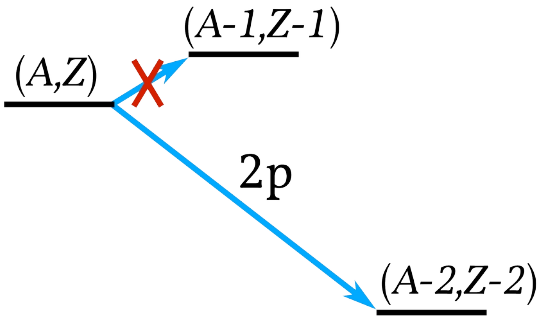
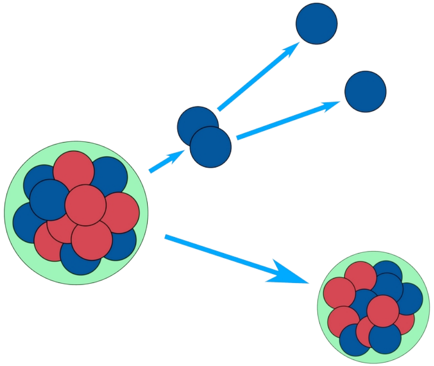
Beta-delayed two-proton spectroscopy at FRIB

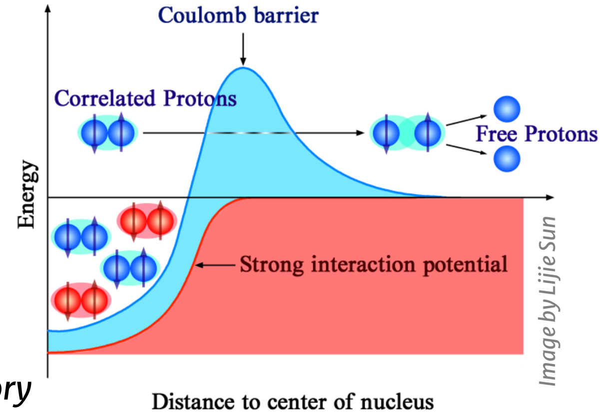
Erik A. M. Jensen — Chalmers — Sweden

Direct two-proton emission

- Final state not directly determined by intermediate configurations





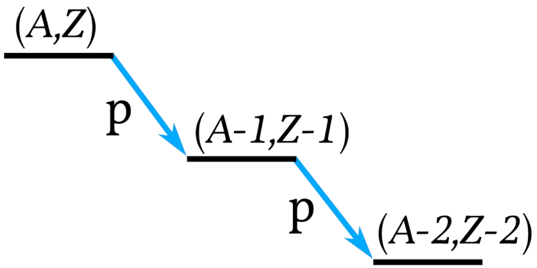


- Known g.s. 2p emitters:
  ^{45}Fe, ^{48}Ni, ^{54}Zn, ^{67}Kr
- Oishi 2025: Entanglement of 2p (2n)
- Zhao et al. 2023: Simultaneous 2α

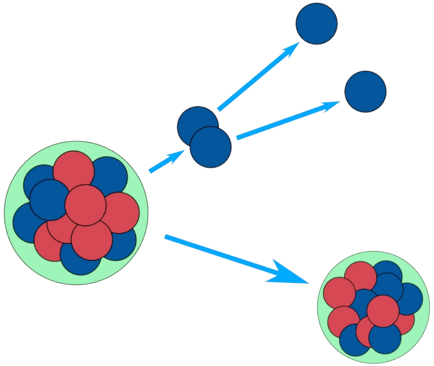
} *Theory*

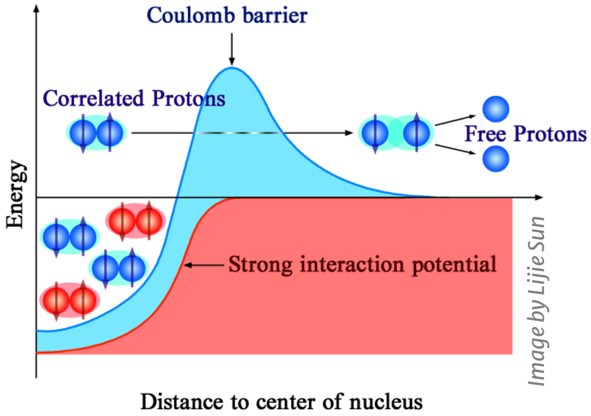
<u>Sequential</u> two-proton emission

- Final state momenta determined by sequences of *on-shell* configurations



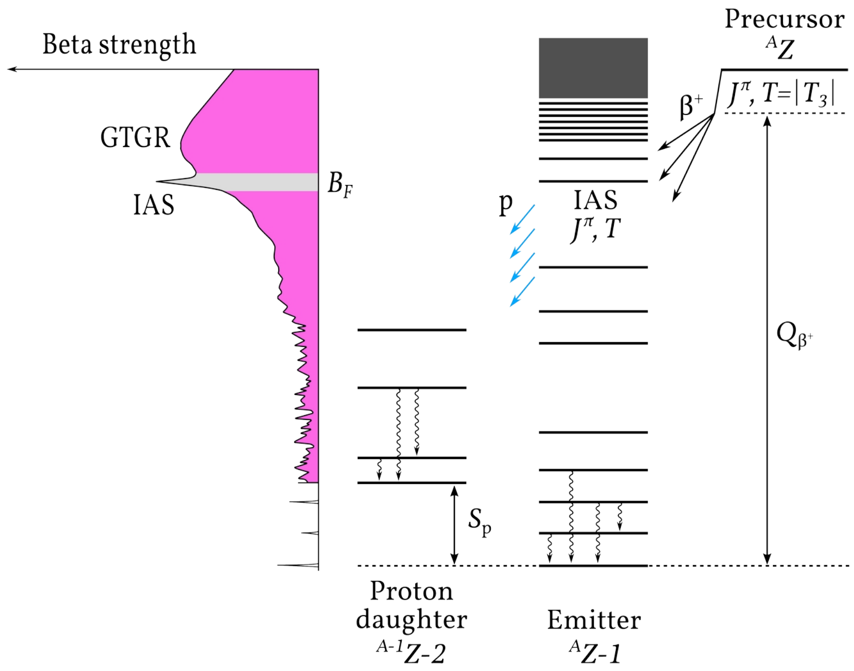
- Competition between direct and sequential?
- Quantum interference…?





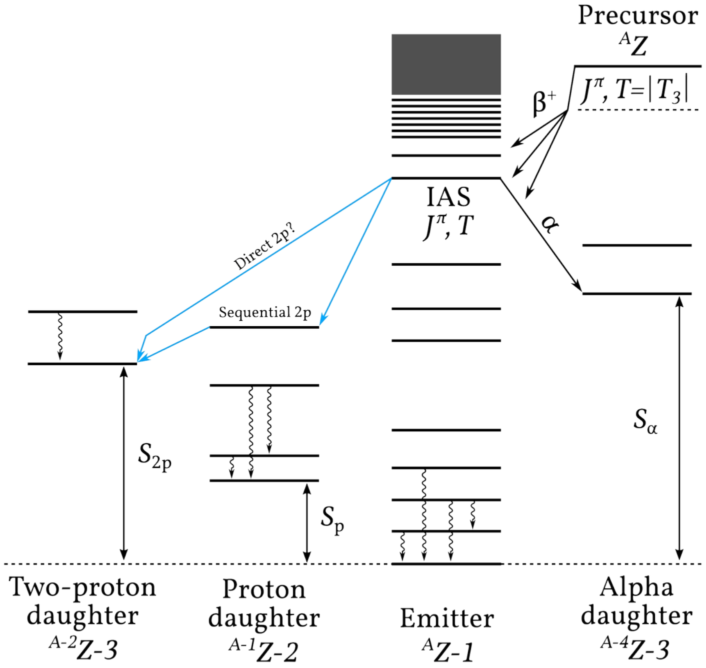
Beta-delayed charged particle emission

- $Z > N$: IAS can be populated
- ~1 MeV above threshold: Charged particle emission dominates gamma radiation
- Isospin-mixing can spread B_F from IAS to other states

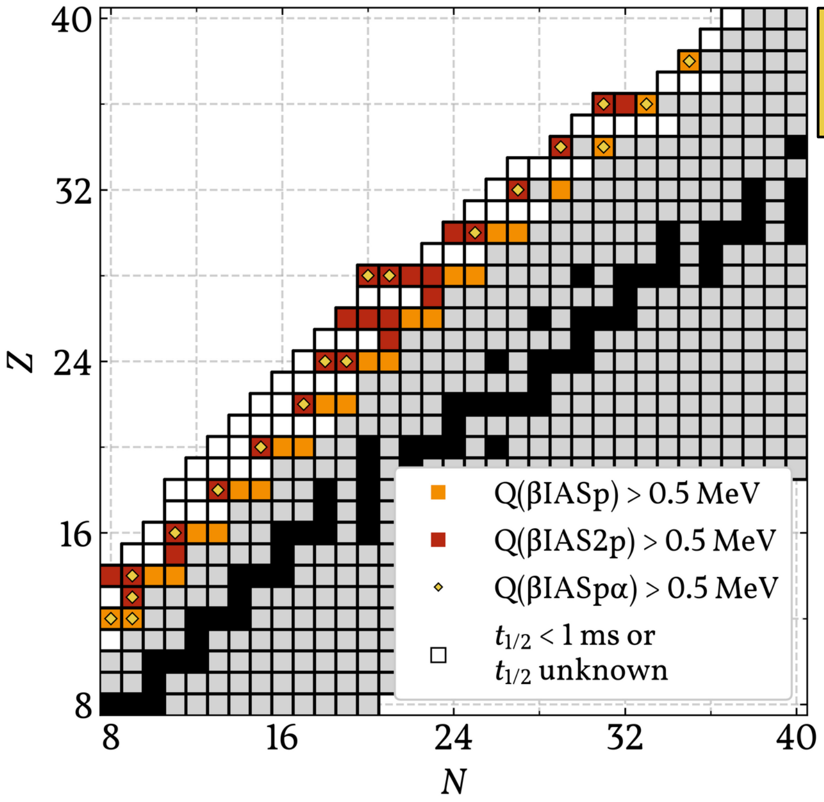


Beta-delayed charged particle emission

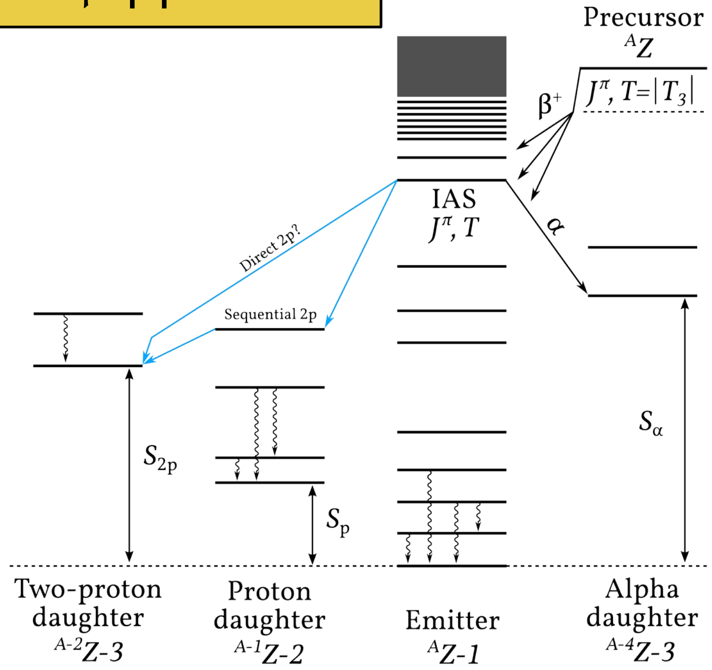
- $Z > N$: IAS can be populated
- ~1 MeV above threshold: Charged particle emission dominates gamma radiation
- Isospin-mixing can spread B_F from IAS to other states
- Sufficiently exotic emitters undergo multi-particle breakup
- How similar is 2p emission to α emission?



Beta-delayed charged particle emission

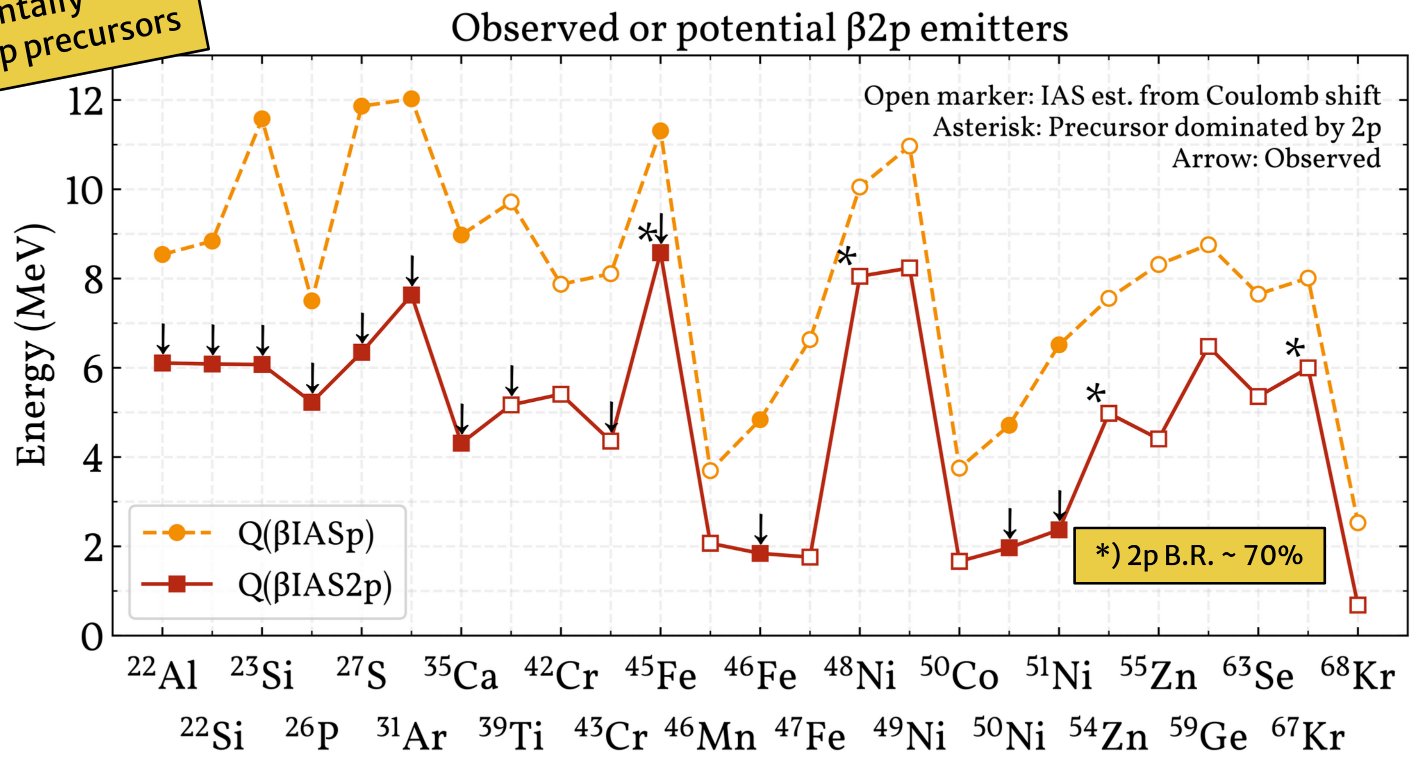


25 experimentally feasible* β2p precursors



Beta-delayed charged particle emission

25 experimentally feasible* β2p precursors



Coulomb barrier →

The prime candidate: ^{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%

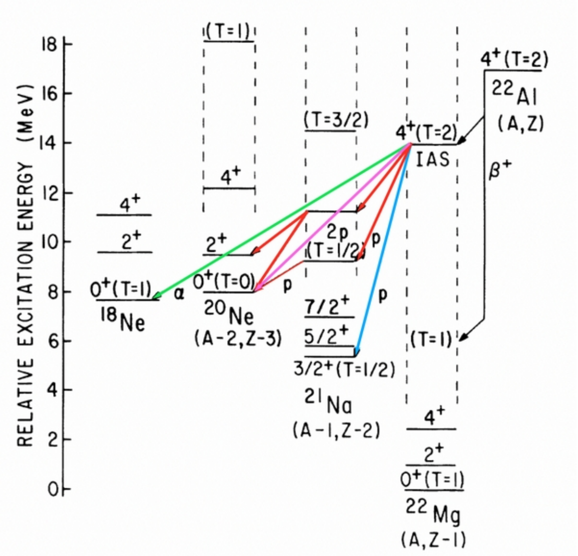
2p and α similar B.R.

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

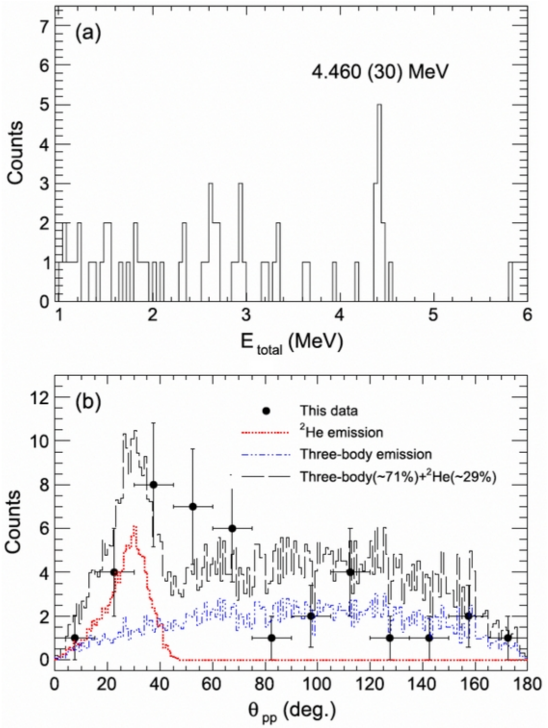
(Received 20 August 1990)

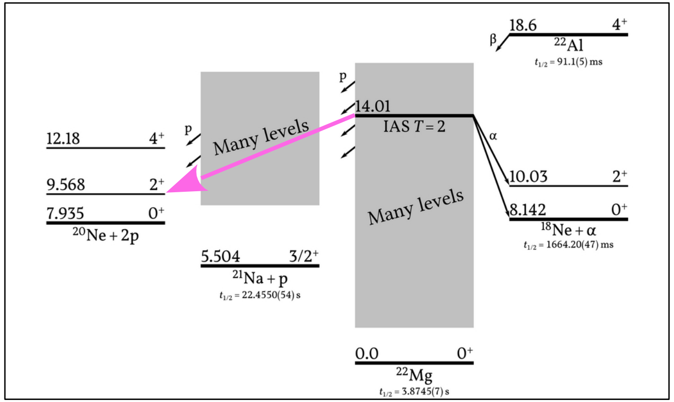


The prime candidate: ^{22}Al – <u>Experiment</u>

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

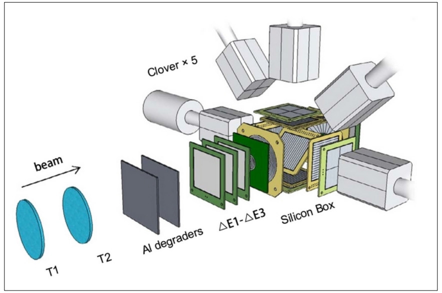
Y.T. Wang *et al.* Phys. Lett. B784 (2018) 12





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

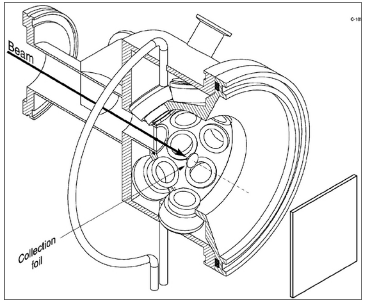
In-flight
@ RIBLL1



A different experimental approach: ^{31}Ar

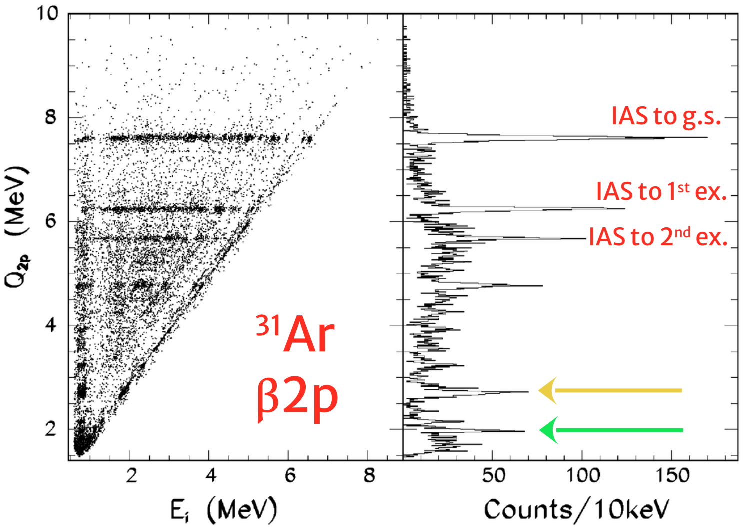
The β2p decay mechanism of ^{31}Ar

H.O.U. Fynbo *et al.* Nucl. Phys. A677 (2000) 38

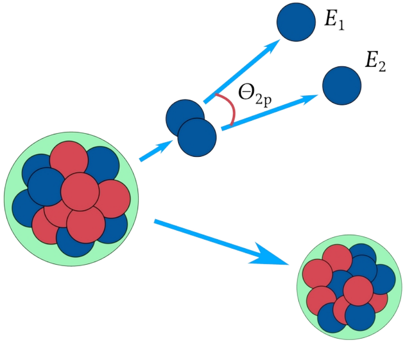


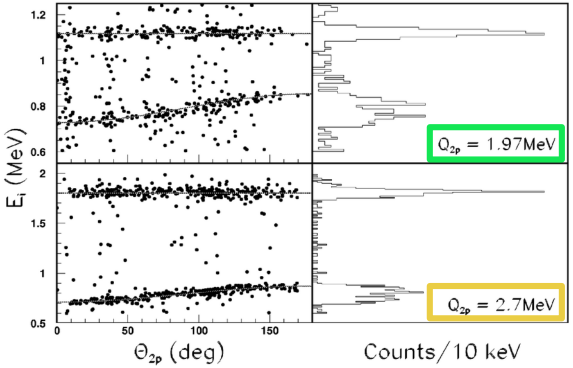
Stopped beam @ ISOLDE/CERN

No "^{2}He"

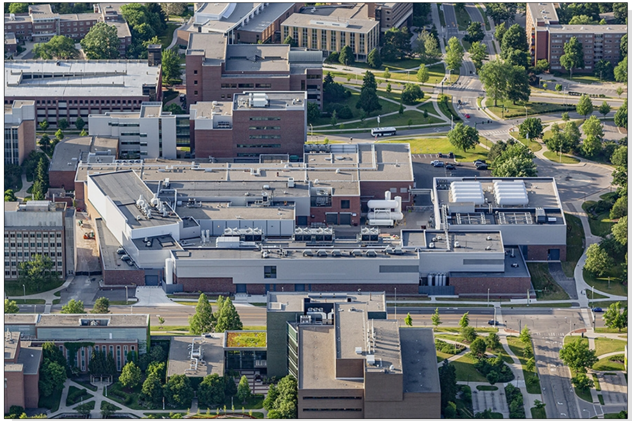


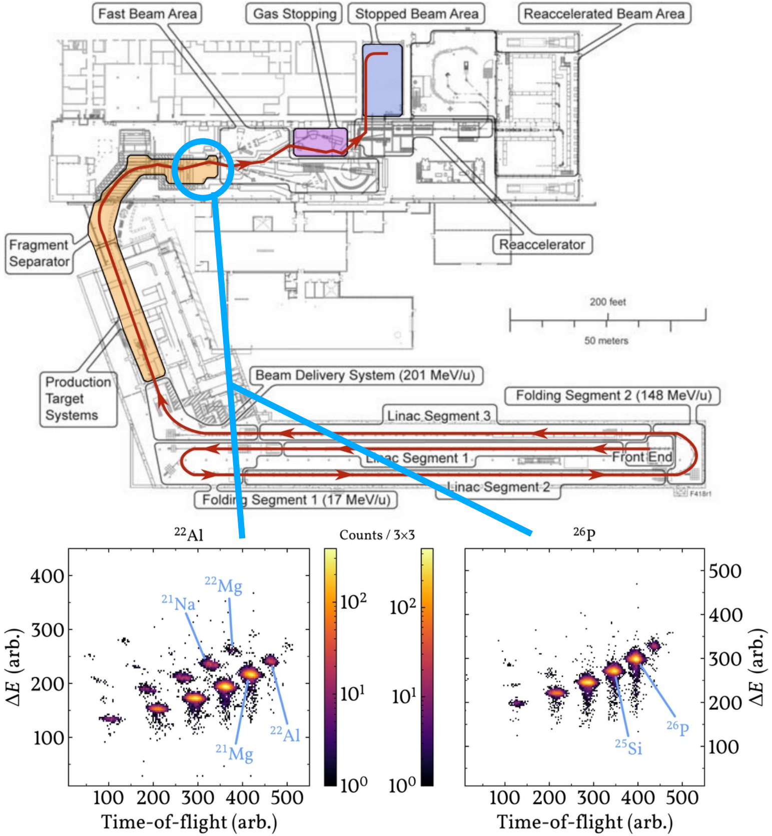
$$Q_{2p} = E_1 + E_2 + \frac{m_p}{M_{D2}}\left(E_1 + E_2 + 2\sqrt{E_1 E_2}\cos\Theta_{2p}\right)$$





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

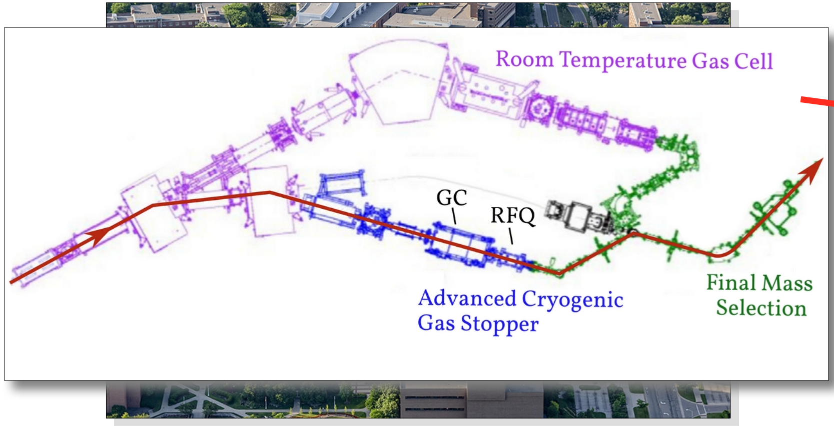


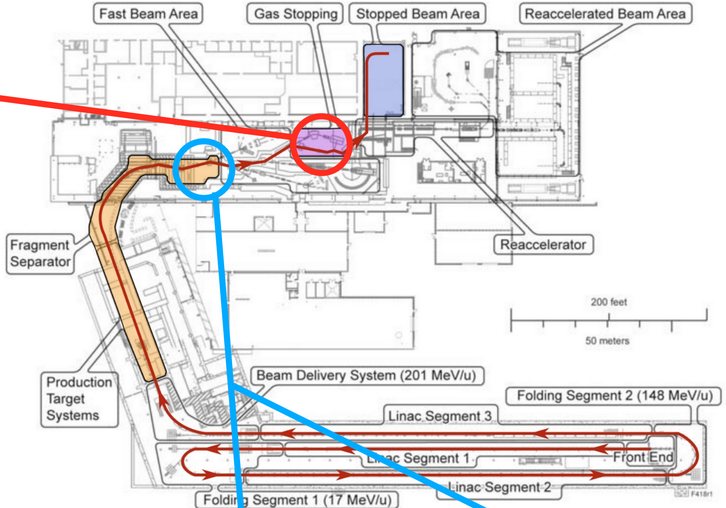


Experiment in June 2023
1st Stopped Beam Experiment at FRIB

- Primary beam ^{36}Ar
- Production target ^{12}C

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



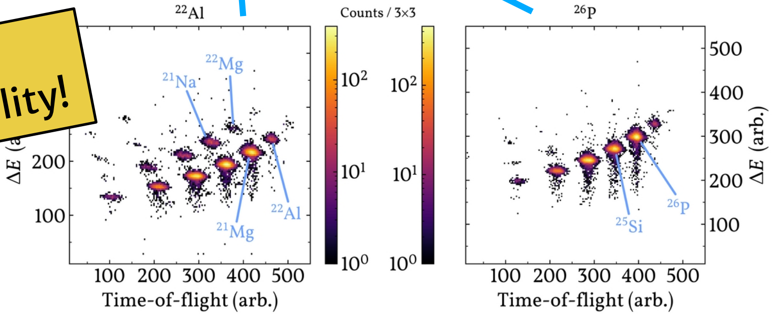


Experiment in June 2023

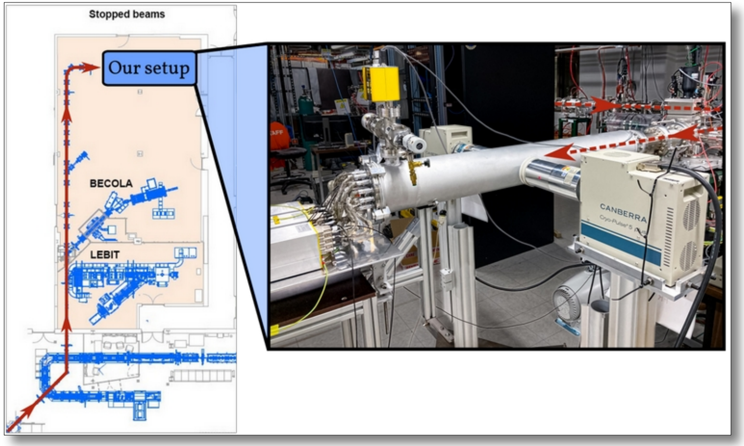
1st Stopped Beam Experiment at FRIB

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

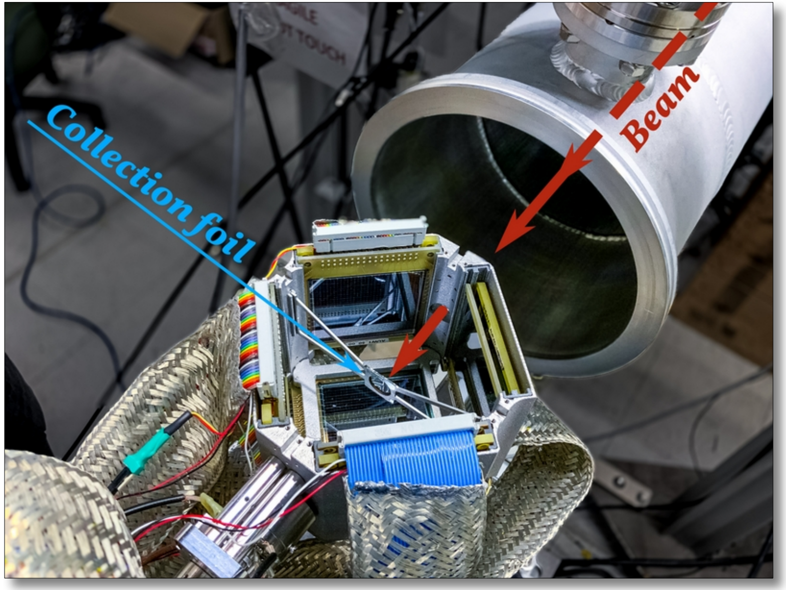
ISOL-like beam quality!



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



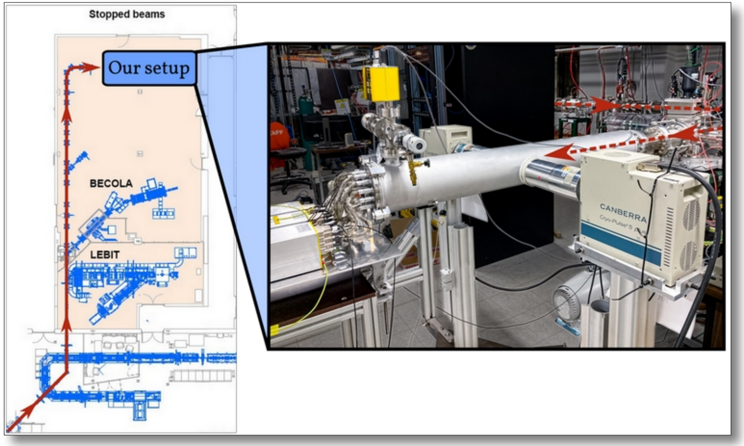
Silicon cube :
- 6 ΔE–E silicon detectors
  ΔE: 16x16 DSSSDs
- 42 % of 4π for p/α
- 18 % of 4π for 2p

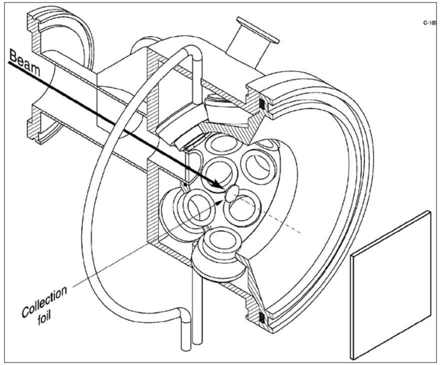


Experiment in June 2023
1^{st} Stopped Beam Experiment at FRIB

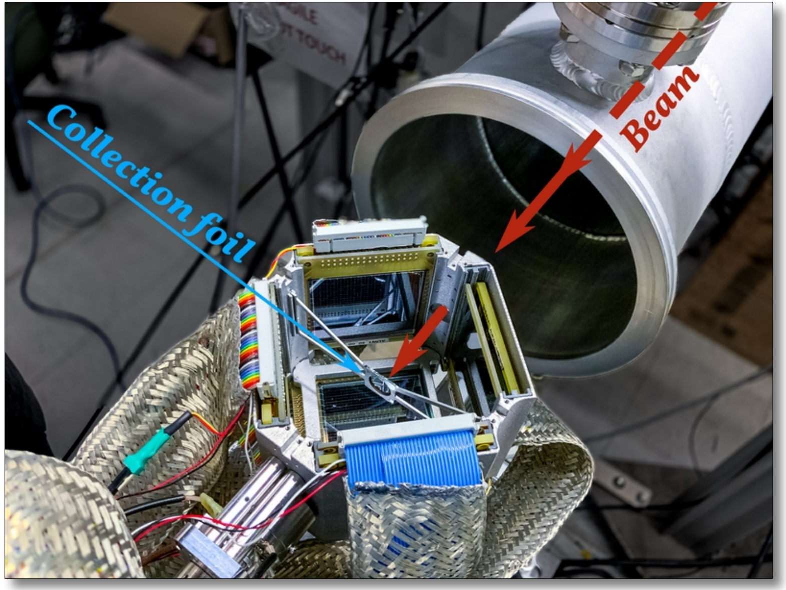
- Primary beam ^{36}Ar
- Production target ^{12}C
- Cooling of in-flight beam in Gas Stopper

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





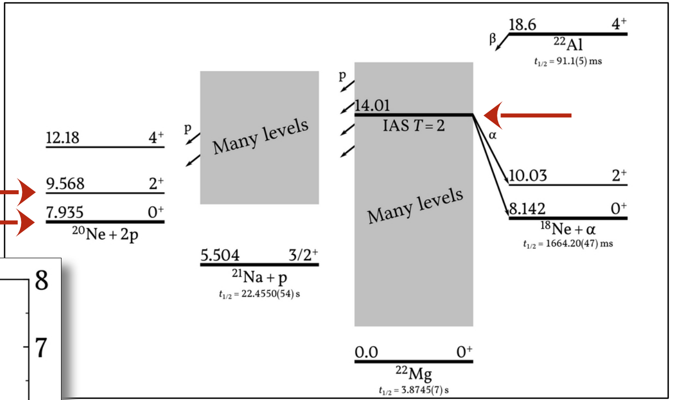
Silicon cube :
- 6 ΔE–E silicon detectors
  ΔE: 16x16 DSSSDs
- 42 % of 4π for p/α
- 18 % of 4π for 2p

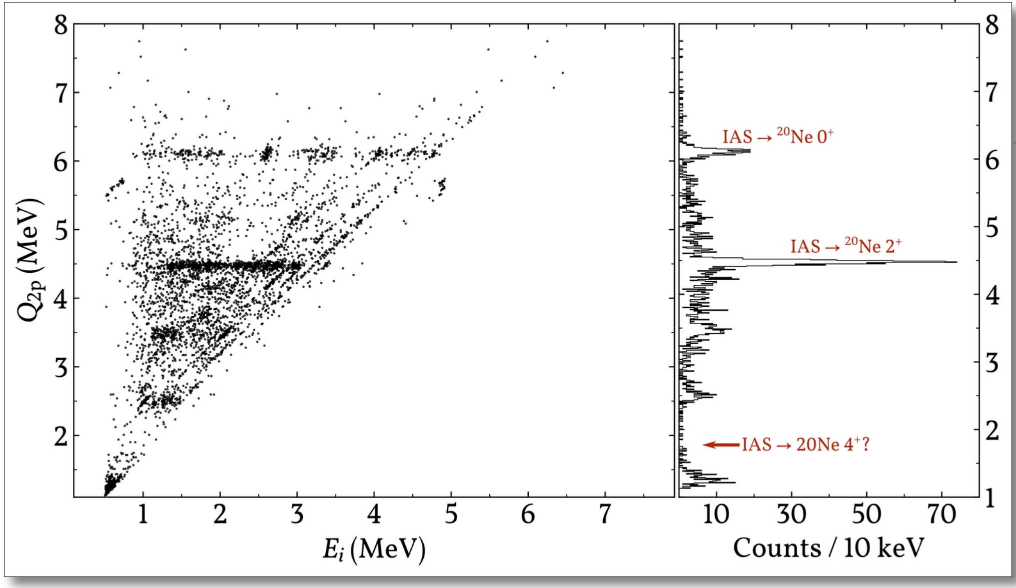


^{22}Al: β2p

33 h beam time
- 9•10^3 pps expected
- 7 pps delivered

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



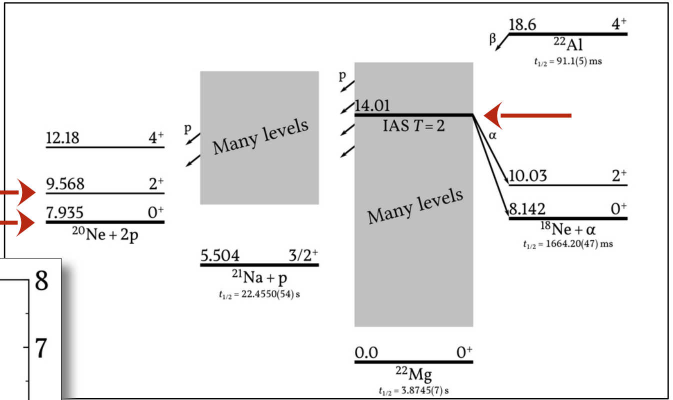


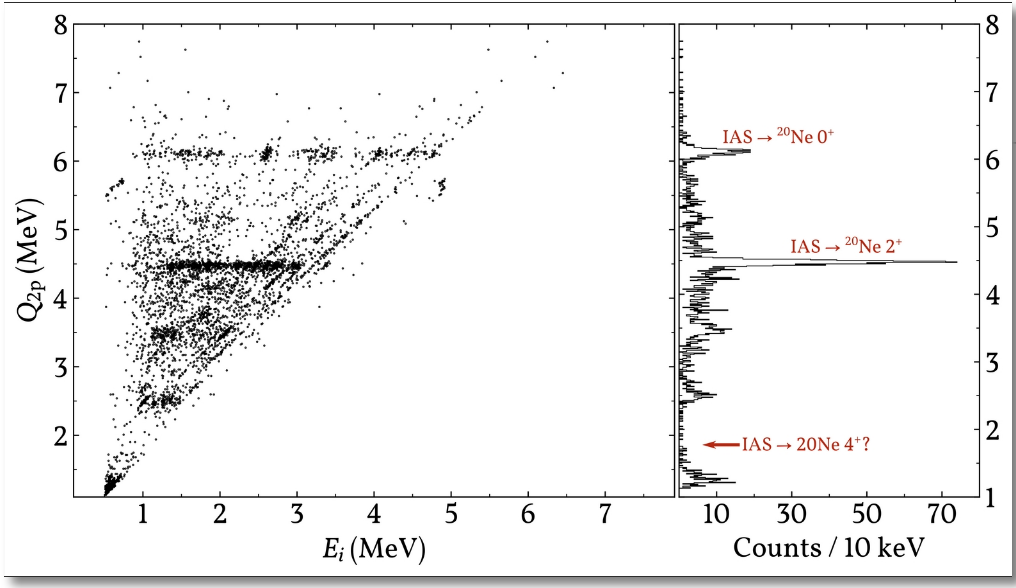
^{22}Al: β2p

Pile-up and dead time not a concern!

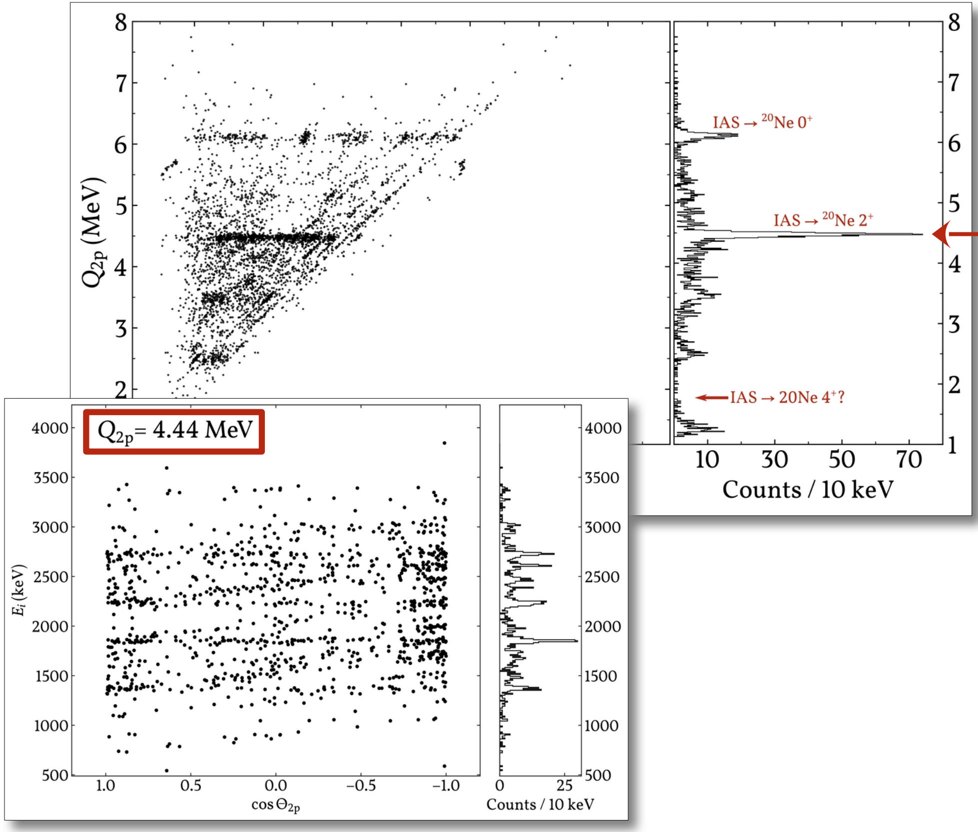
33 h beam time
- $9 \cdot 10^3$ pps expected
- 7 pps delivered

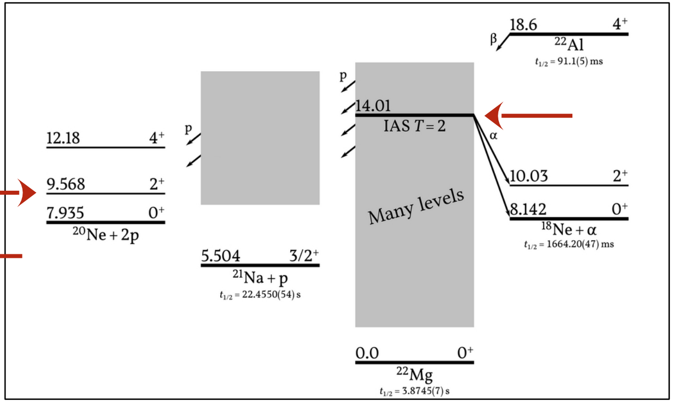
- $1.2 \cdot 10^5$ 1p events
- $2.4 \cdot 10^3$ 2p events





^{22}Al: β2p

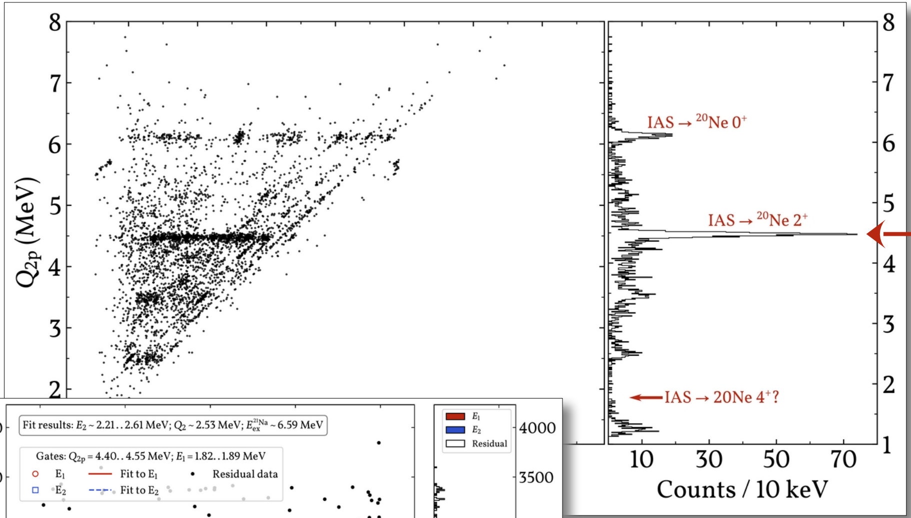


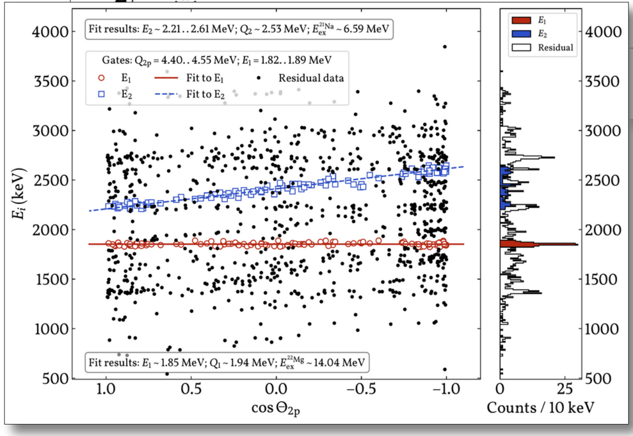


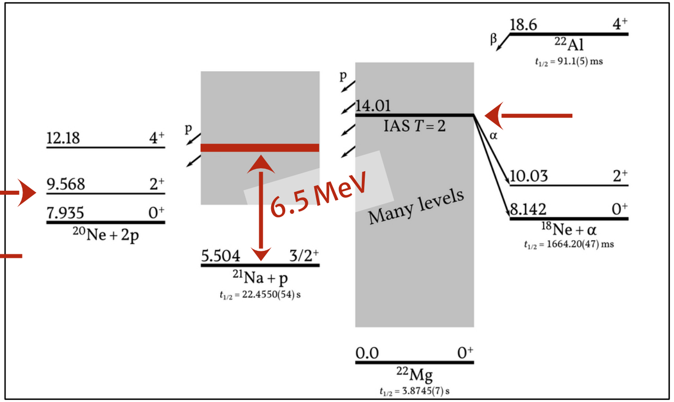
Nucl. Data Sheets: ^{21}Na

E(level) (keV)	J$^\pi$(level)	E(γ) (keV)	I(γ)	Final Levels	
0.0	3/2+				
331.90 *10*	5/2+	331.91 *10*	100	0.0	3/2+
1716.1 *3*	7/2+	1384.1 *3* 1715.9 *7*	100.0 *22* 7.5 *22*	331.90 0.0	5/2+ 3/2+
2423.8 *4*	1/2+	2423.3 *5*	100	0.0	3/2+
2797.9 *5*	1/2-	373.3 2466 2797.6 *14*	100 *7* 20 *4* 59 *7*	2423.8 331.90 0.0	1/2+ 5/2+ 3/2+
2829.1 *7*	9/2+	1113 2497	100 *8* 58 *8*	1716.1 331.90	7/2+ 5/2+
3544.3 *4*	5/2+	1828.0 *9* 3212.1 *6* 3544.0 *6*	6.5 *5* 2.2 *5* 100 *3*	1716.1 331.90 0.0	7/2+ 5/2+ 3/2+
3678.9 *4* Etc. ... ↓	3/2-	880.7 *5* 1255 *1* 3346.8 *4*	38 *3* 28 *3* 100 *5*	2797.9 2423.8 331.90	1/2- 1/2+ 5/2+

^{22}Al: β2p







Nucl. Data Sheets: ^{21}Na

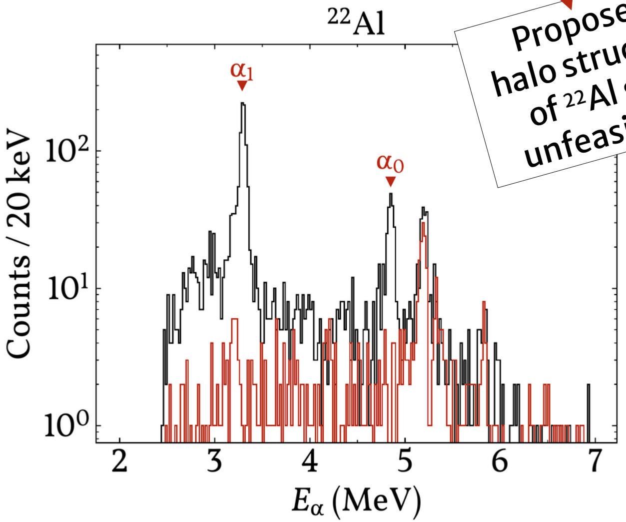
E(level) (keV)	Jπ(level)	E(γ) (keV)	I(γ)	Final Levels
0.0	3/2+			
331.90 10	5/2+	331.91 10	100	0.0 3/2+
1716.1 3	7/2+	1384.1 3 1715.9 7	100.0 22 7.5 22	331.90 5/2+ 0.0 3/2+
2423.8 4	1/2+	2423.3 5	100	0.0 3/2+
2797.9 5	1/2-	373.3 2466 2797.6 14	100 7 20 4 59 7	2423.8 1/2+ 331.90 5/2+ 0.0 3/2+
2829.1 7	9/2+	1113 2497	100 8 58 8	1716.1 7/2+ 331.90 5/2+
3544.3 4	5/2+	1828.0 9 3212.1 6 3544.0 6	6.5 5 2.2 5 100 3	1716.1 7/2+ 331.90 5/2+ 0.0 3/2+
3678.9 4 Etc. ... ↓	3/2-	880.7 5 1255 1 3346.8 4	38 3 28 3 100 5	2797.9 1/2- 2423.8 1/2+ 331.90 5/2+

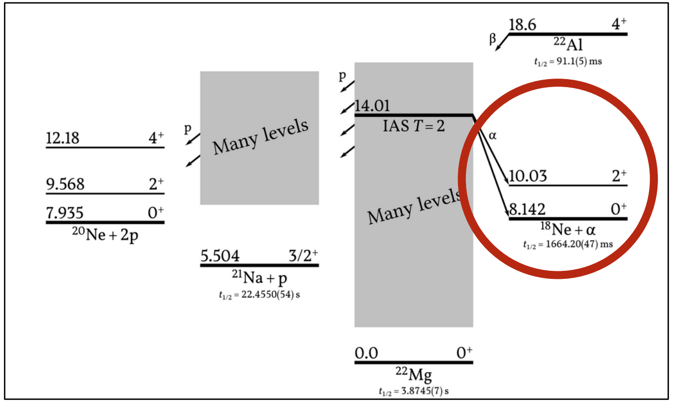
^{22}Al: βα

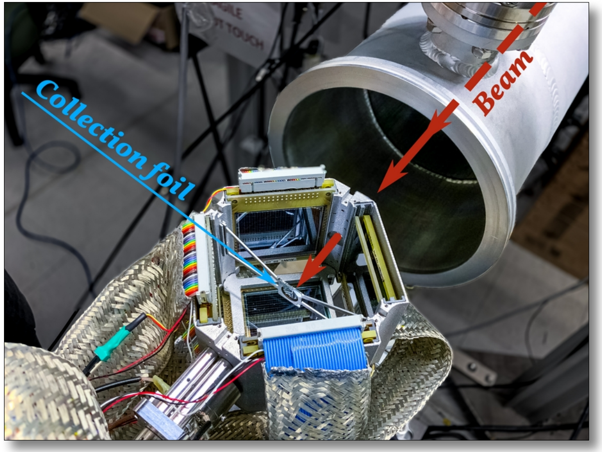
First observation of βα from IAS to g.s. in alpha daughter settles ^{22}Al spin/parity assignment: 4^+

(The alternative 3^+ is ruled out)

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





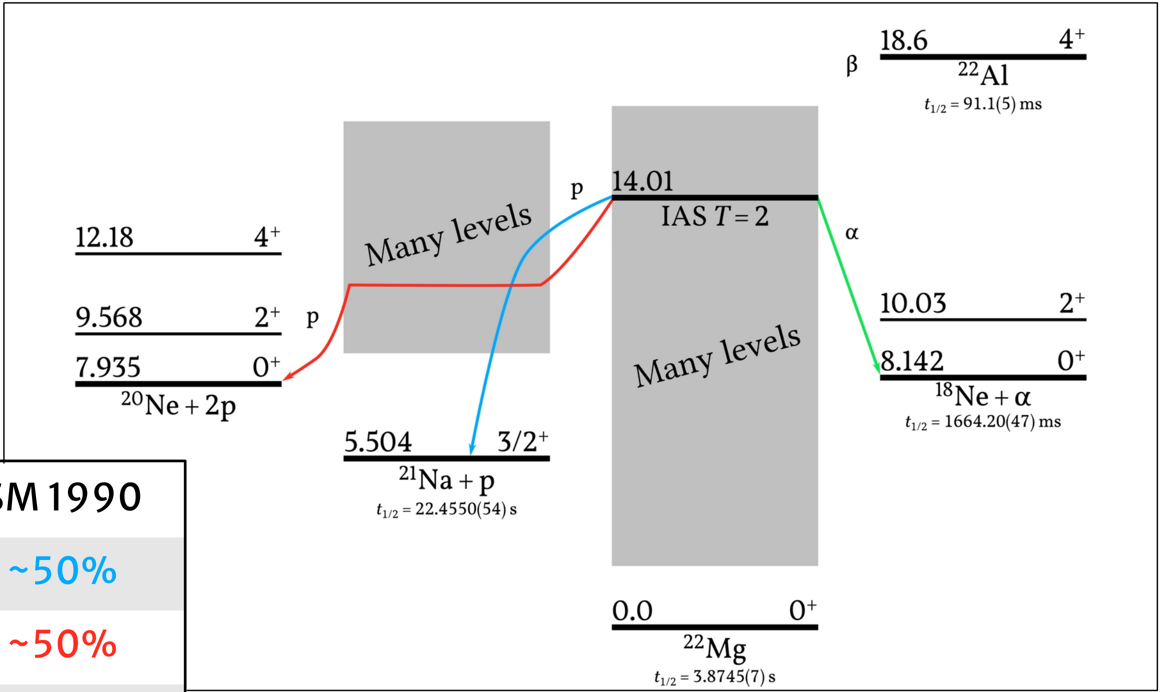


^{22}Al: β1p, β2p, βα

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"	<2%	~1%

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

Outlook

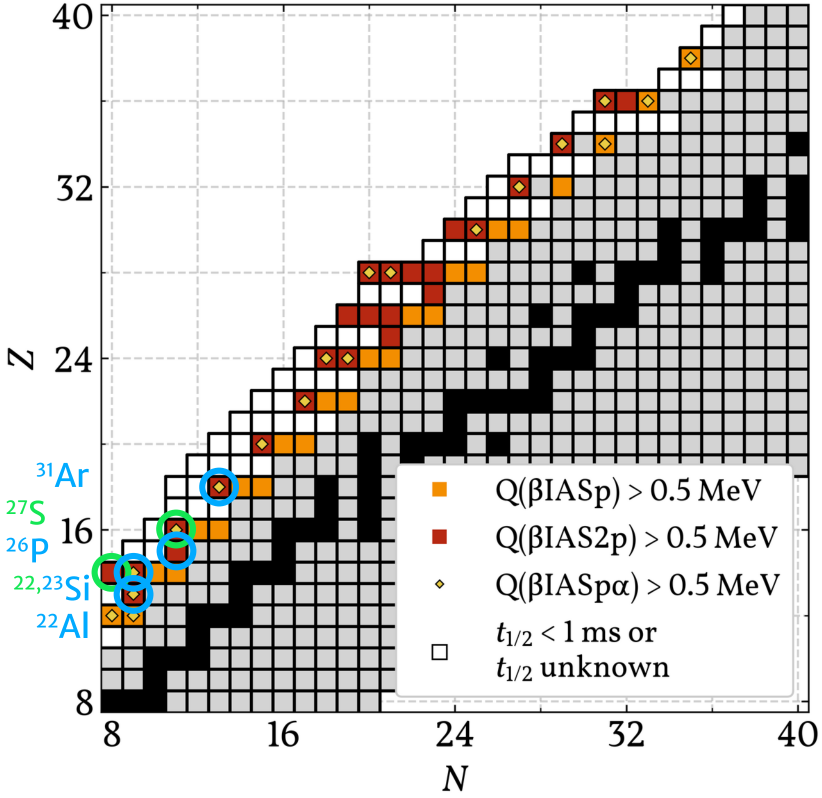
Present yields at FRIB:

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

✓Measured

✓Estimated

The search for statistically significant direct β2p is now possible



New theoretical evaluations welcome!

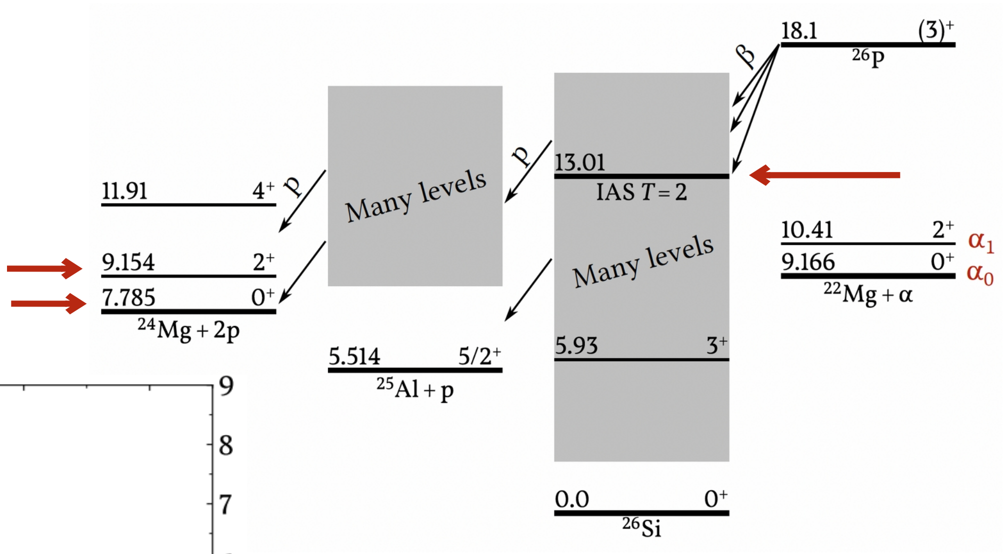
Thanks to all collaborators!

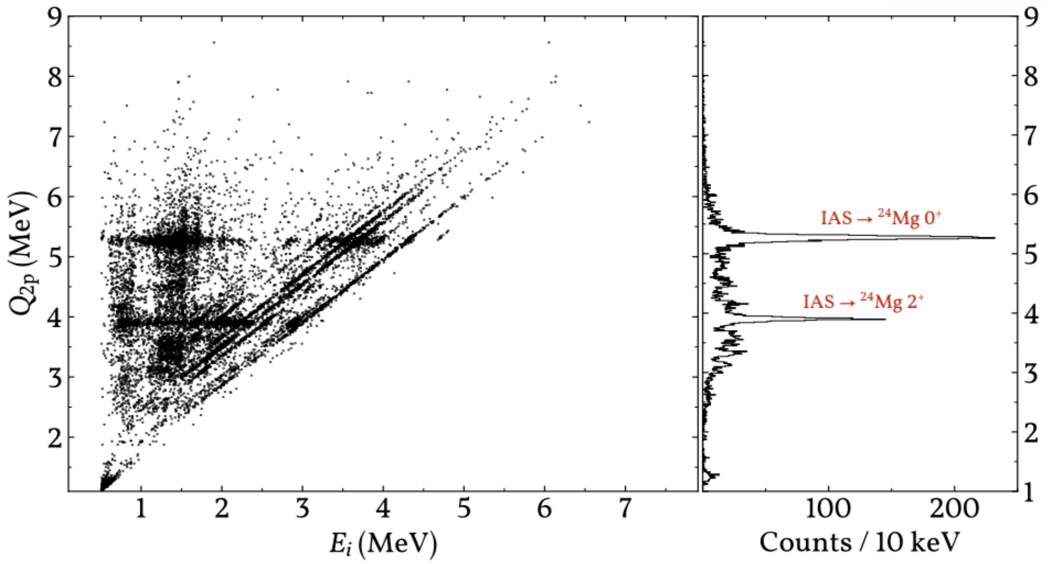
And thank you!

Extra slides

31h beam time
5 10^3 pps expected
30 pps delivered
2.3 10^5 1p events
8.0 10^3 2p events

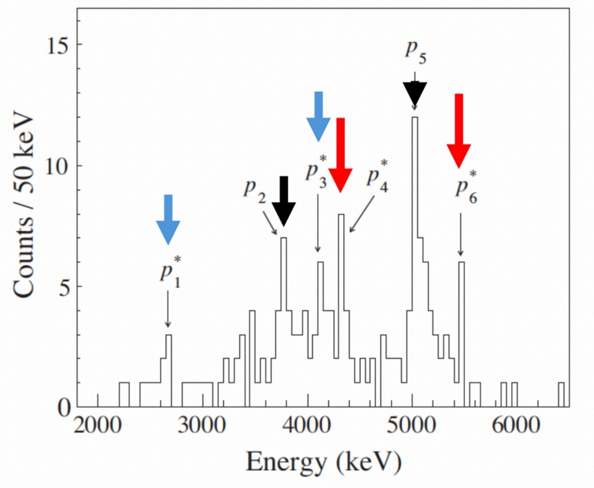
26P: b2p

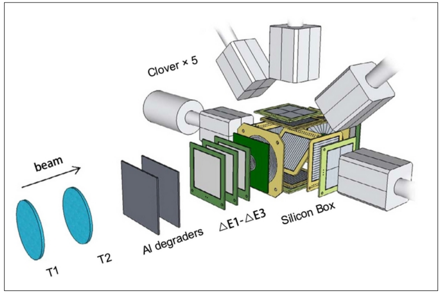


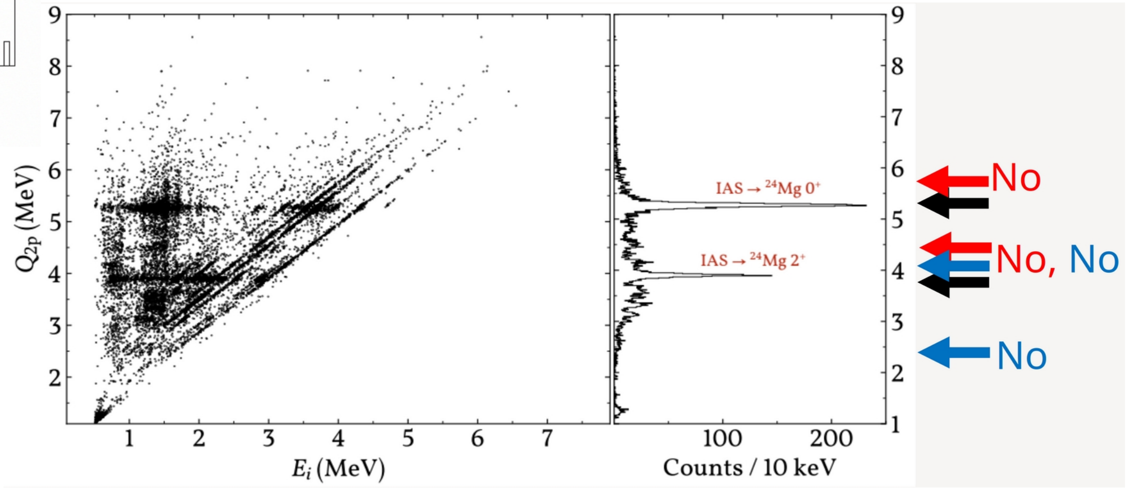


26P: b2p

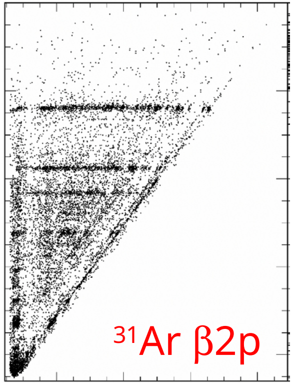
J.J. Liu *et al*. Phys.Rev.Lett. **129** (2022) 242502

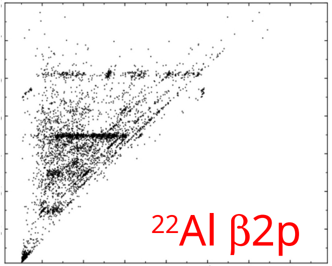


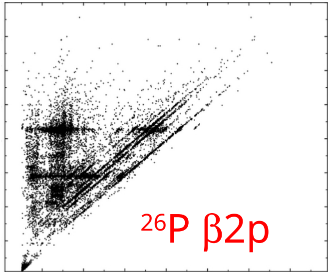


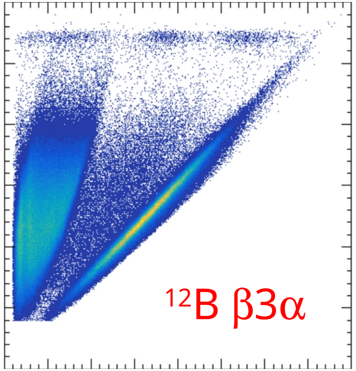


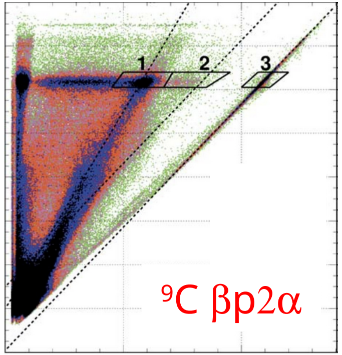
β-delayed multi-particle emission

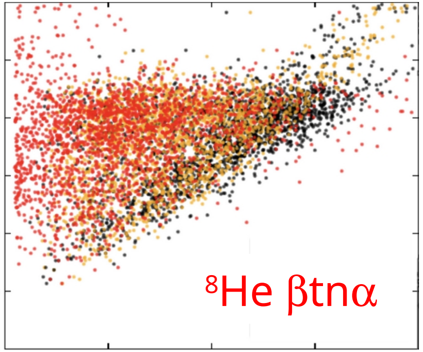






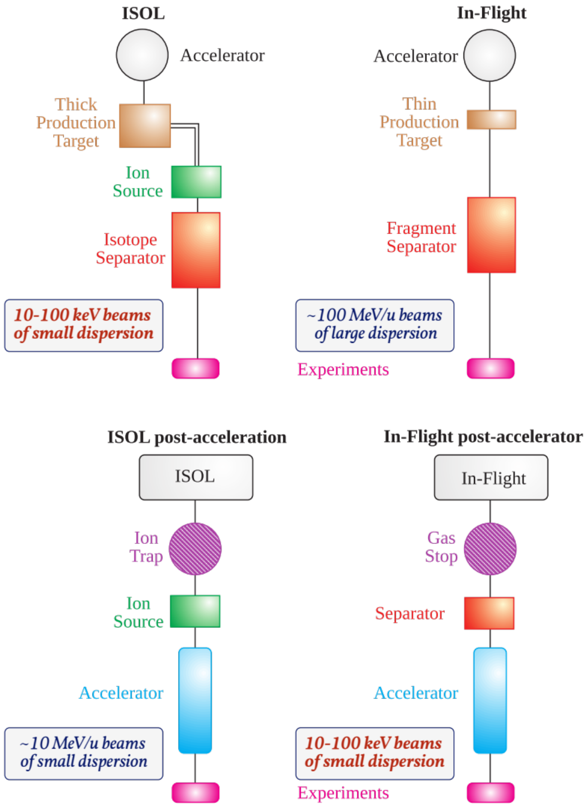






Also β2n, β3n, β2αn, βαp, βαn

Rare Ion Beam Production



Björn Jonson, NuPECC Report, 2000

In-Flight for implantation in stacks of Si detectors is error-prone, interpretation-wise

ISOL-like method is necessary!

Low-energy beam challenges:

	Constrained by cross sections at ...	**Constrained by chemistry at ...**
ISOL	Target	Target + Ion Source
In-flight	Target	Gas gell

What else can we do?

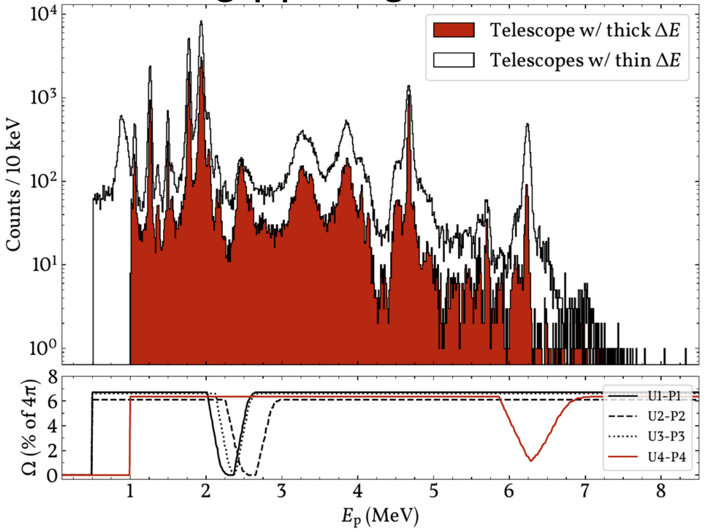
Tremenduous resoultion in charged particle spectra

- Credit to beam quality from Gas Stopping Area
- Credit to MAGISOL's decades of experience and expertise with Si-cube setups

Data on 21Mg and 25Si also taken for calibration and contamination analyses

Can improve decay schemes, level assignments, etc.

21Mg βp singles



(See also NIM A 1055:168531, 2023)

Sequential 2p kinematics

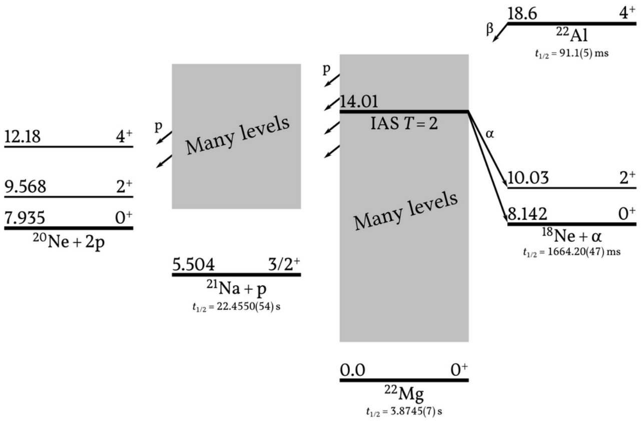
Q_{2p} determined from E_1, E_2, Θ_{2p}:

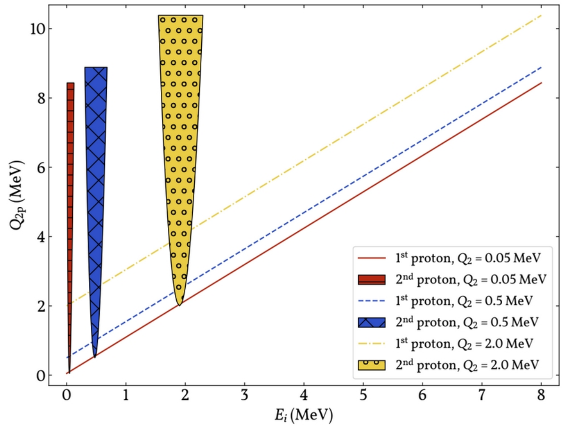
$$Q_{2\text{p}} = E_1 + E_2 + m_\text{p}(E_1 + E_2 + 2\sqrt{E_1 E_2}\cos\Theta_{2\text{p}})/M_{^{20}\text{Ne}}$$

For sequential decay, we have

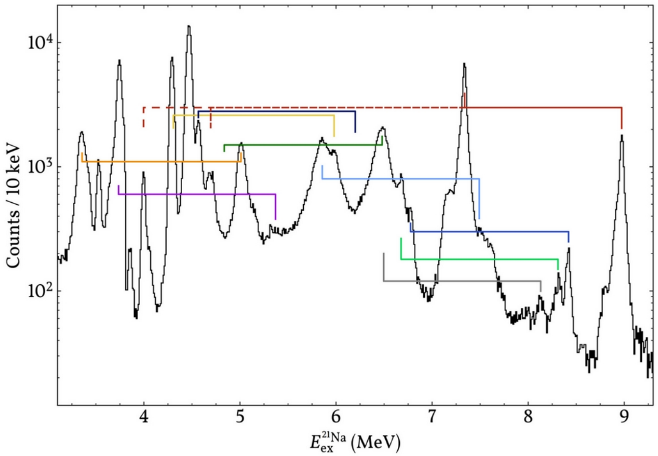
$$\begin{aligned} Q_{2\text{p}} &= Q_1 + Q_2 \\ &= \frac{M_{^{21}\text{Na}} + m_\text{p}}{M_{^{21}\text{Na}}} E_1 + Q_2 \end{aligned}$$

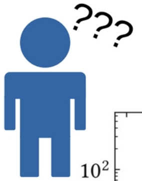
i.e. 1st emitted proton generally follows straight line of slope ~1, with offset determined by energy release of 2nd proton, Q_2

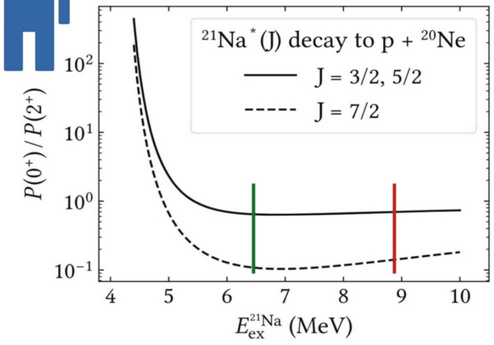


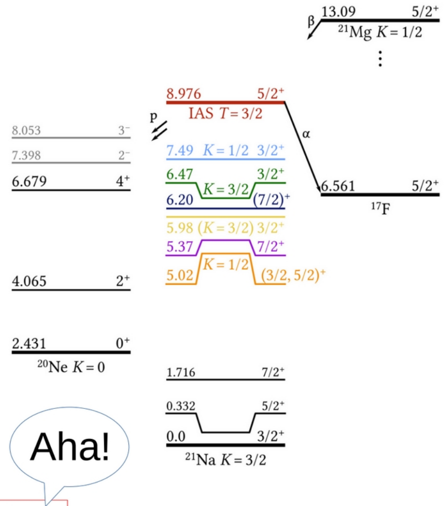


Deform proton-rich sd-shell nuclei

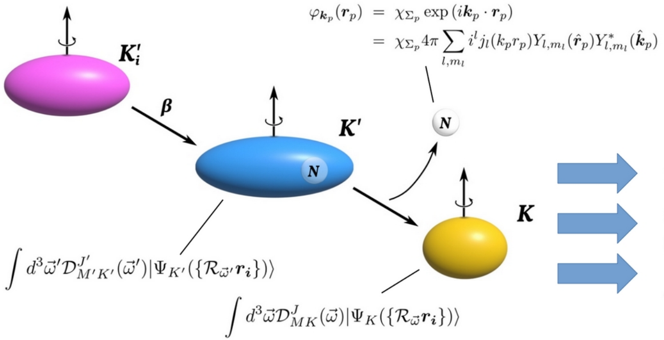




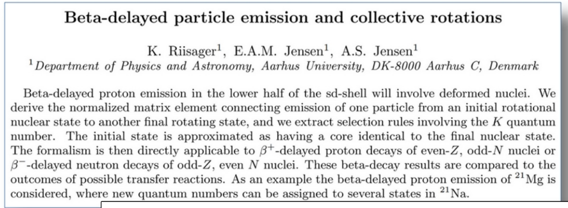




$$\vec{J} + \vec{j} = \vec{J}' \ , \ |M - M'| \le j \ , \ |K - K'| \le j$$



$$\frac{ME}{\sqrt{N_i N_f}} = 4\pi \sqrt{\frac{2J+1}{2J'+1}} \sum_{j,l,m_l,m'_l,\Sigma'_p} (-i)^l Y_{l,m_l}(\hat{\boldsymbol{k}}_p)$$
$$\langle JMjm_l + \Sigma_p | J'M' \rangle \langle JKjm'_l + \Sigma'_p | J'K' \rangle$$
$$\langle l m_l s \Sigma_p | j m_l + \Sigma_p \rangle \langle l m'_l s \Sigma'_p | j m'_l + \Sigma'_p \rangle$$
$$\int d^3\boldsymbol{r_p} \chi^\dagger_{\Sigma'_p} j^*_l(k_p r_p) Y^*_{l,m'_l}(\hat{\boldsymbol{r}}_p) \varphi_{K'}(\boldsymbol{r}_p) \ .$$



Beta-delayed particle emission and collective rotations

K. Riisager[1], E.A.M. Jensen[1], A.S. Jensen[1]

[1] *Department of Physics and Astronomy, Aarhus University, DK-8000 Aarhus C, Denmark*

Beta-delayed proton emission in the lower half of the sd-shell will involve deformed nuclei. We derive the normalized matrix element connecting emission of one particle from an initial rotational nuclear state to another final rotating state, and we extract selection rules involving the K quantum number. The initial state is approximated as having a core identical to the final nuclear state. The formalism is then directly applicable to β^+-delayed proton decays of even-Z, odd-N nuclei or β^--delayed neutron decays of odd-Z, even N nuclei. These beta-decay results are compared to the outcomes of possible transfer reactions. As an example the beta-delayed proton emission of ^{21}Mg is considered, where new quantum numbers can be assigned to several states in ^{21}Na.

Eur. Phys. J. **A61** (2025) 87