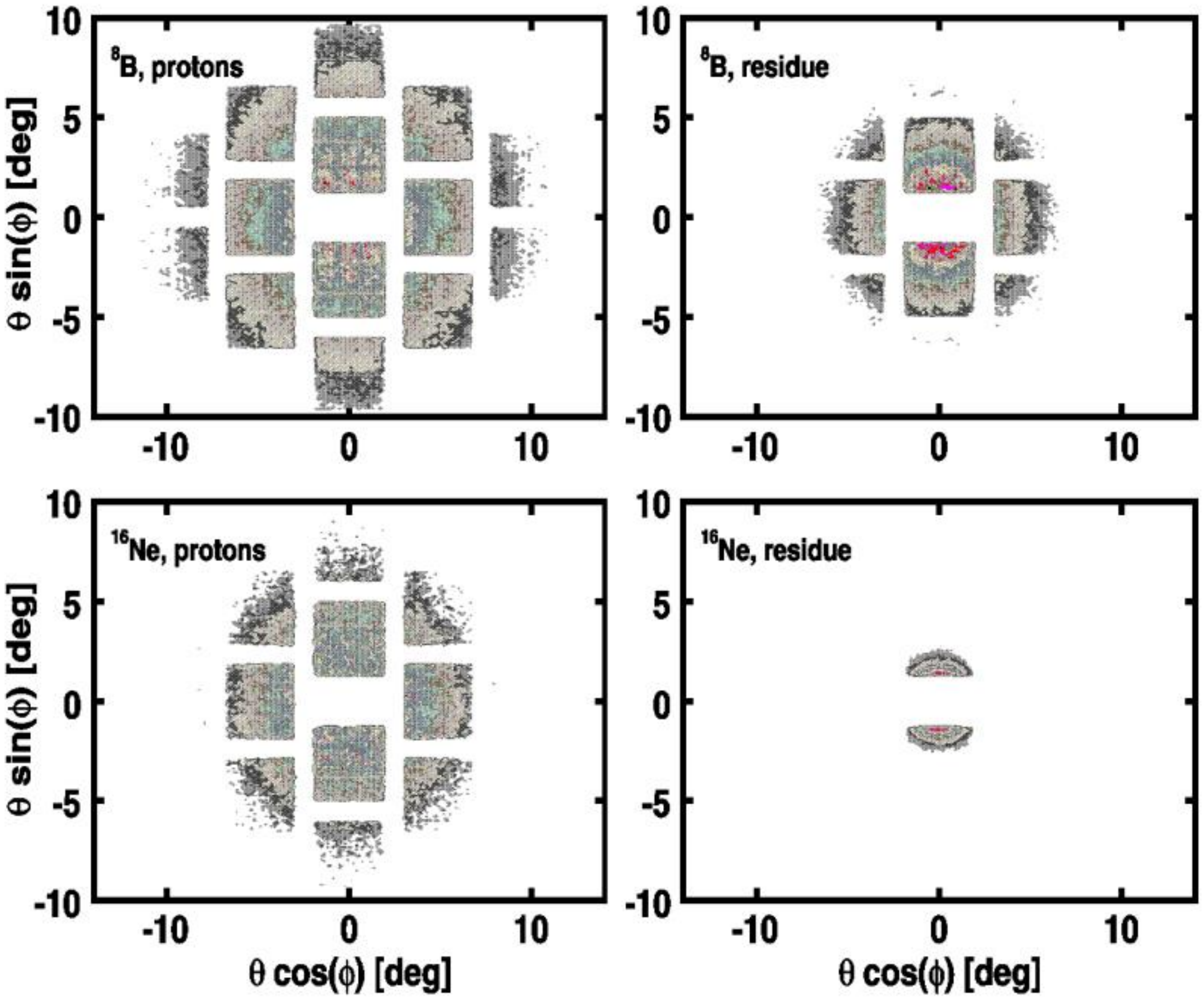
detector to avoid ambiguity in the exit channel

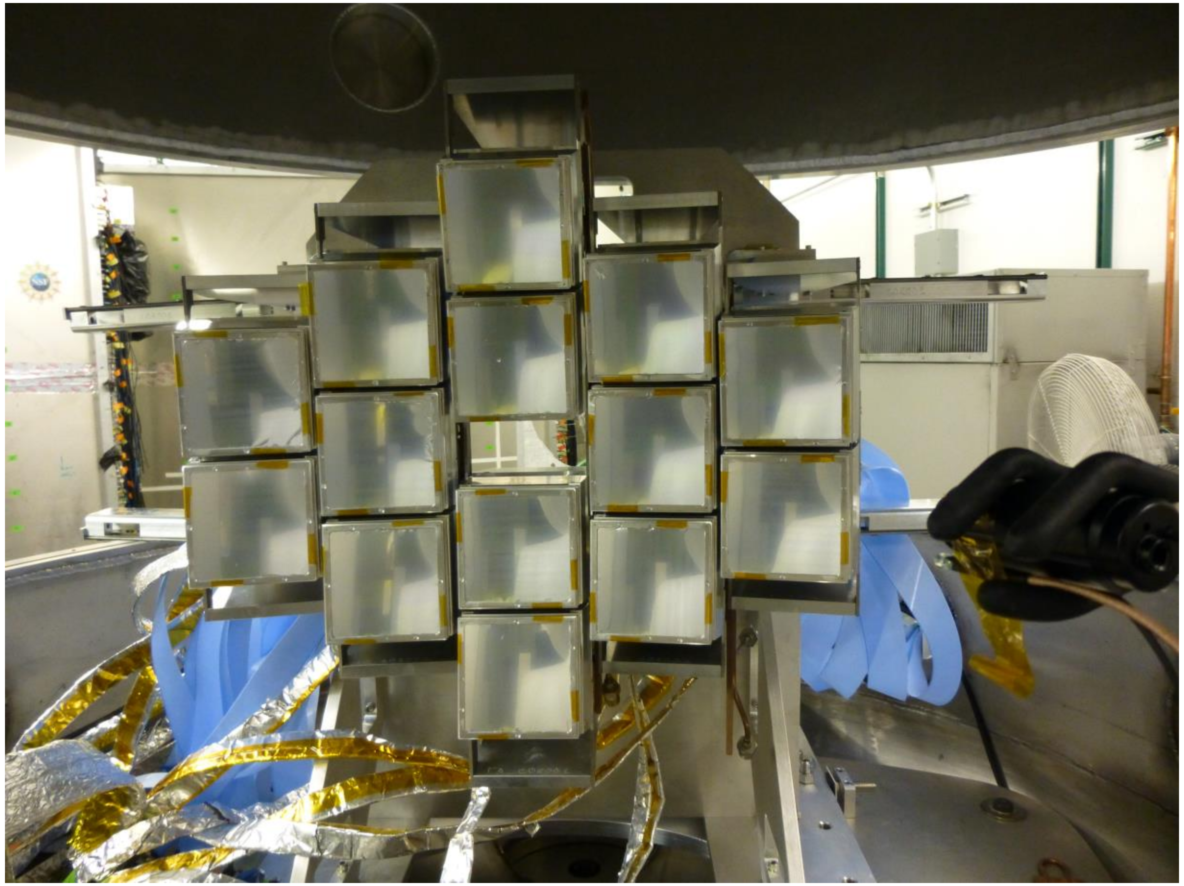


Overview for light systems: Z ≤ 10

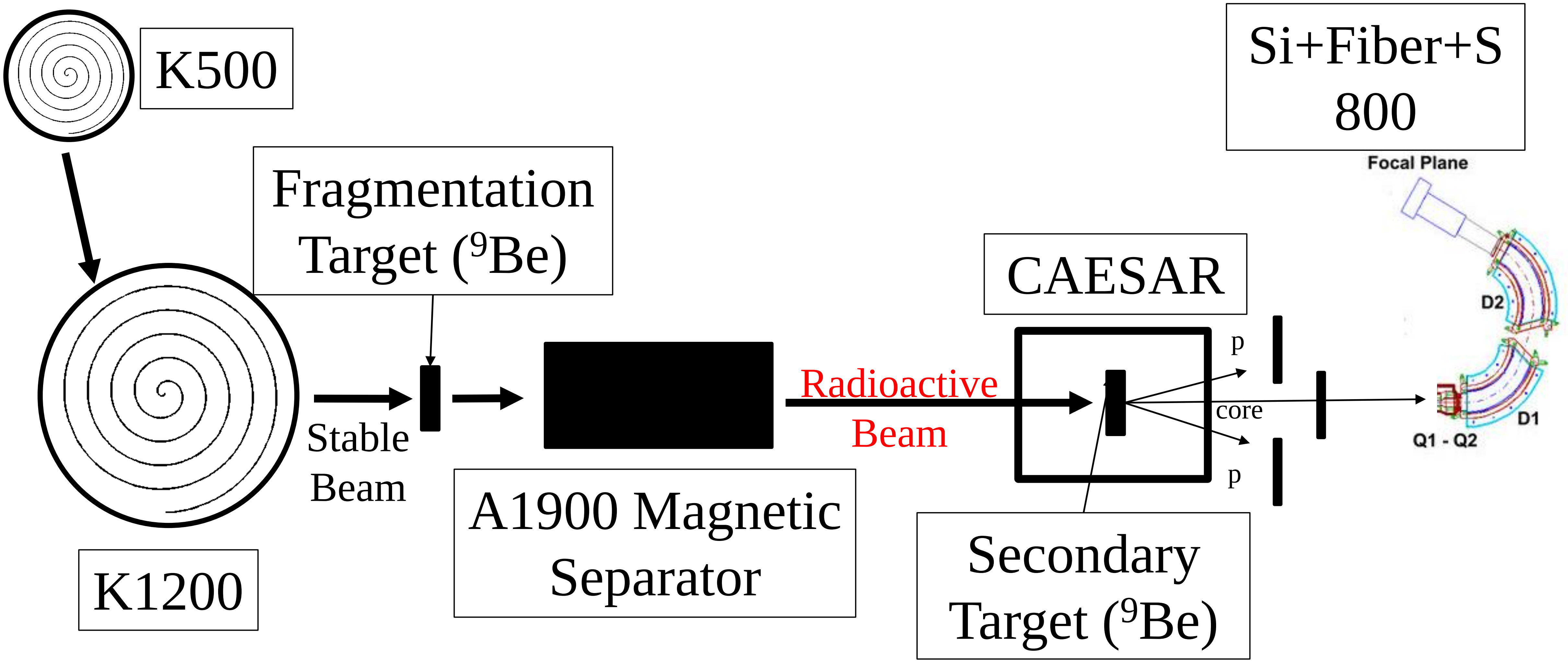


Moving Heavier

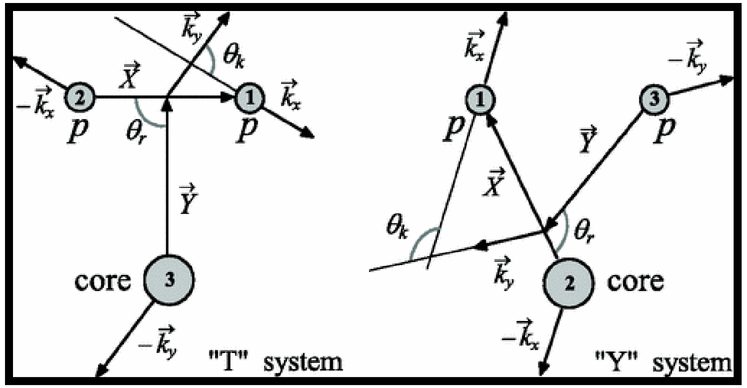




Moving Heavier



Comparing ground-states

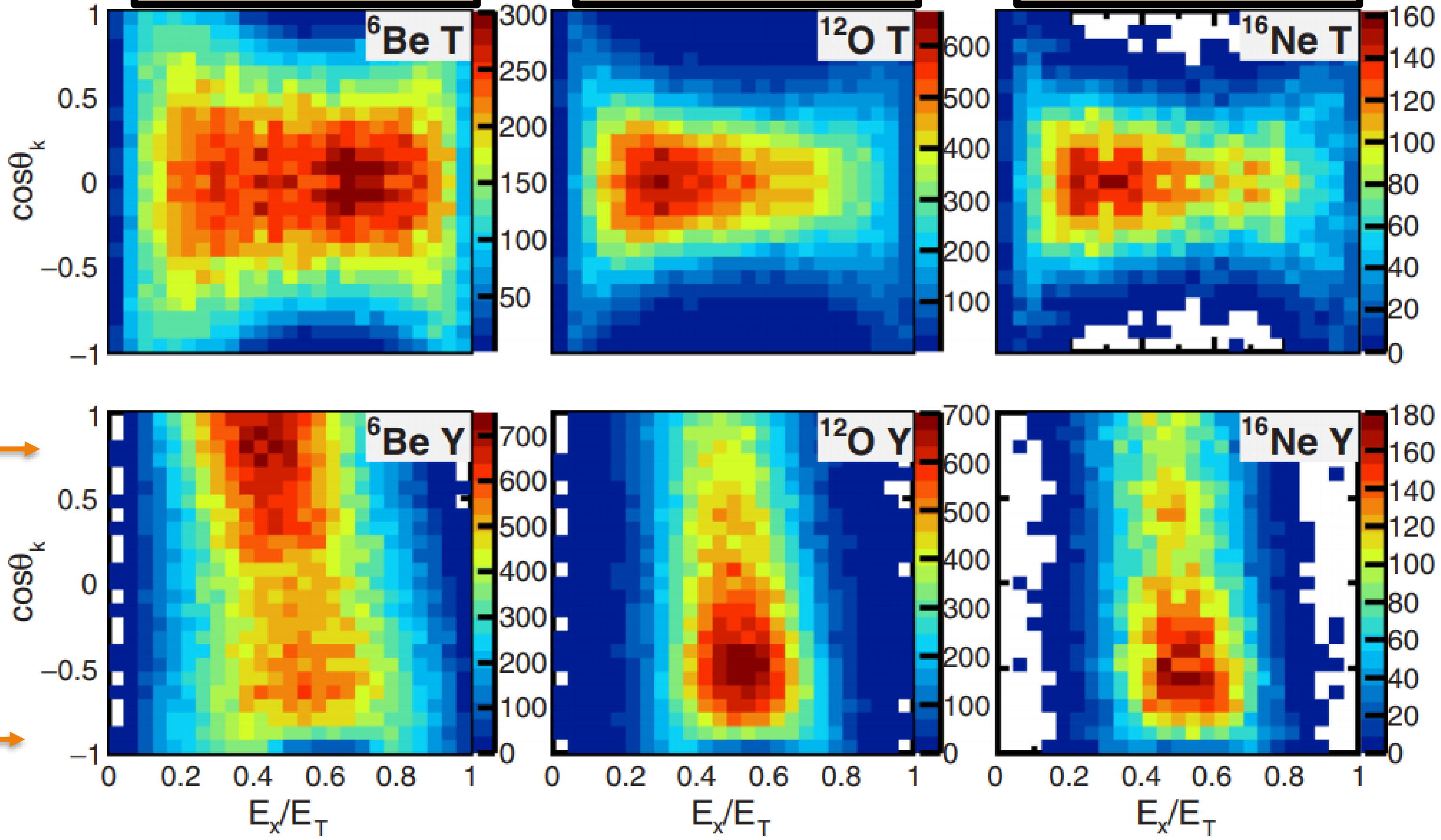


Correlations reveal the underlying structure of the state

^{6}Be->2p+α | ^{12}O->2p+^{10}C | ^{16}Ne->2p+^{14}O

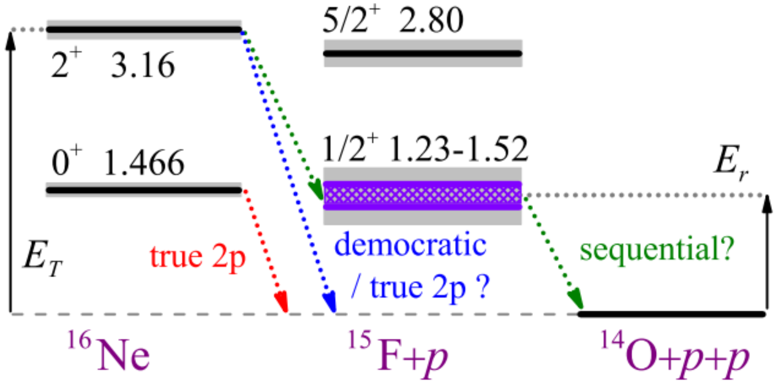
cigar

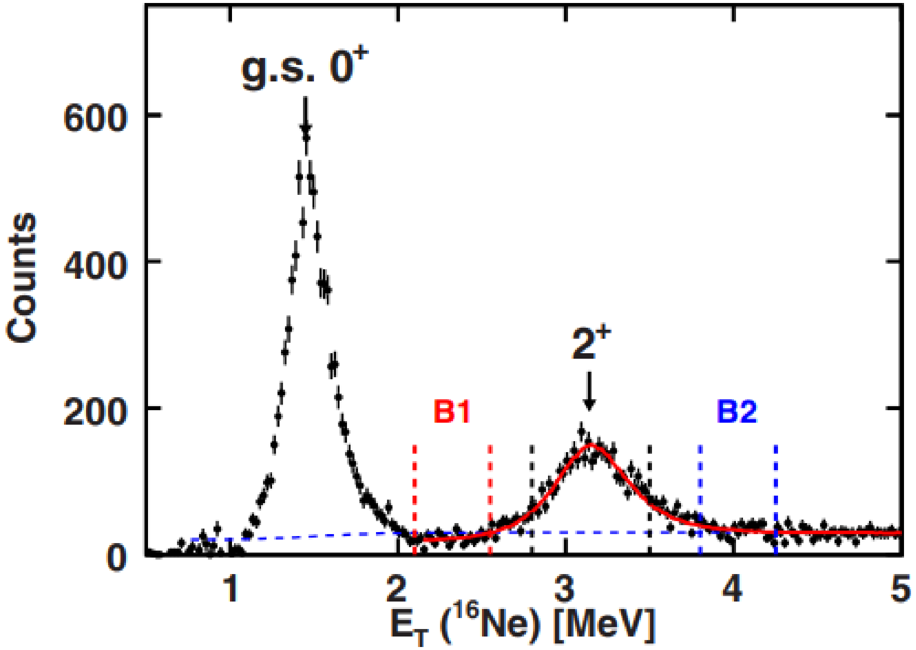
diproton

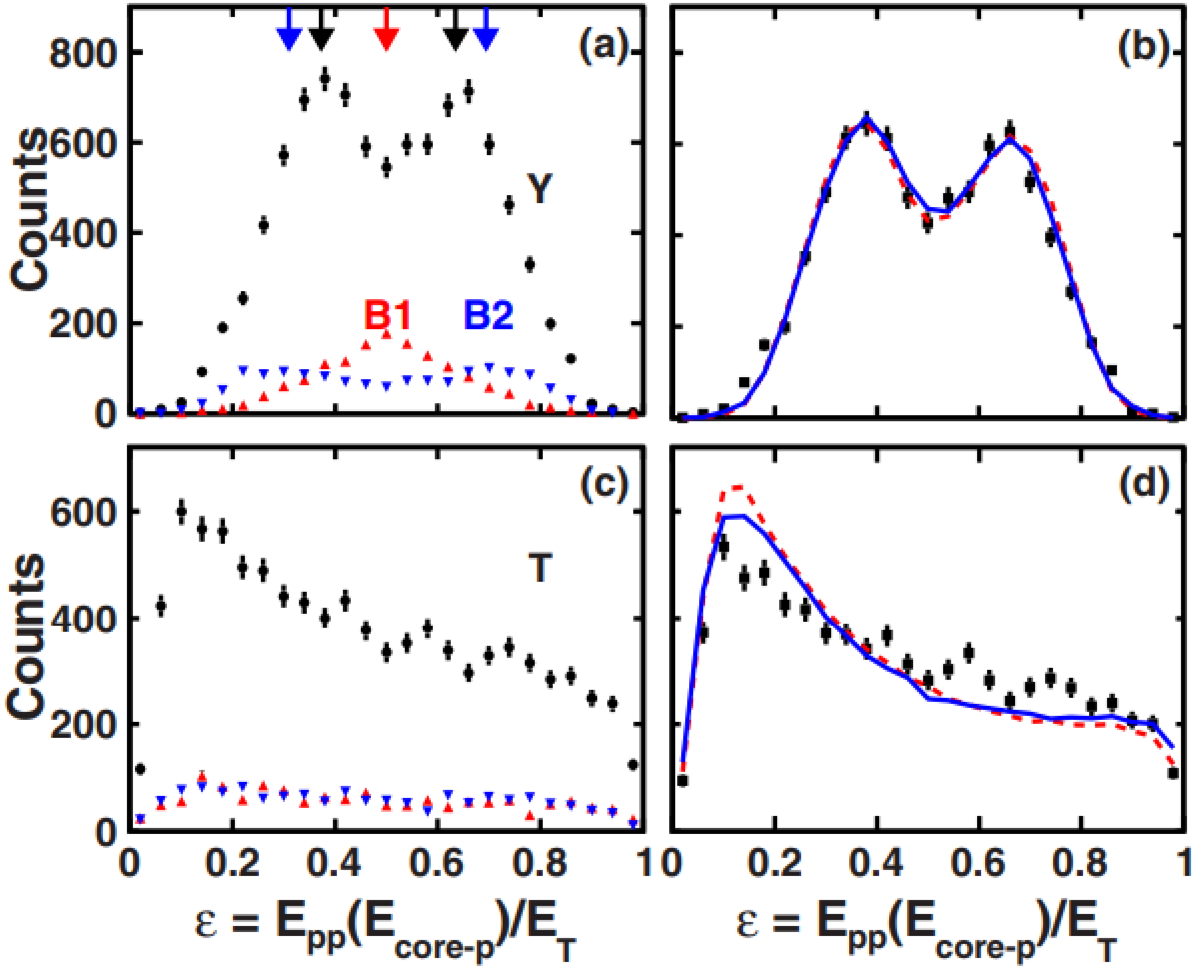


^{6}Be$_{g.s.}$ J=0$^+$	^{12}O$_{g.s.}$ J=0$^+$	^{16}Ne$_{g.s.}$ J=0$^+$
E_T = 1.372 (5) MeV	E_T = 1.688(29) MeV	E_T = 1.466(20) MeV
$(p_{3/2})^2$	$(s_{1/2})^2$, $(p_{1/2})^2$	$(s_{1/2})^2$, $(d_{5/2})^2$

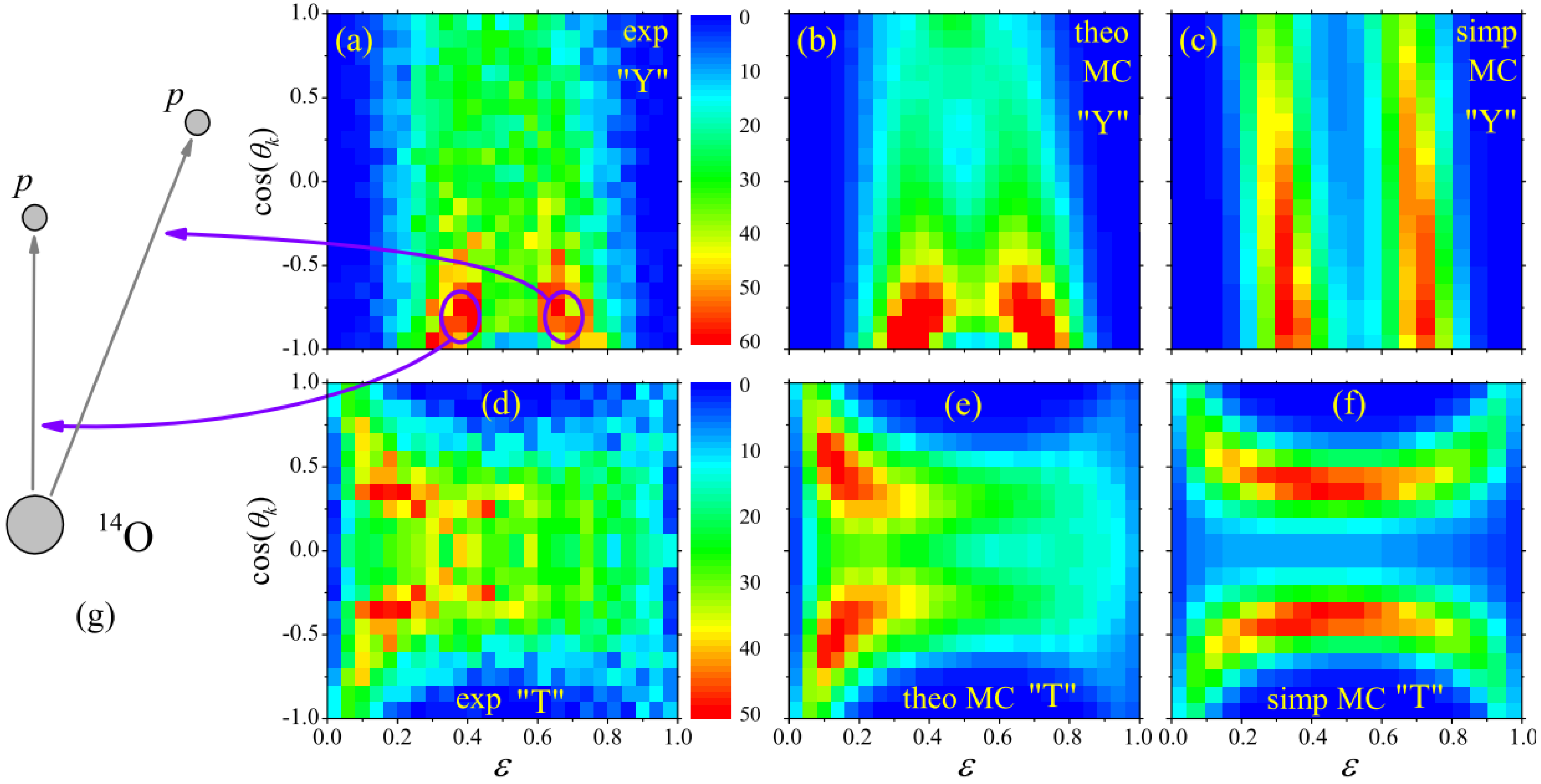
Adding in excitation energy: ^{16}Ne





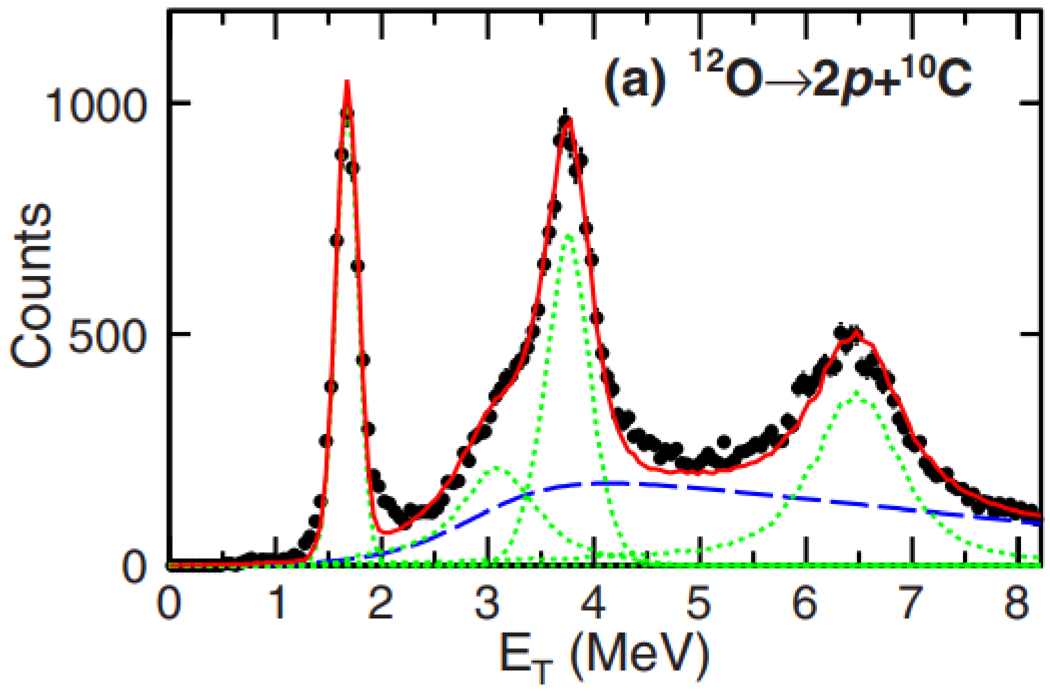


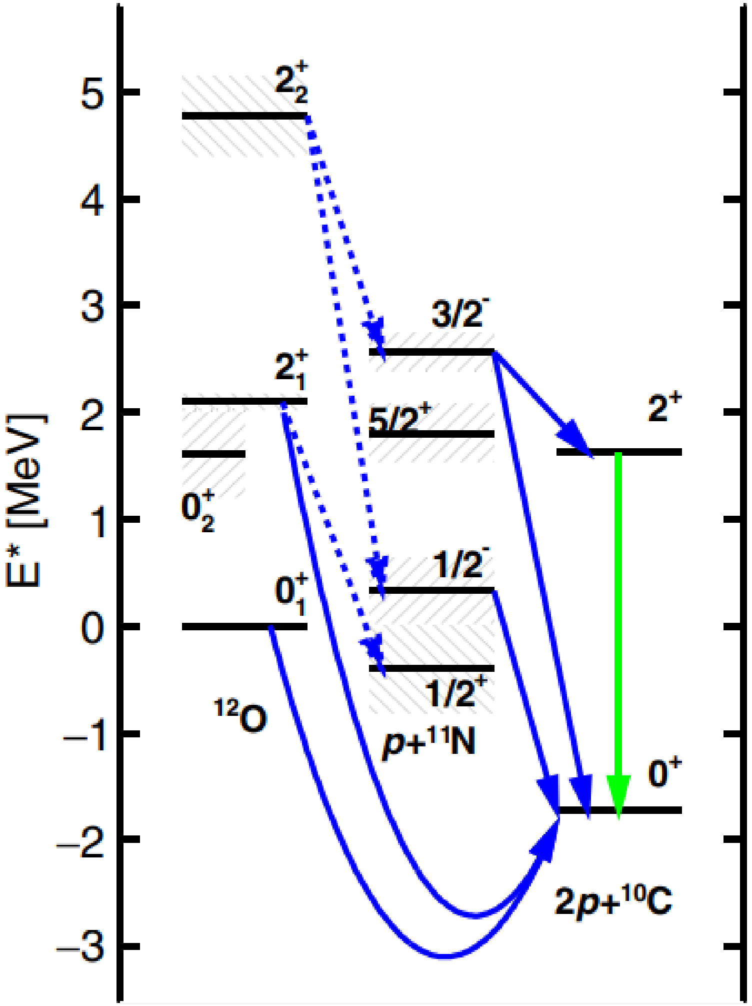
Interplay between prompt and sequential



Sequential decay with memory!

Wider range of excitation energy: ^{12}O



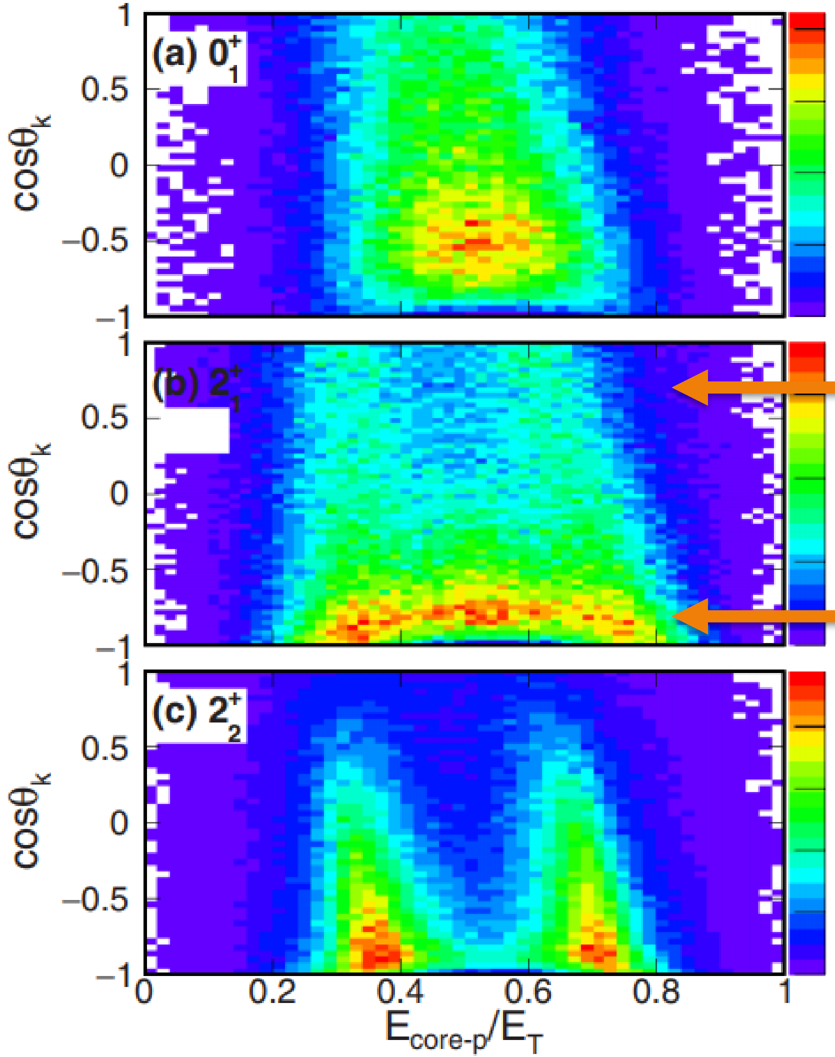


Evolving correlations

Ground State
Democratic 2p Decay

2^+_1 State
Democratic and sequential 2p Decay

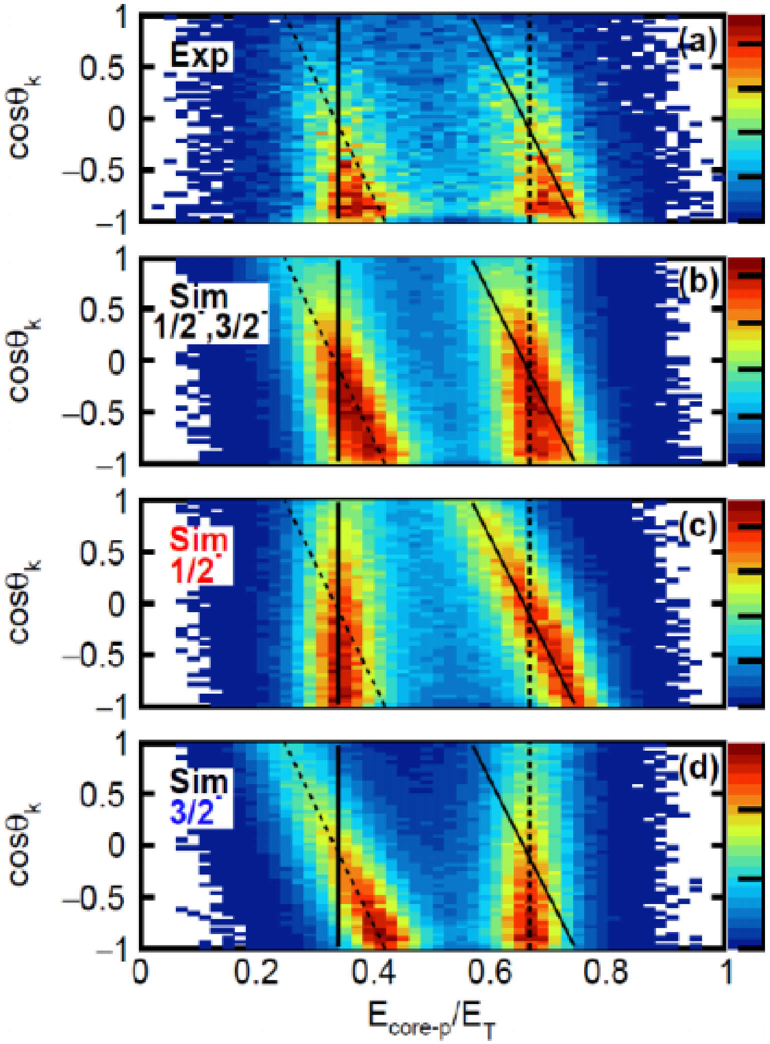
2^+_2 State
Sequential, but with memory



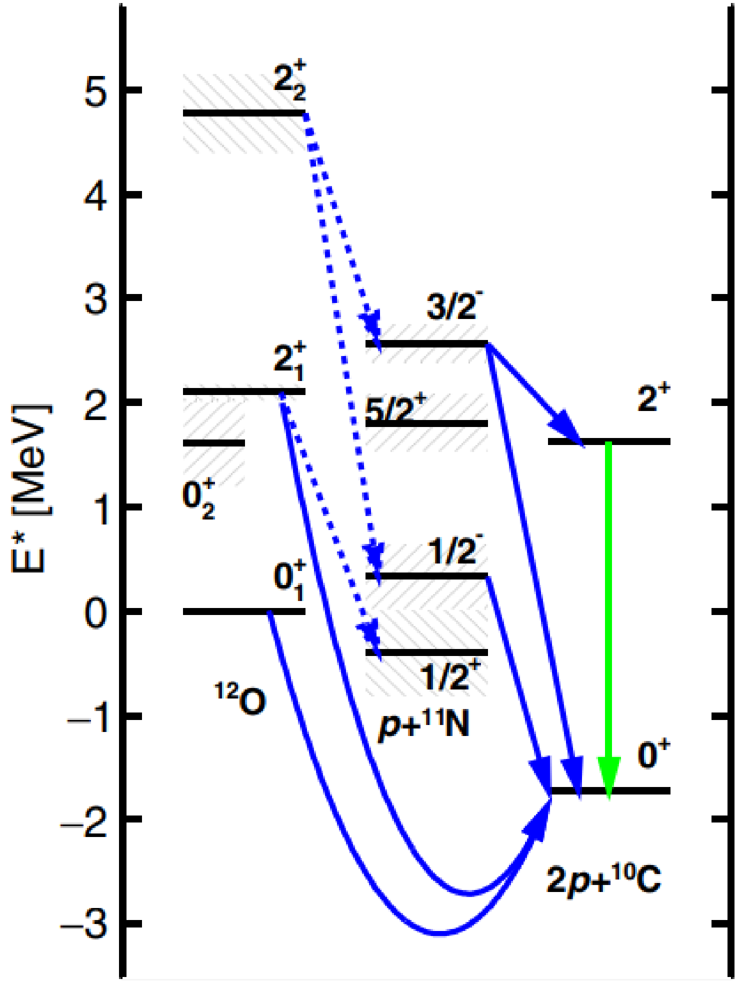
Cigar

Diproton banana

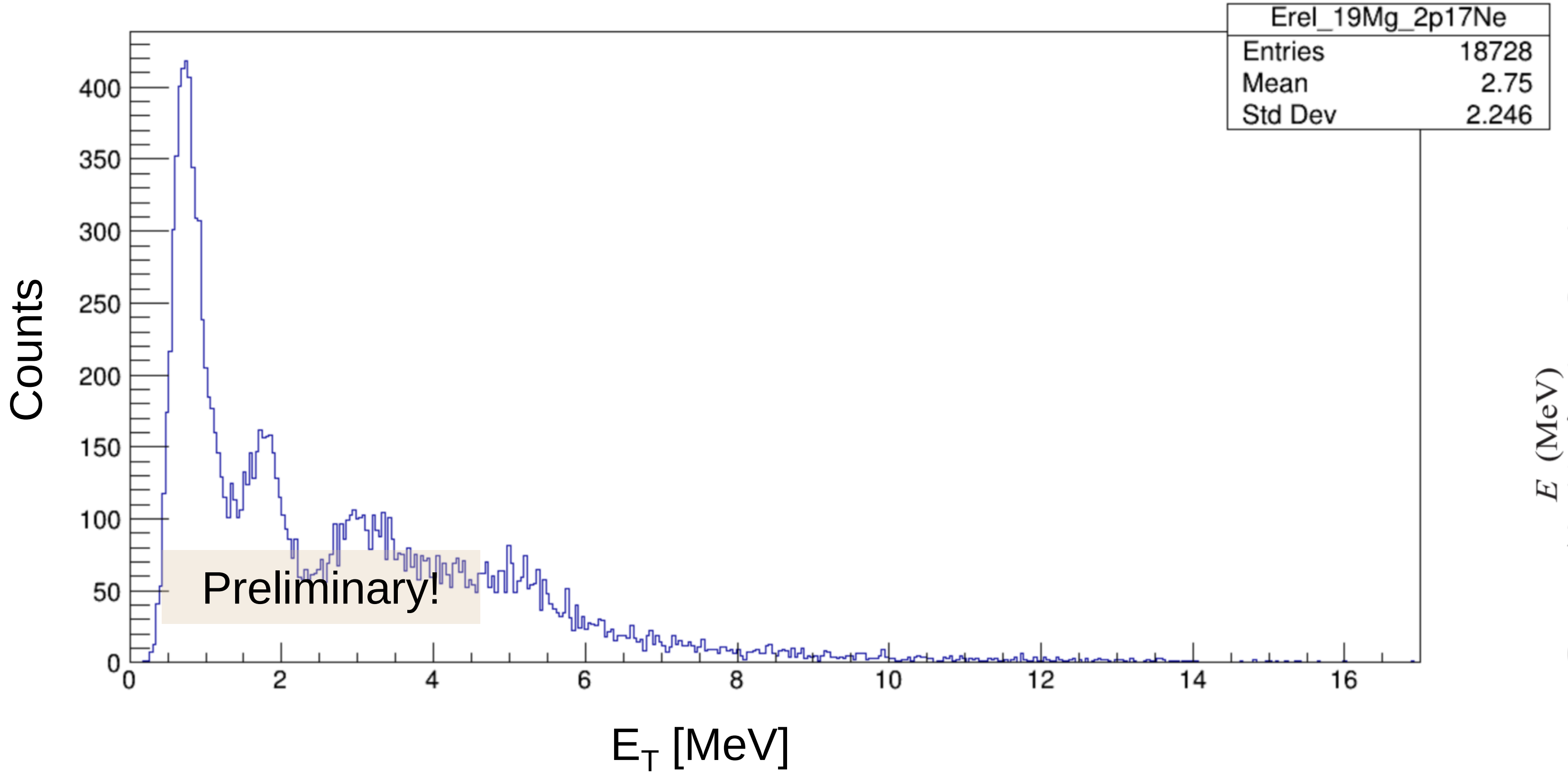
Focusing on the 2^+_2 state

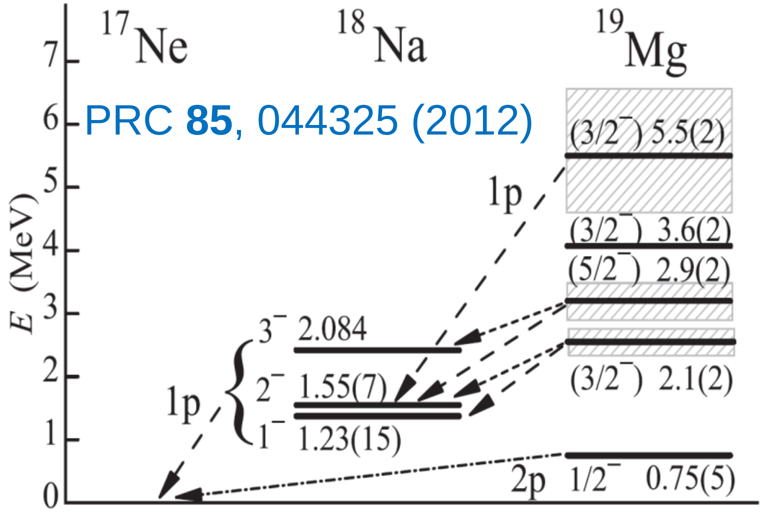


- R-matrix simulations of sequential decay, filtered by the detector response.
- An incoherent sum of the simulations through the $1/2^-$ and $3/2^-$ do a decent job at reproducing the shape
- All simulations fail to reproduce the enhancement in the diproton region



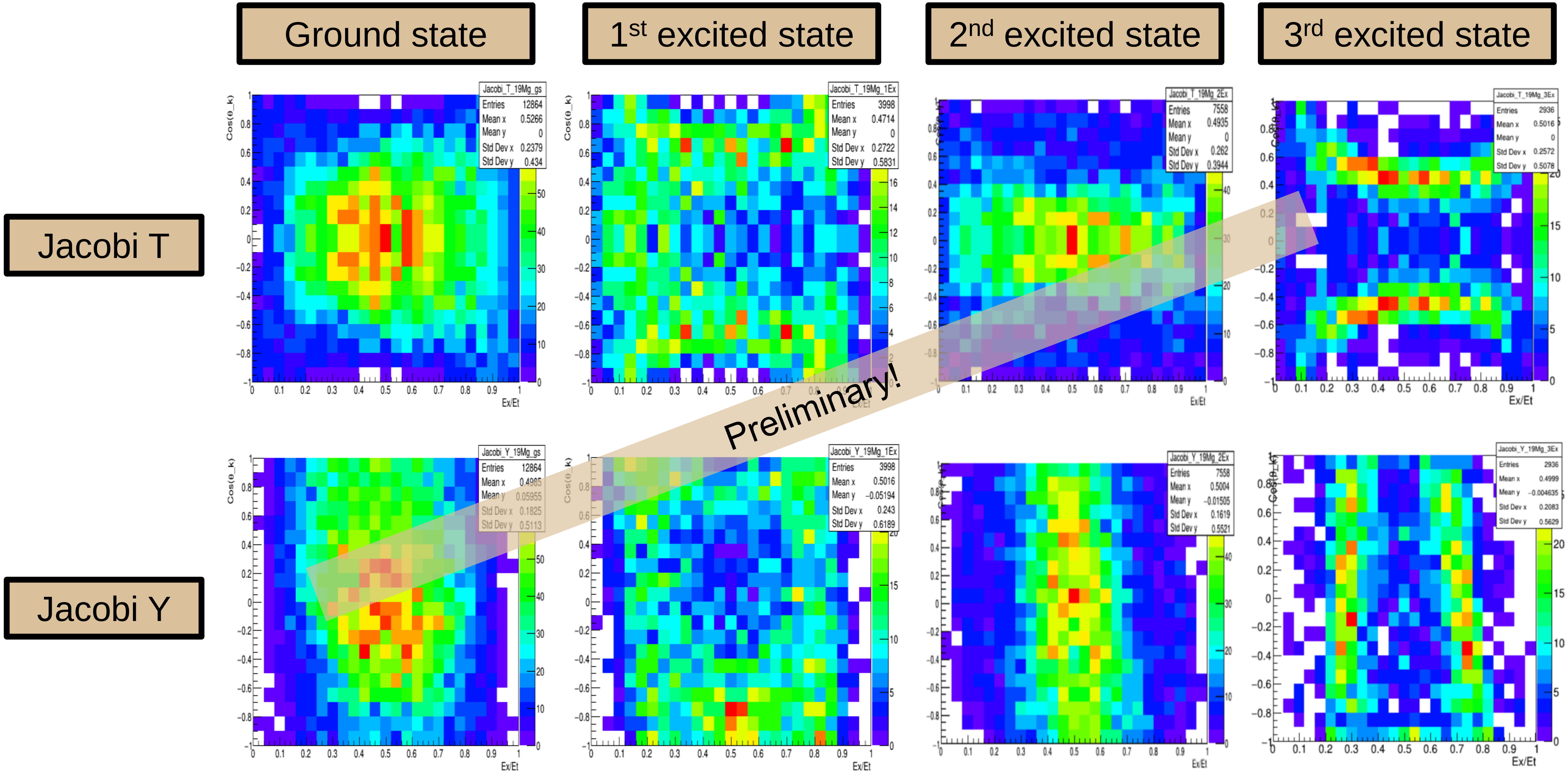
New Results in the *sd*-shell: ^{19}Mg





Rough consistency, but new level energies!

^{19}Mg Correlations



Thesis work of Jin Yu

Conclusions

- 2 proton (or neutron) decays provide a unique window into the internal structure of the nucleus
- With the invariant-mass method and HiRA or the S4+S800, we can make high resolution and high statistics measurements of 2p decays across a wide range of excitation energy

  →With FRIB we can start pushing to heavier nuclei, ie ^{34}Ca
- We have observed very similar decays from the ground states of ^{6}Be, ^{12}O,^{16}Ne, and ^{19}Mg, with small differences coming from the differing shells
- As one moves higher in excitation energy, the decay mode shifts to sequential as those exit channels open, but it is not a sharp transition.
- The excited states of ^{12}O, ^{16}Ne, and ^{19}Mg all show similar behavior