Beta-delayed two-proton spectroscopy at FRIB

Erik A. M. Jensen — Experimental Subatomic Physics — Chalmers

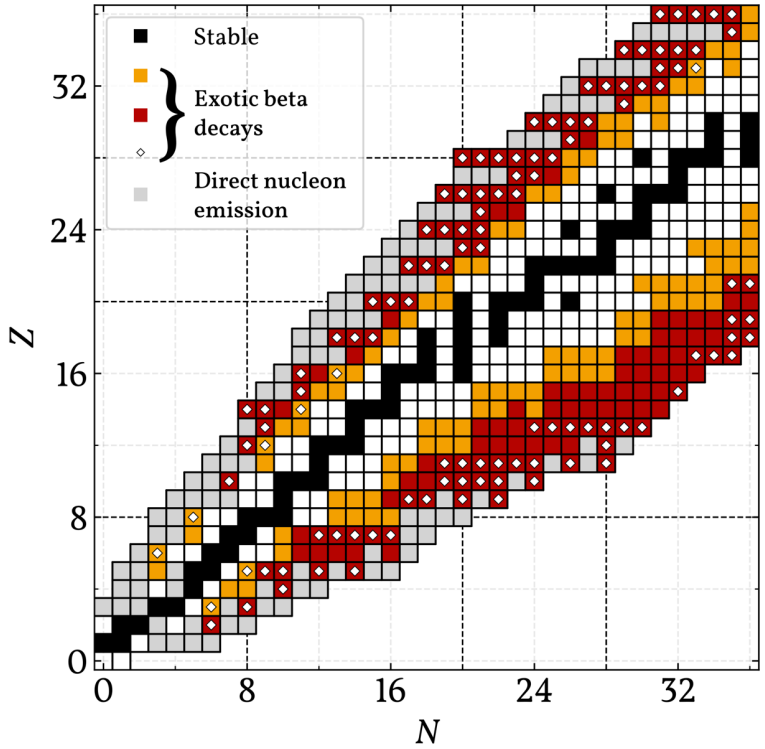
Background

Exotic low-mass nuclei

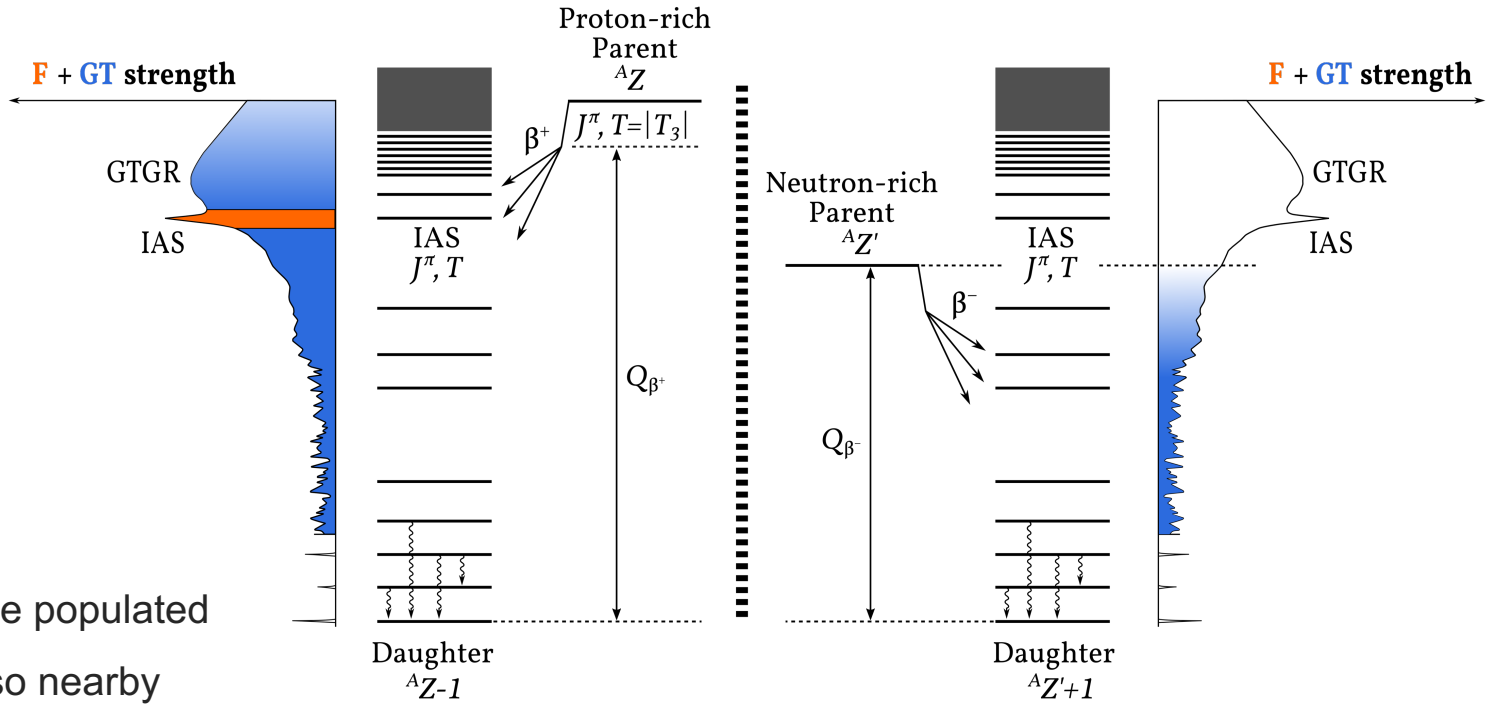
As $A = Z + N$ goes towards ~70:

- Level density becomes greater
- Level widths become smaller
- Clustering in light nuclei evolves into competition between single particle and collective degrees of freedom

Beta decay is an excellent tool to study nuclear structure evolution far from stability!



Beta-decays far from stability



$Z > N$:

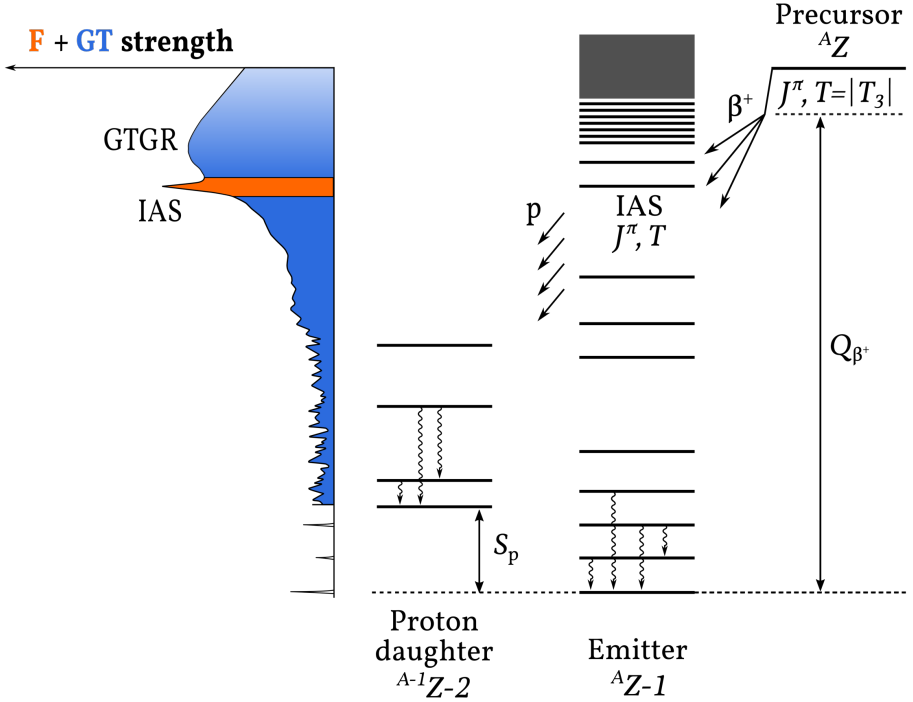
- IAS can be populated
- GTGR also nearby

Beta-decays far from stability

Far from stability, gamma decay and charged particle emission from daughter compete

~1 MeV above threshold:
Charged particle emission dominates gamma radiation

Experimentally: Detection of gammas and charged particles reveal the beta strength & nuclear structure via selective (allowed) and “clean” population of levels



Beta-decays far from stability

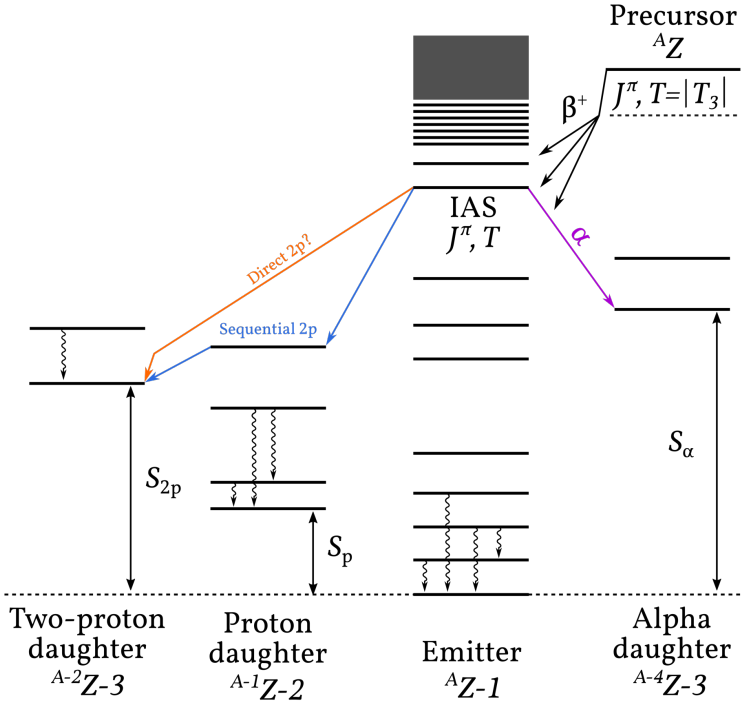
Sufficiently exotic emitters undergo multi-particle breakup

We observe:

- Beta-delayed proton emission (βp)
- Beta-delayed 2-proton emission (β2p)
- Beta-delayed α emission (βα)

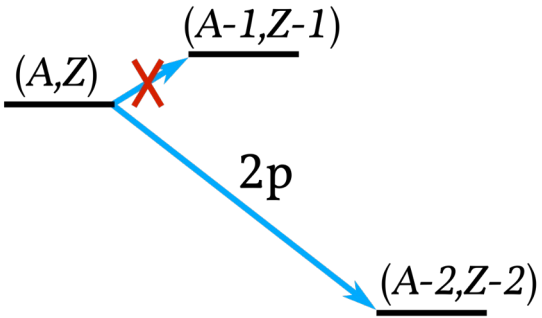
How similar is β2p to βα?

Can 2p happen directly as ”^{2}He”?



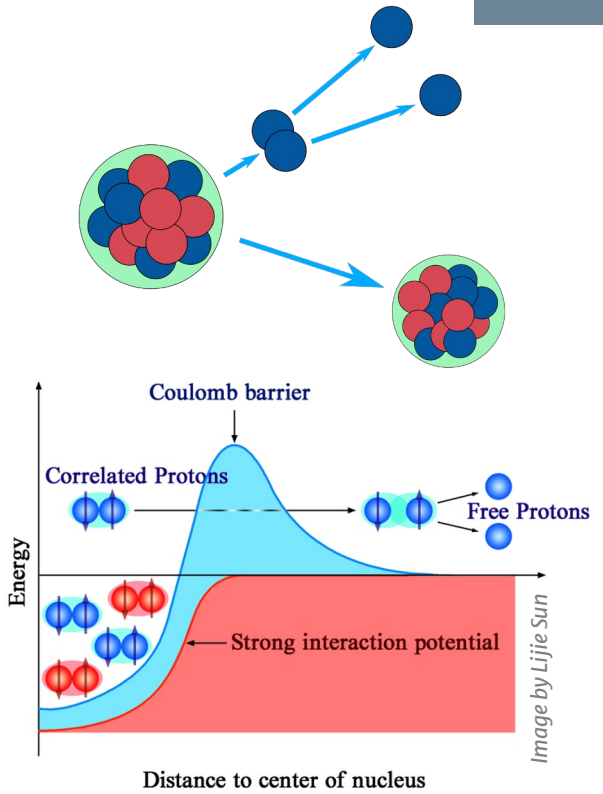
Can 2p happen directly as ”^{2}He”?

Yes, if 1p-daughter is kinematically inaccessible



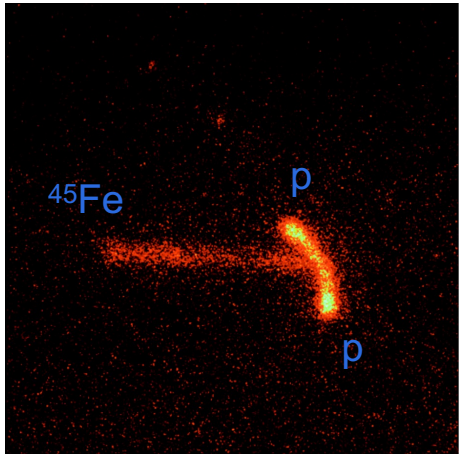
Known long-lived ground state 2p emitters:

^{45}Fe, ^{48}Ni, ^{54}Zn, ^{67}Kr

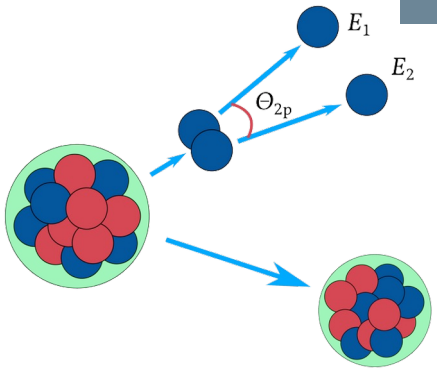


Can 2p happen directly as "^{2}He"?

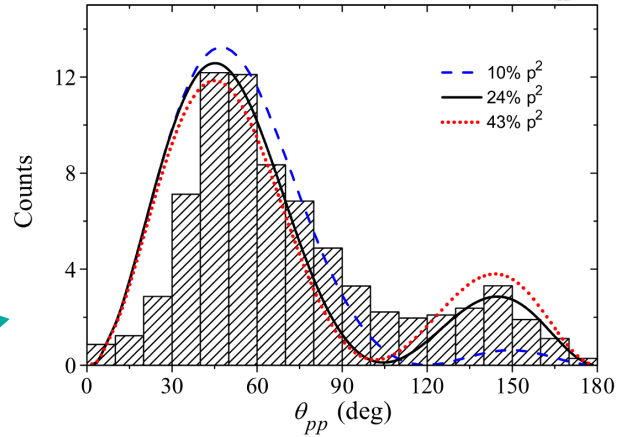
Ground state 2p emission in ^{45}Fe using Optical Time Projection Chamber



K. Miernik et al., PRL **99**, 192501 (2007)

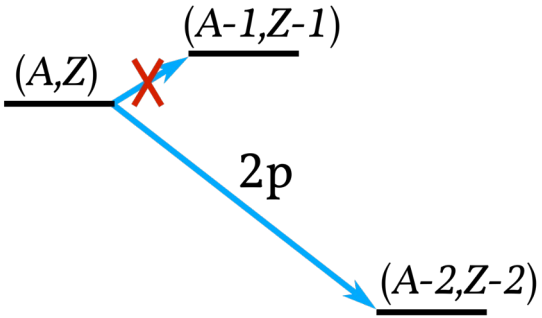


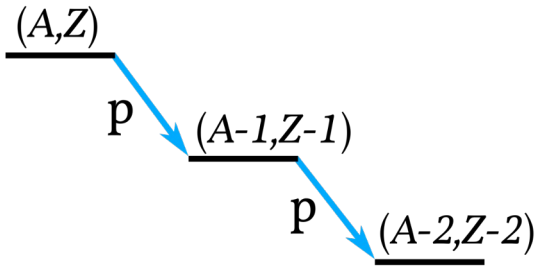
(Model-dependent) signature of direct (as opposed to sequential) 2p emission

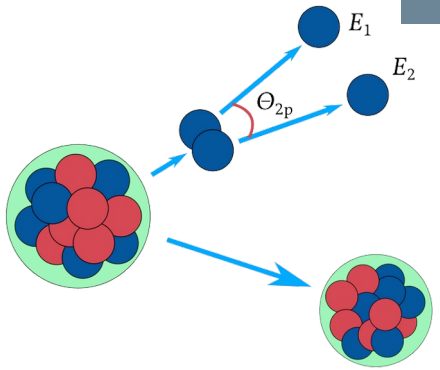


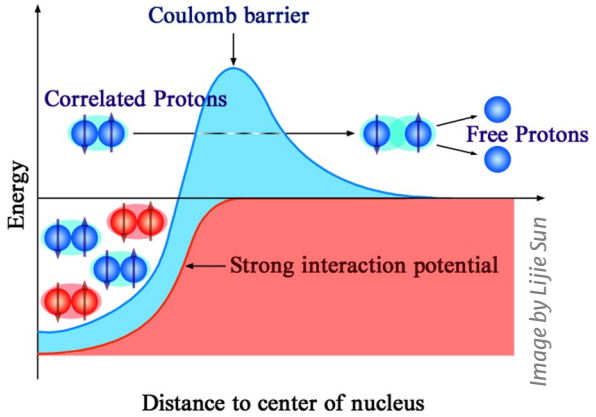
Can 2p happen directly as ”^{2}He”?

But, in beta-delayed case, 1p-daughter will always be kinematically accessible…









… and the sequential branches then dominate

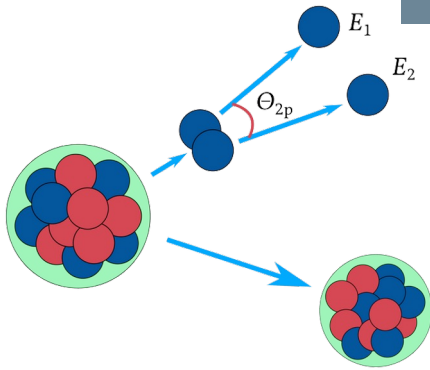
Could there be competition between sequential and direct decay? Interference, even?

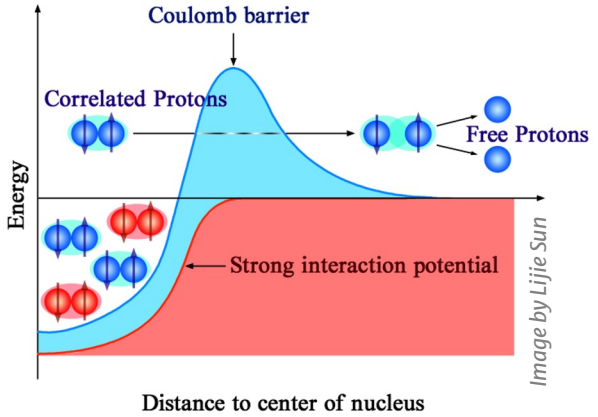
Can 2p happen directly as ”^{2}He”?

But, in beta-delayed case, 1p-daughter will always be kinematically accessible…

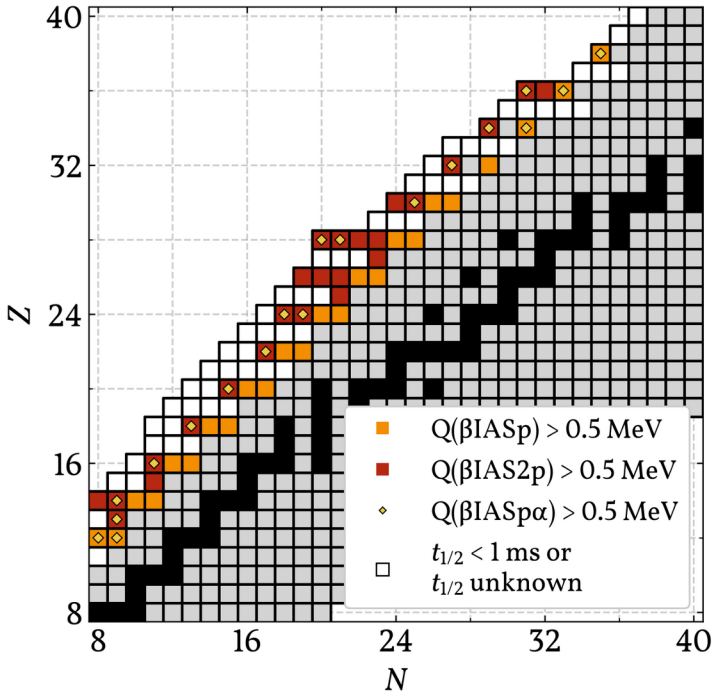
… and the sequential branches then dominate

Could there be competition between sequential and direct decay? Interference, even?

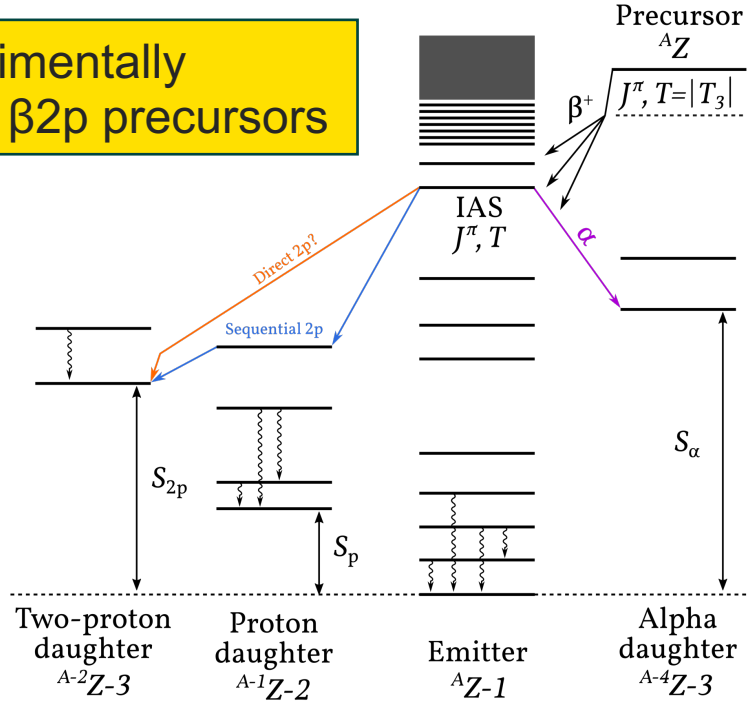




β2p: The available options

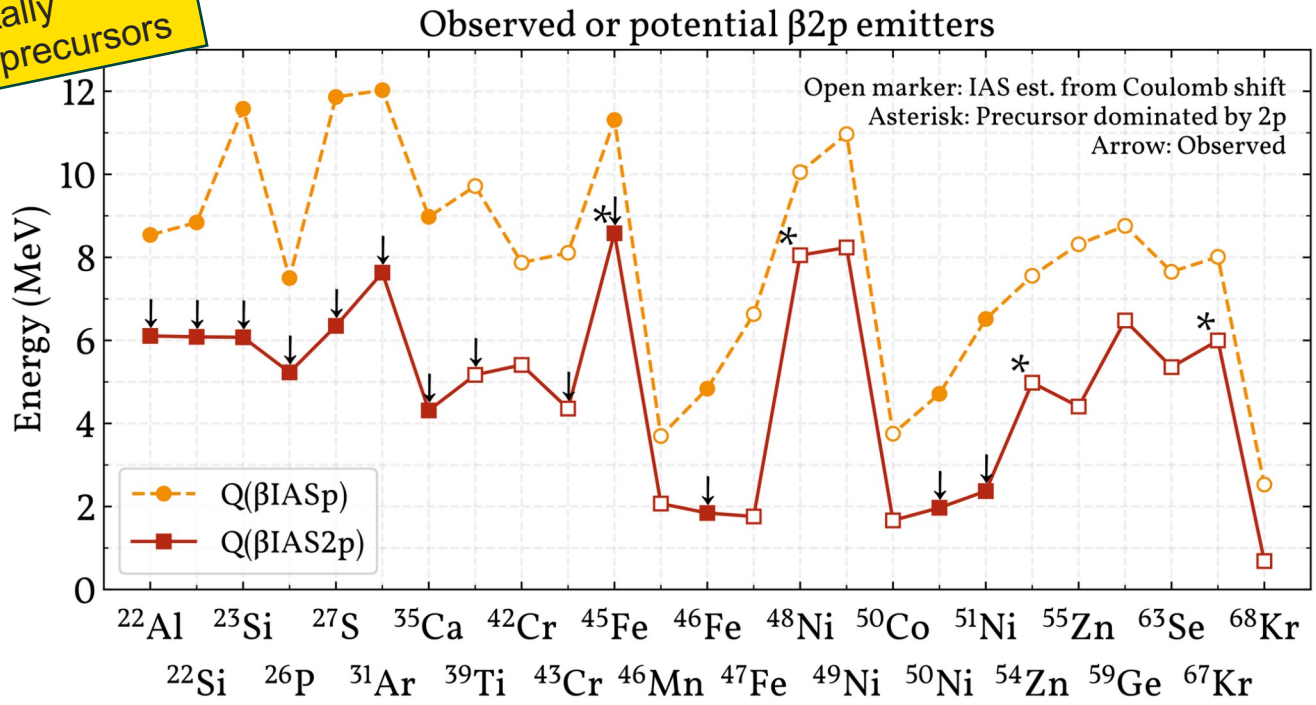


25 experimentally feasible* β2p precursors



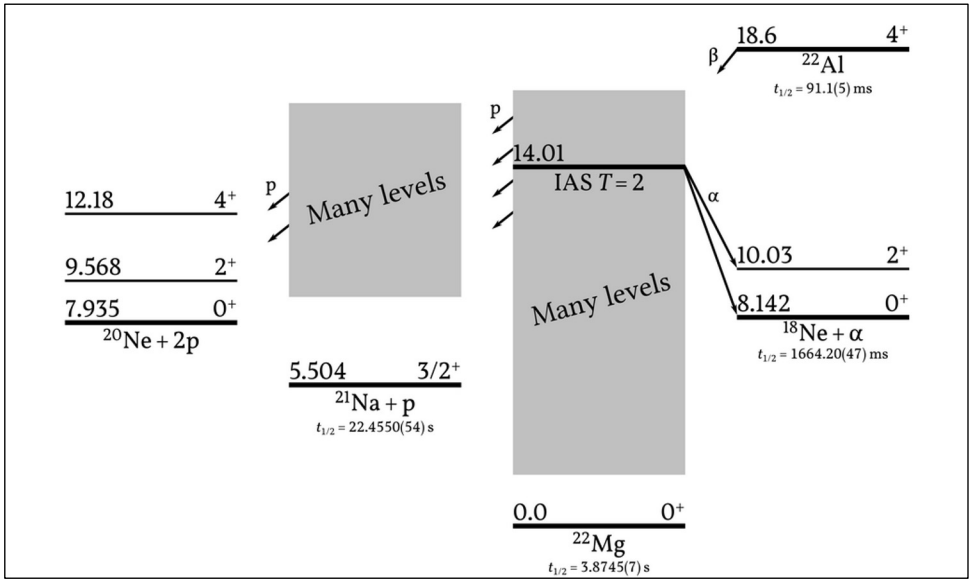
β2p: The available options

25 experimentally feasible* β2p precursors



Coulomb barrier →

The prime candidate for direct β2p: ^{22}Al



The prime candidate for direct β2p: ^{22}Al

Theory

J^π	E_x (MeV)	Γ (keV) $l=0$	Γ (keV) $l=2$
$\frac{3}{2}^+$	0.000		0.055
$\frac{5}{2}^+$	0.239		0.071
$\frac{7}{2}^+$	1.773	0.041	0.371
$\frac{9}{2}^+$	2.779	0.073	0.071
$\frac{13}{2}^+$	2.780		0.004
$\frac{5}{2}^+$	3.664		0.017
$\frac{11}{2}^+$	4.449		0.041
$\frac{5}{2}^+$	4.502		0.043
$\frac{3}{2}^+$	4.753		0.012
$\frac{7}{2}^+$	5.341	0.000	0.001
$\frac{3}{2}^+$	5.700		0.000
$\frac{13}{2}^+$	5.810		0.004
$\frac{9}{2}^+$	6.066	0.008	0.000
$\frac{9}{2}^+$	6.191	0.157	0.012
$\frac{7}{2}^+$	6.299	0.023	0.020
	> 6.3		

1p ~50%

2p ~50%

Final nucleus	J^π	Γ (keV)
^{20}Ne	0^+	6.2×10^{-5}
^{20}Ne	2^+	1.2×10^{-2}
^{20}Ne	4^+	3.3×10^{-5}
^{18}Ne	0^+	3.8×10^{-4}
^{18}Ne	2^+	7.1×10^{-3}
^{18}Ne	4^+	3.0×10^{-5}

"^{2}He" ~1%

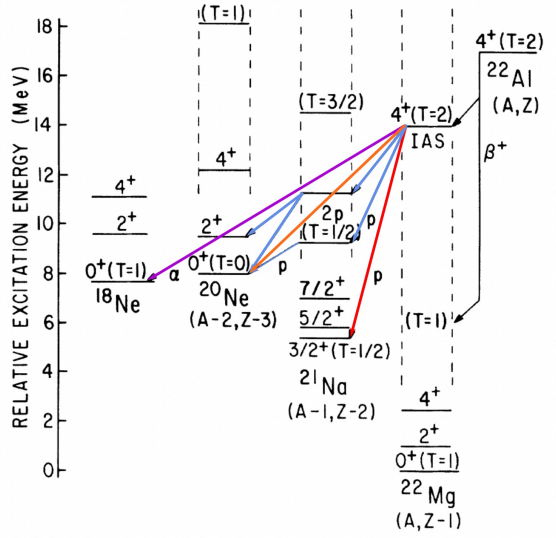
α ~1%

} "^{2}He" and α similar B.R.

VOLUME 65, NUMBER 22 PHYSICAL REVIEW LETTERS 26 NOVEMBER 1990

Isospin-Forbidden β-Delayed Proton Emission

B. Alex Brown
National Superconducting Cyclotron Laboratory and Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan 48824-1321
(Received 20 August 1990)

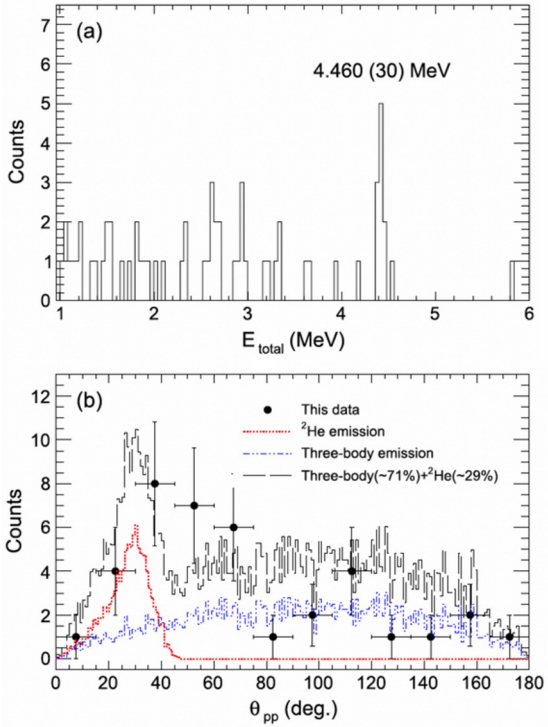


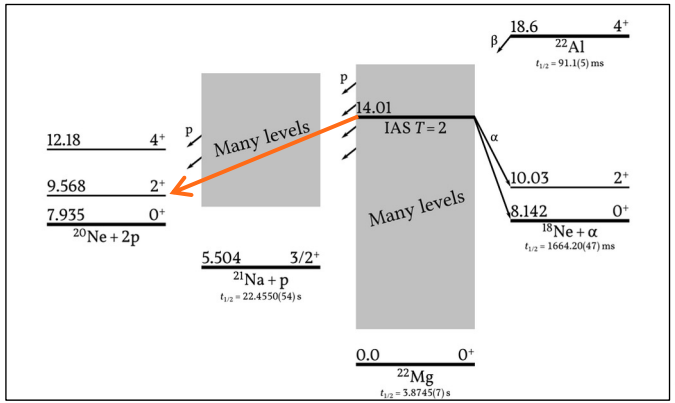
The prime candidate for direct β2p: ^{22}Al

Observation of β-delayed ^{2}He emission from the proton-rich nucleus ^{22}Al

Y.T. Wang *et al.* Phys. Lett. **B784** (2018) 12

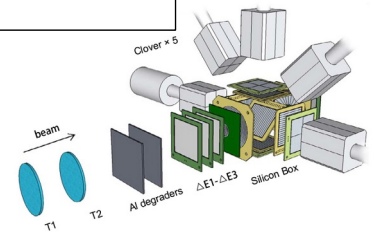
Experiment





"^{2}He"
29(13)%

In-flight
@ RIBLL1

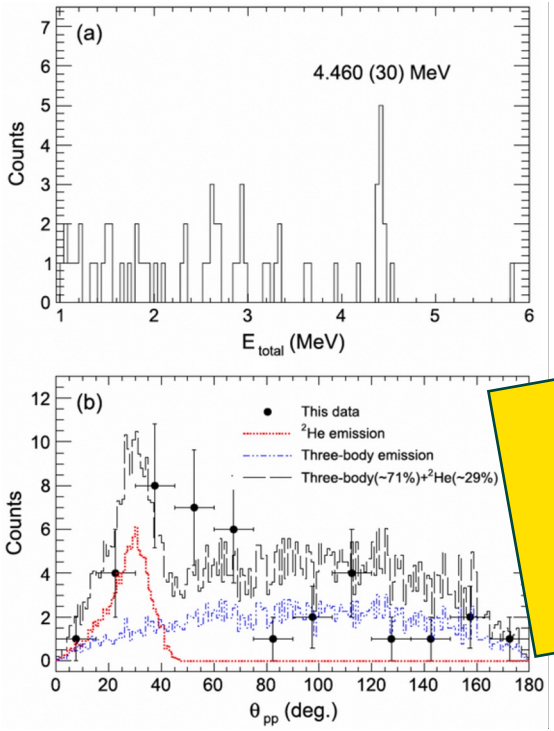


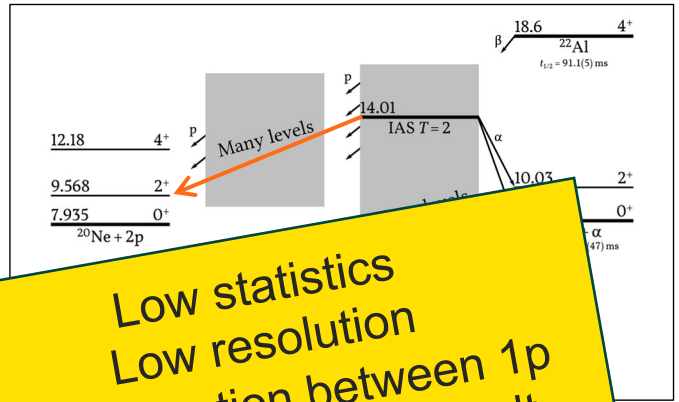
The prime candidate for direct β2p: ^{22}Al

Observation of β-delayed ^{2}He emission from the proton-rich nucleus ^{22}Al

Y.T. Wang *et al.* Phys. Lett. **B784** (2018) 12

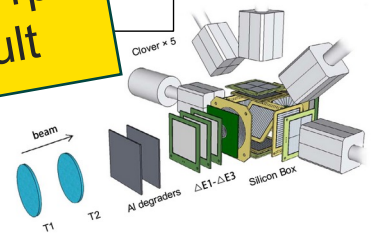
Experiment





Low statistics
Low resolution
Discrimination between 1p and 2p branches difficult

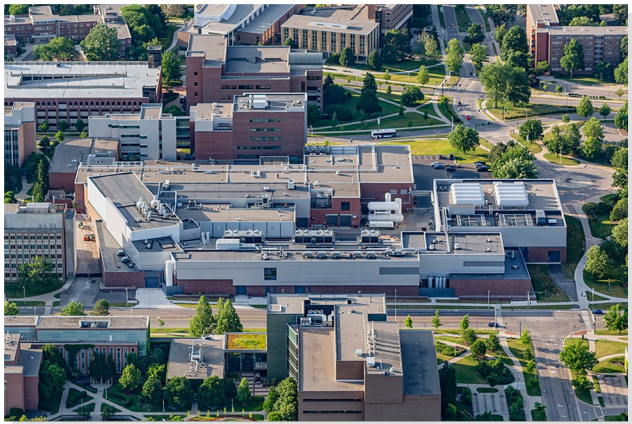
In-flight @ RIBLL1

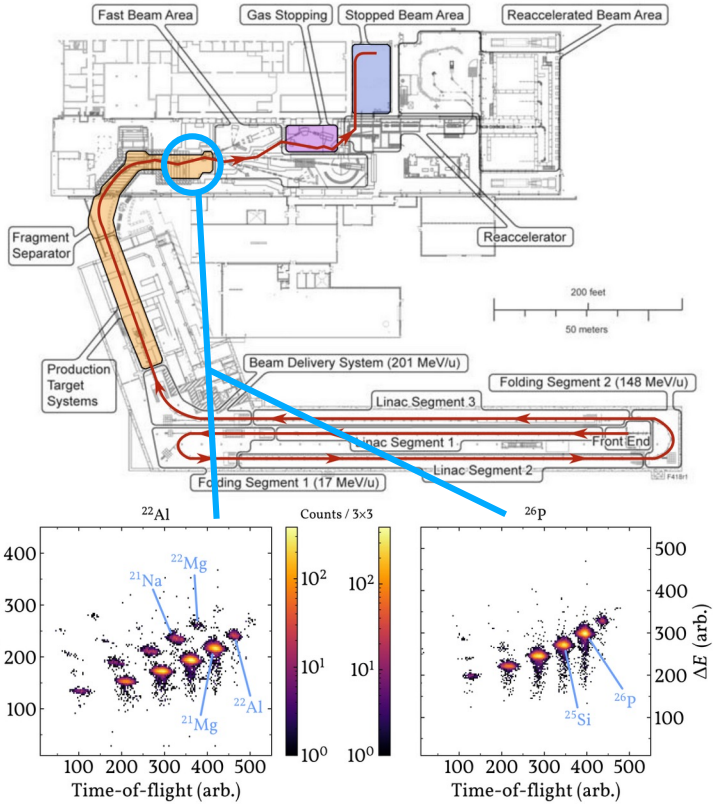


"^{2}He"
29(13)%

Enter FRIB and MAGISOL

Stopped Beams at FRIB: ^{22}Al and ^{26}P

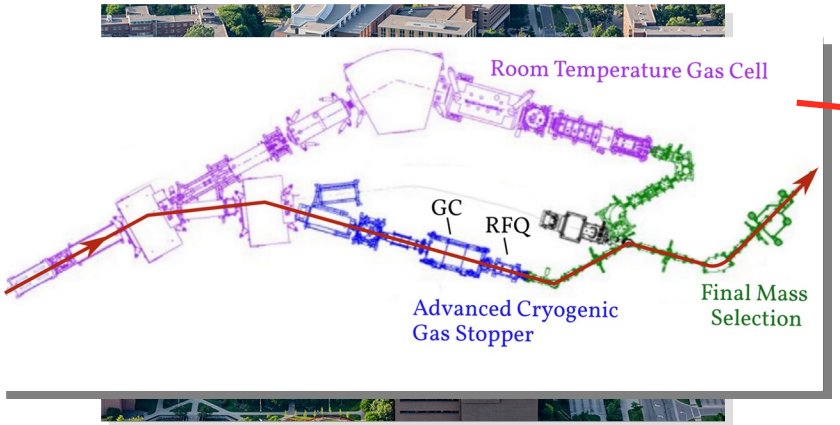


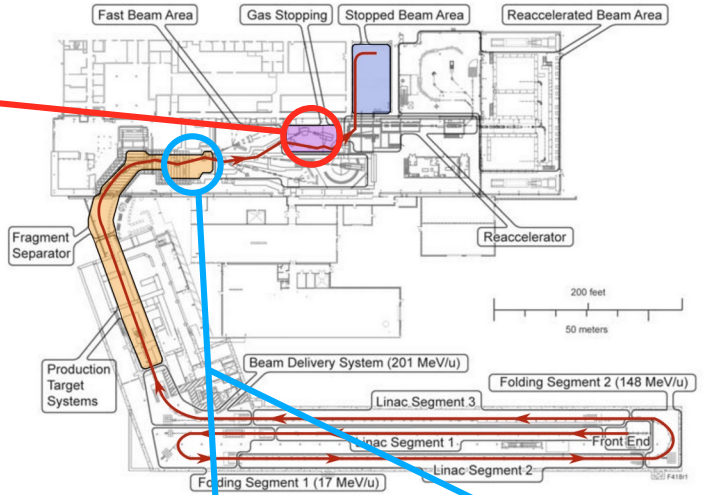


Experiment in June 2023
1st Stopped Beam Experiment at FRIB, USA

- Primary beam ^{36}Ar @ 210 MeV/u
- Production target ^{12}C
- Cooling of in-flight beam in Gas Stopper

Stopped Beams at FRIB: ^{22}Al and ^{26}P

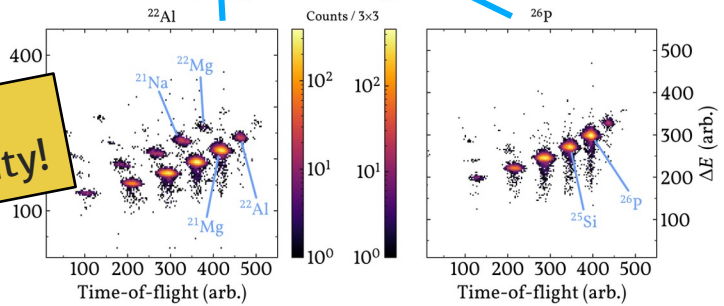




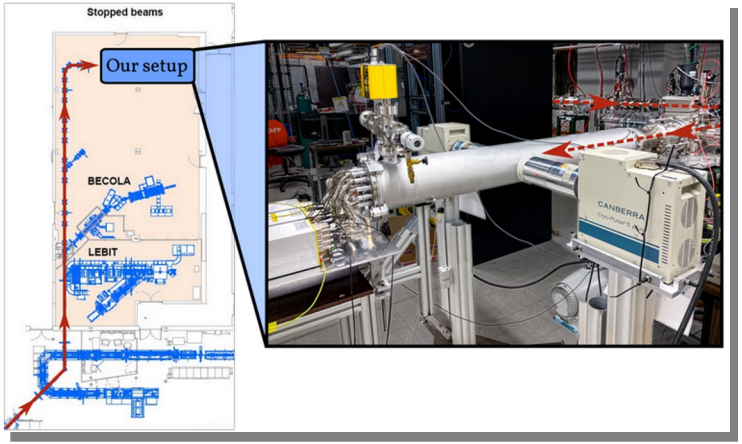
Experiment in June 2023
1st Stopped Beam Experiment at FRIB, USA

- Primary beam ^{36}Ar @ 210 MeV/u
- Production target ^{12}C
- Cooling of in-flight beam in Gas Stopper

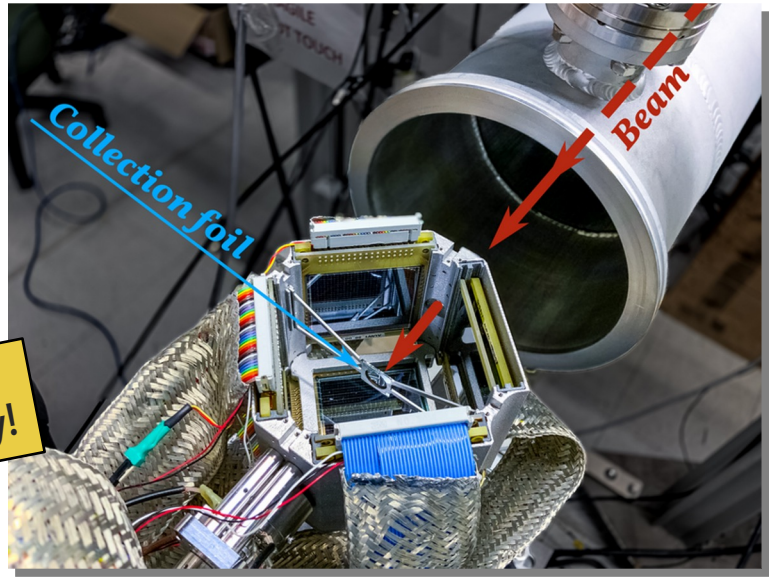
ISOL-like beam quality!



Stopped Beams at FRIB: ^{22}Al and ^{26}P



MAGISOL Silicon Cube :
- 6 ΔE–E silicon detectors
  ΔE: 16x16 DSSSDs
- 42 % of 4π for p/α
- 18 % of 4π for 2p



Experiment in June 2023
1st Stopped Beam Experiment at FRIB, USA

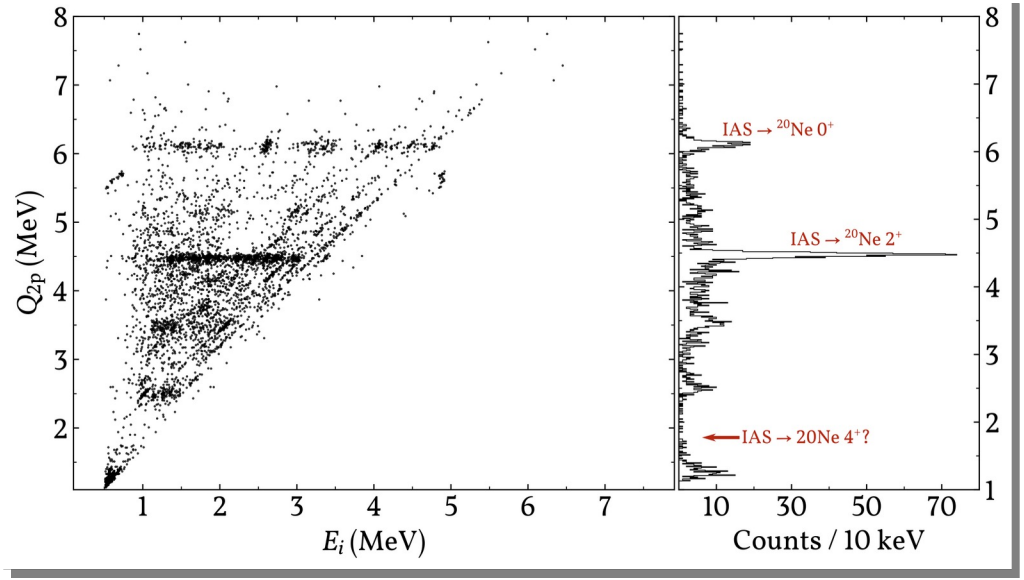
- Primary beam ^{36}Ar @ 210 MeV/u
- Production target ^{12}C
- Cooling of in-flight beam in Gas Stopper

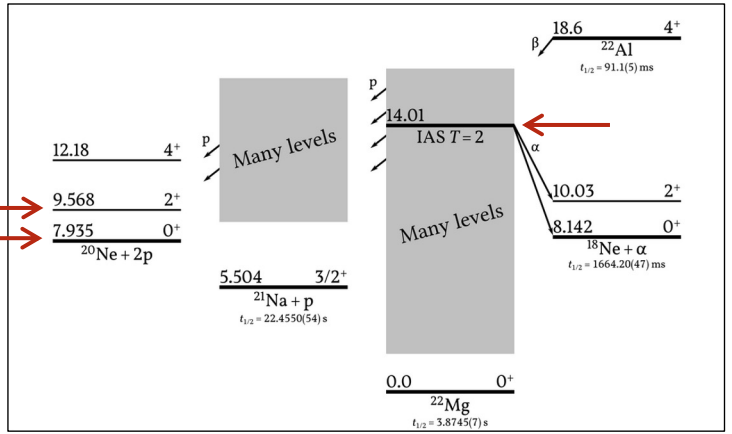
ISOL-like beam quality!

β2p: ^{22}Al

33 h beam time

- 9*10^3 pps expected
- 7*10^0 pps delivered



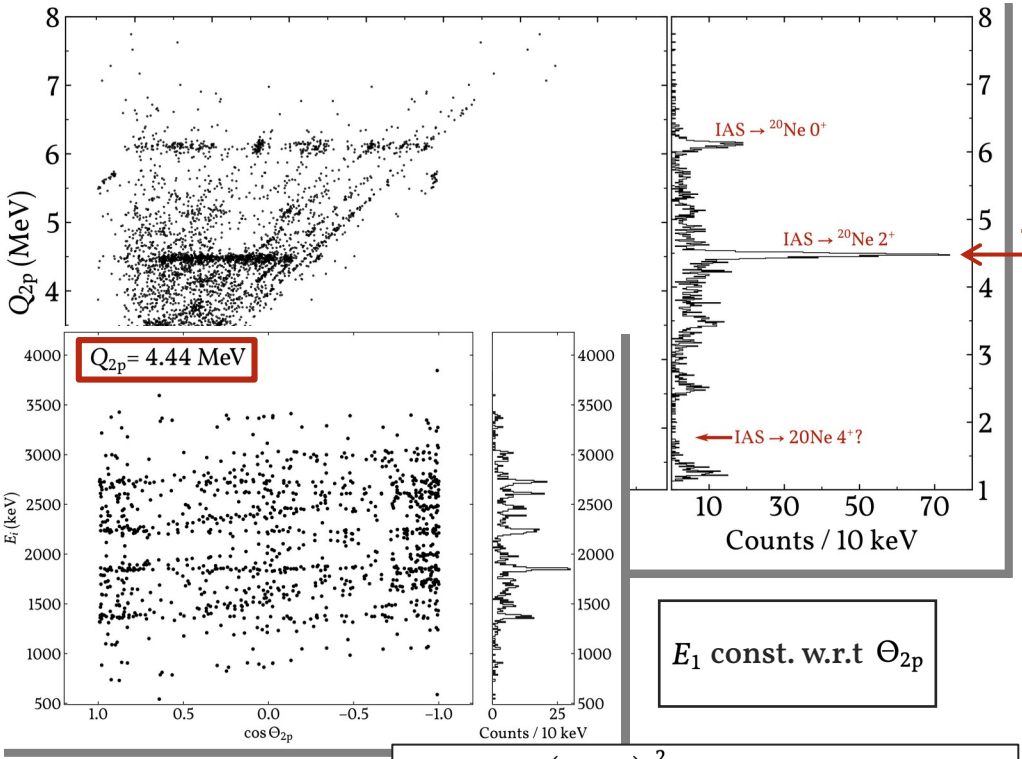


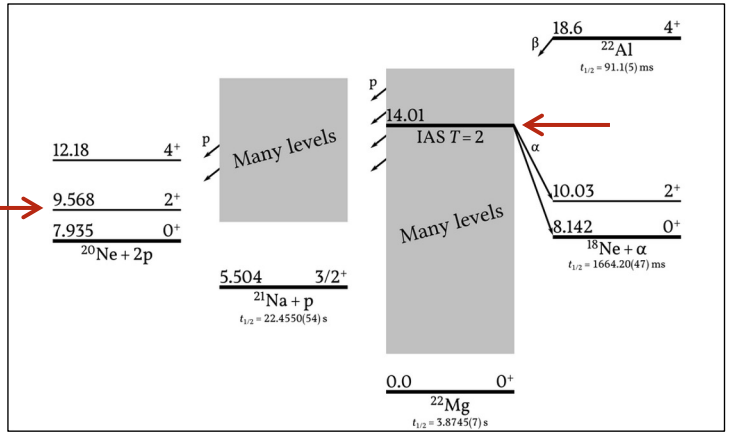
Nevertheless,

- 1.2*10^5 1p events
- 2.4*10^3 2p events

Order of magnitude more than ever before; with superior resolution!

β2p: ^{22}Al

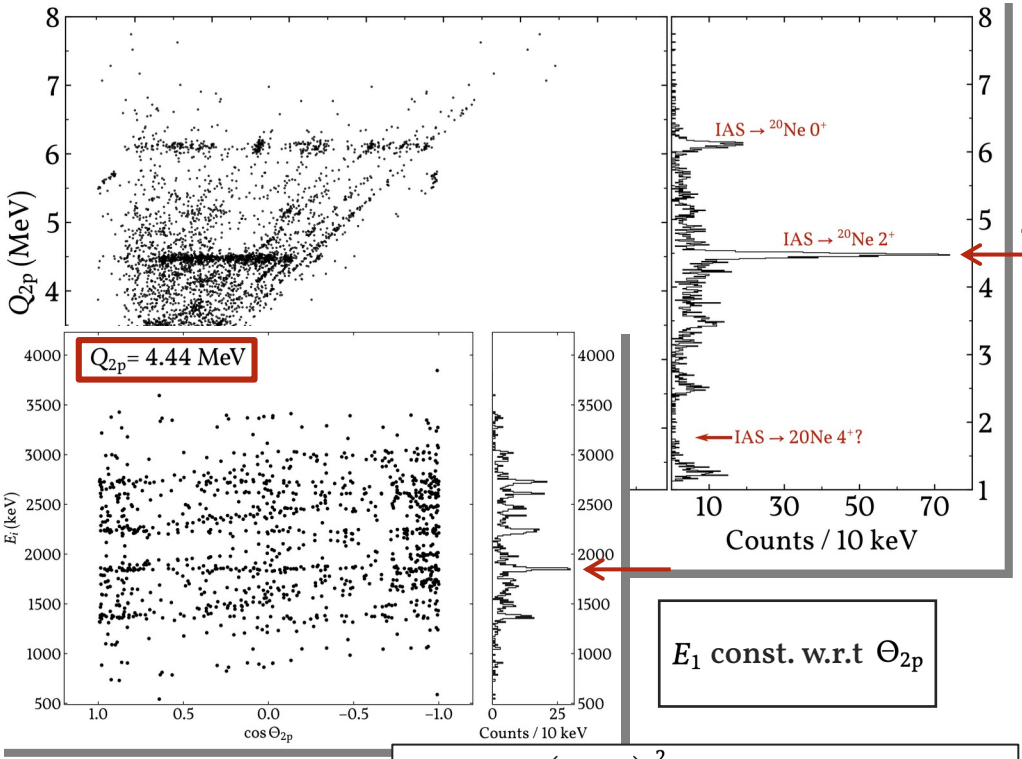




E_1 const. w.r.t Θ_{2p}

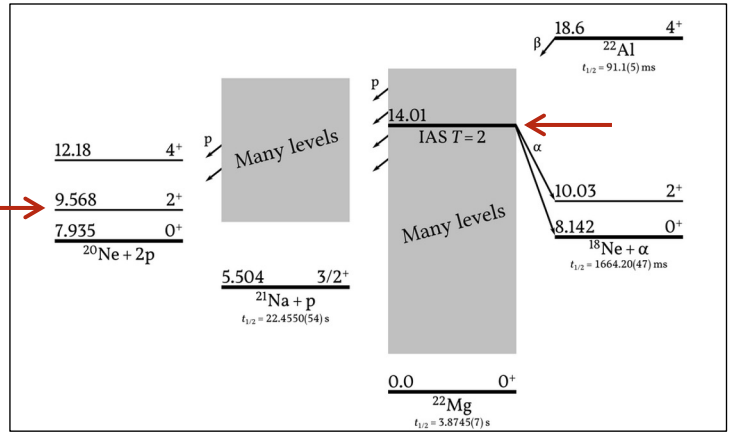
$$E_2 = E_2' + \left(\frac{m_p}{M_{1pD}}\right)^2 E_1 - 2\frac{m_p}{M_{1pD}}\sqrt{E_1 E_2'}\cos\Theta_{2p}$$

β2p: ^{22}Al

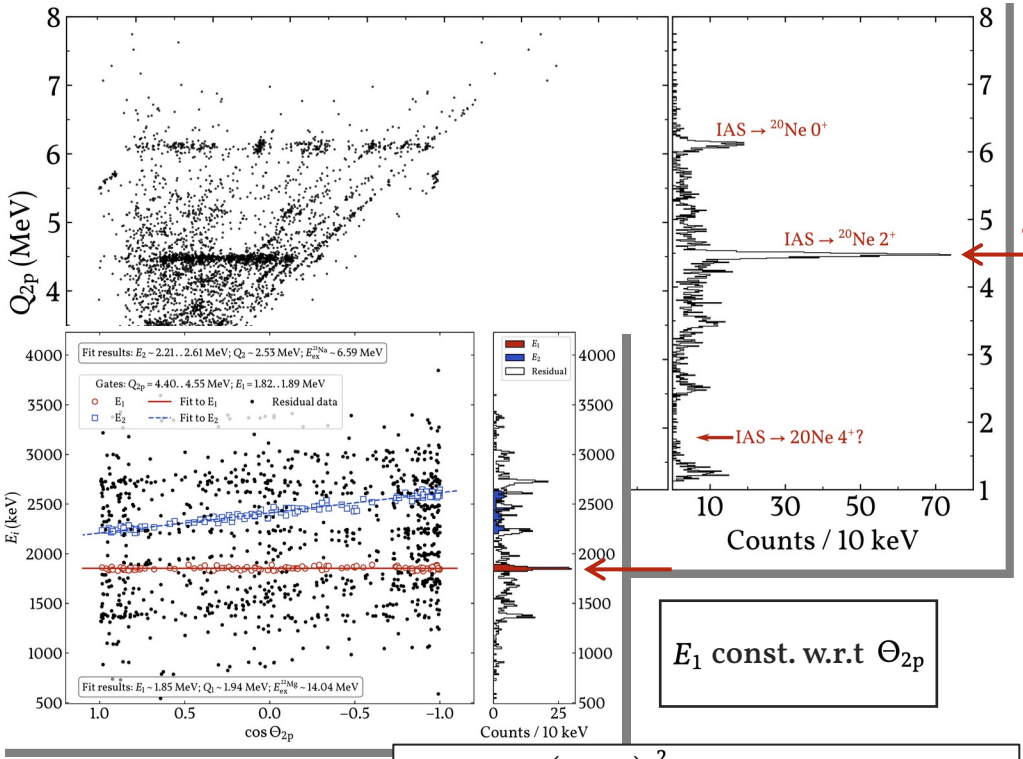


E_1 const. w.r.t Θ_{2p}

$$E_2 = E_2' + \left(\frac{m_p}{M_{1pD}}\right)^2 E_1 - 2\frac{m_p}{M_{1pD}}\sqrt{E_1 E_2'}\cos\Theta_{2p}$$

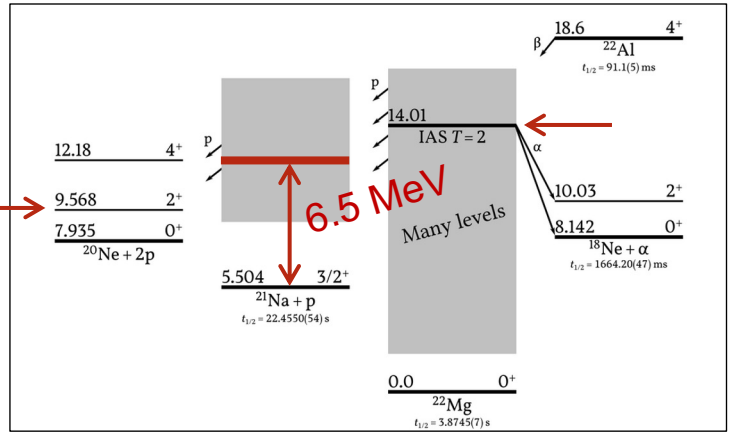


β2p: ^{22}Al



E_1 const. w.r.t Θ_{2p}

$$E_2 = E_2' + \left(\frac{m_p}{M_{1pD}}\right)^2 E_1 - 2\frac{m_p}{M_{1pD}}\sqrt{E_1 E_2'}\cos\Theta_{2p}$$



Never-before seen level in ^{21}Na!

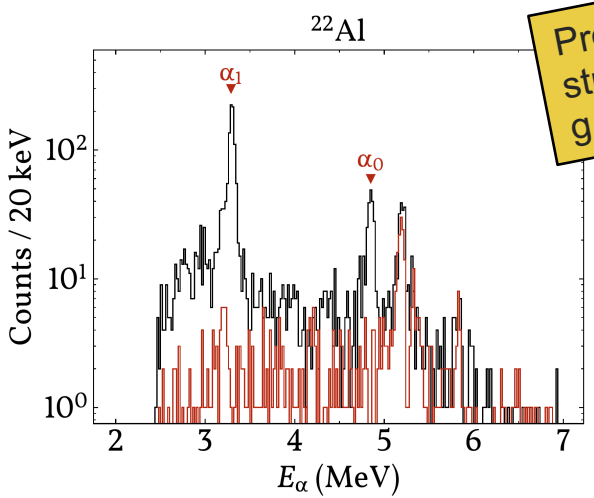
- Hence, likely 9/2$^+$ via s-wave

2 other never-before seen levels within this energy gate

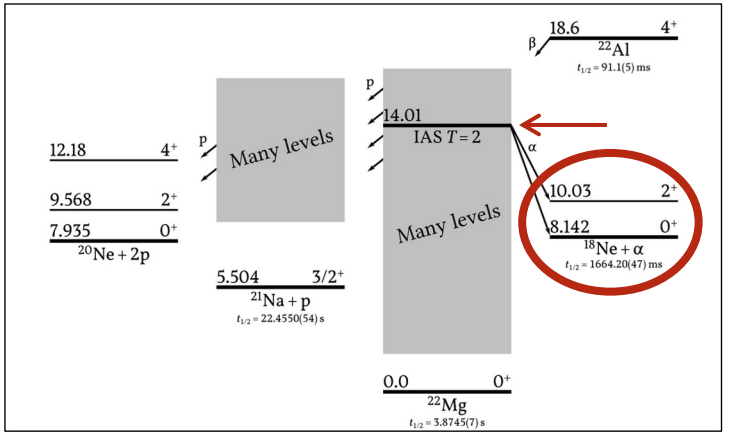
βα: ^{22}Al

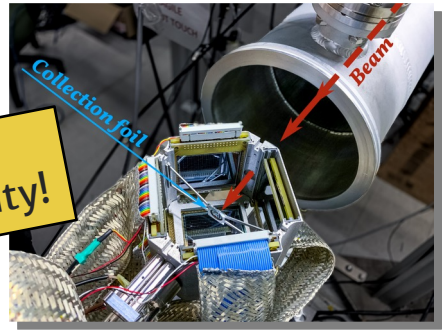
First ever observation of βα from IAS to g.s. in alpha daughter:

- ✓ Settles 22Al spin/parity assignment: 4⁺
- ✓ (The alternative 3⁺ is ruled out)



Proposed halo structure of ^{22}Al g.s. unfeasible...





ISOL-like beam quality!

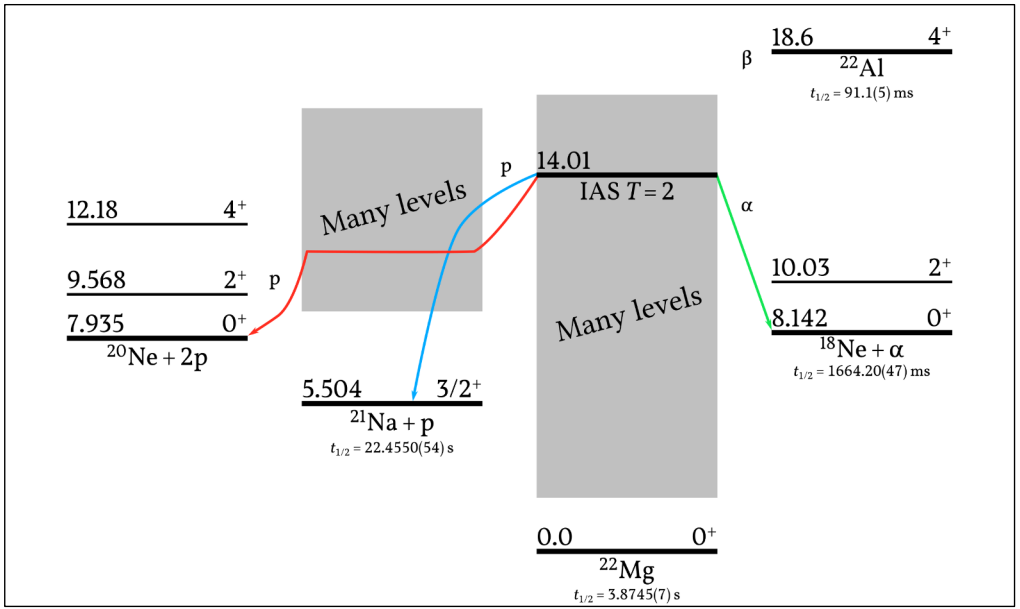
^{22}Al: β1p, β2p, βα

Clarifications and many new 2p branches!

No indication of "^{2}He"

However, large α branch…

	Exp @ FRIB	SM 1990
β1p	42(10)%	~50%
β2p	35(2)%	~50%
βα	23(2)%	~1%
β"^{2}He"	<<1%	~1%



Things needed:
- Refinements of present analyses
- More statistics…

Outlook

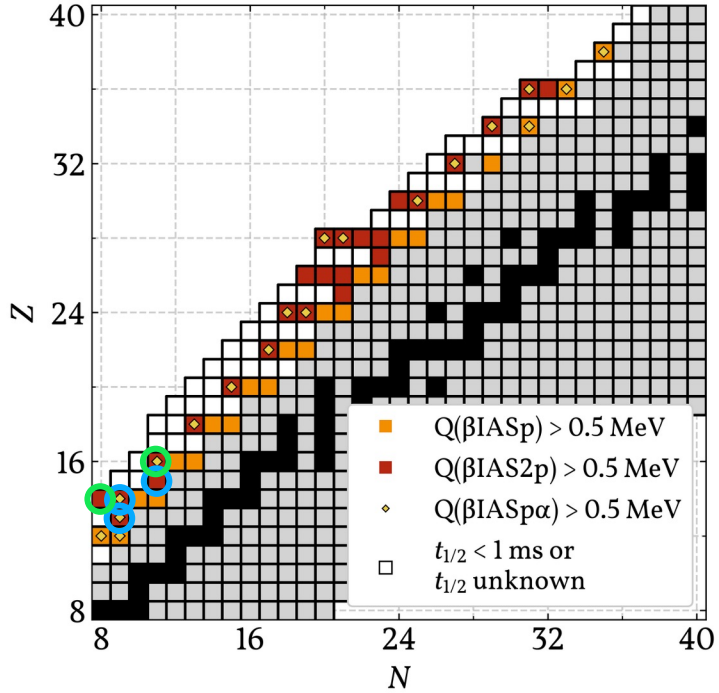
The search for statistically significant direct β2p is now possible!

Present yields at FRIB:

^{22}Al	2.4*10^3 pps
^{22}Si	10~20 pps
^{23}Si	4*10^2 pps
^{26}P	1~2*10^3 pps
^{27}S	80 pps

✓ Measured

✓ Estimated



New theoretical evalutations welcome!

Thanks to all collaborators

And thank you!

CHALMERS

UNIVERSITY OF TECHNOLOGY