# Observation and spectroscopy of new proton-unbound nuclei $^{21}$Al and $^{20}$Al

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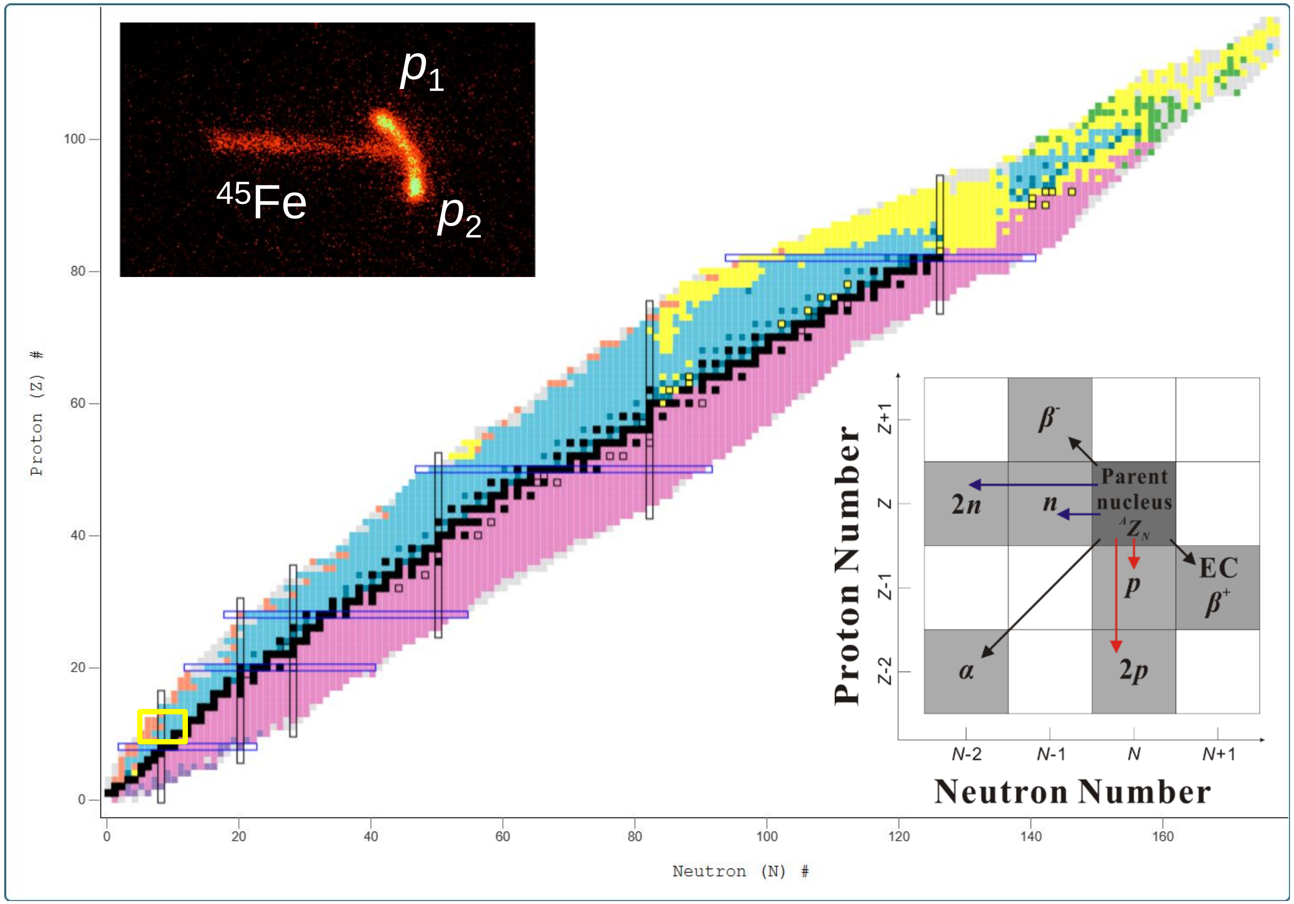
- Introduction
- Experiment overview
- Observation and spectroscopy of $^{21}$Al
- Discovery of $^{20}$Al and study of its three-proton decay
- Summary and outlook

# Nuclear chart and decay modes

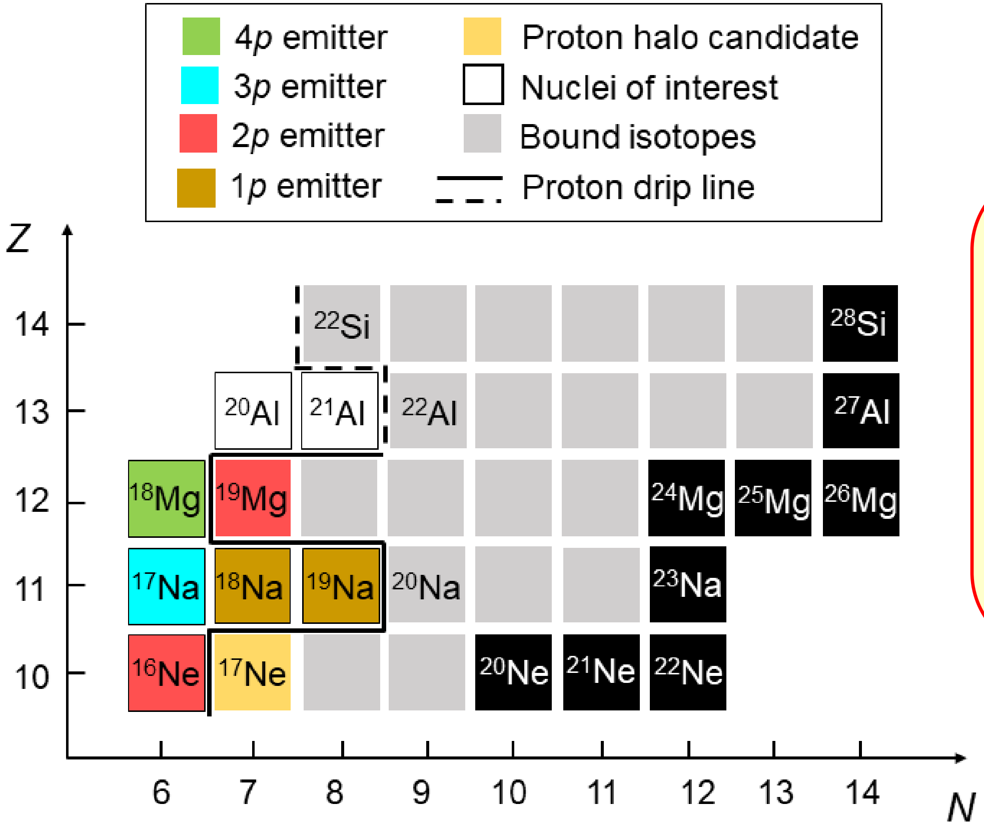



- What are the limits of nuclear existence?
- What features arise near those limits and beyond?

https://www.nndc.bnl.gov/nudat3/

K. Miernik, W. Dominik, Z. Janas *et al.*, PRL 99, 192501 (2007)

# Proton-unbound isotopes in Ne-Si region

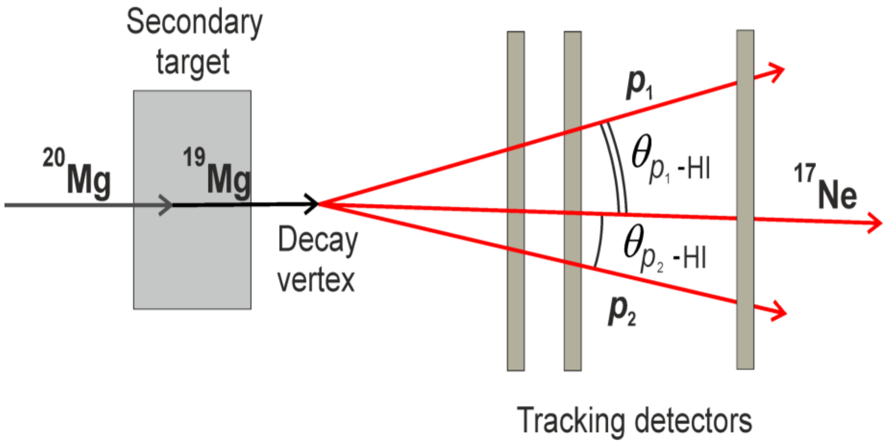


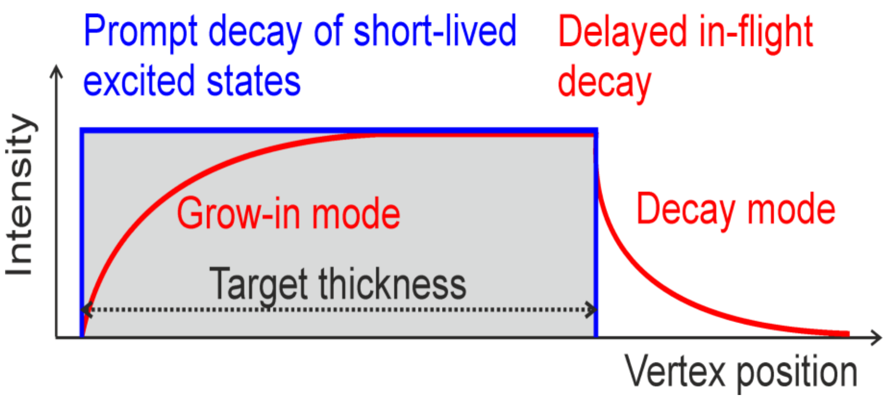

**$^{21}$Al and $^{20}$Al:**

- **How can we discover them?**
- **What are their structure and decay properties?**

# In-flight decay technique

- Studies of proton-unbound nuclei with ps to ns lifetimes
- Unambiguous identification of heavy decay product
- Measurement of trajectories of all decay products
  - ☞ Decay vertex → half-life
  - ☞ Angular correlations → decay energy




I. Mukha and G. Schrieder, NPA 690, 280 (2001)

# In-flight decay spectroscopy

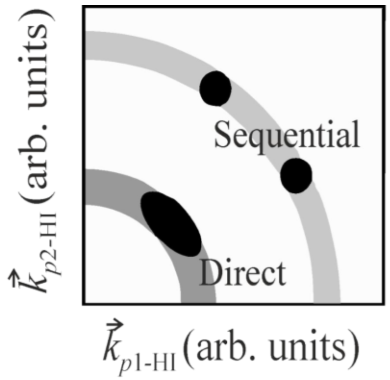
- **Angular correlations are in analogy to momentum correlations.**
- **Kinematic enhancement around $\theta_{\mathrm{HI-p}}$(max)**
- **Two protons share the total decay energy.**

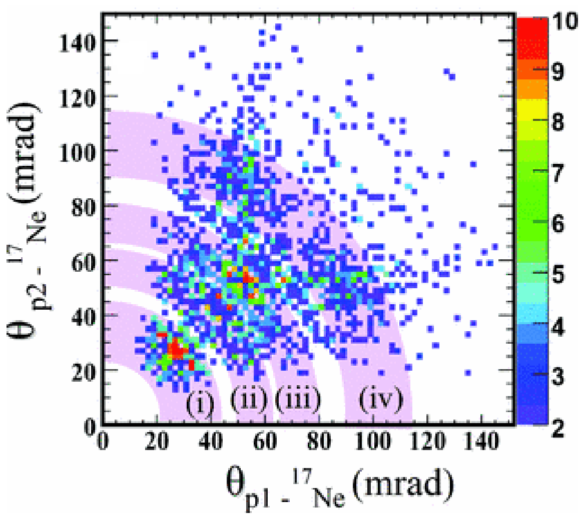
☞ Direct 2*p* decay

✓ $\rho_\theta = \sqrt{\theta^2_{\mathrm{HI}-p_1} + \theta^2_{\mathrm{HI}-p_2}} \sim \sqrt{Q_{2p}}$

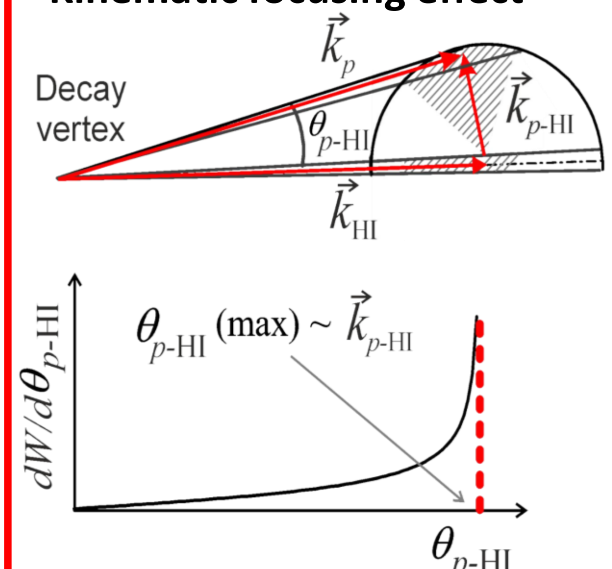
☞ Sequential 2*p* decay

✓ $\theta_{\mathrm{HI-p}}(\mathrm{max}) \sim \sqrt{Q_p}$




**Kinematic focusing effect**



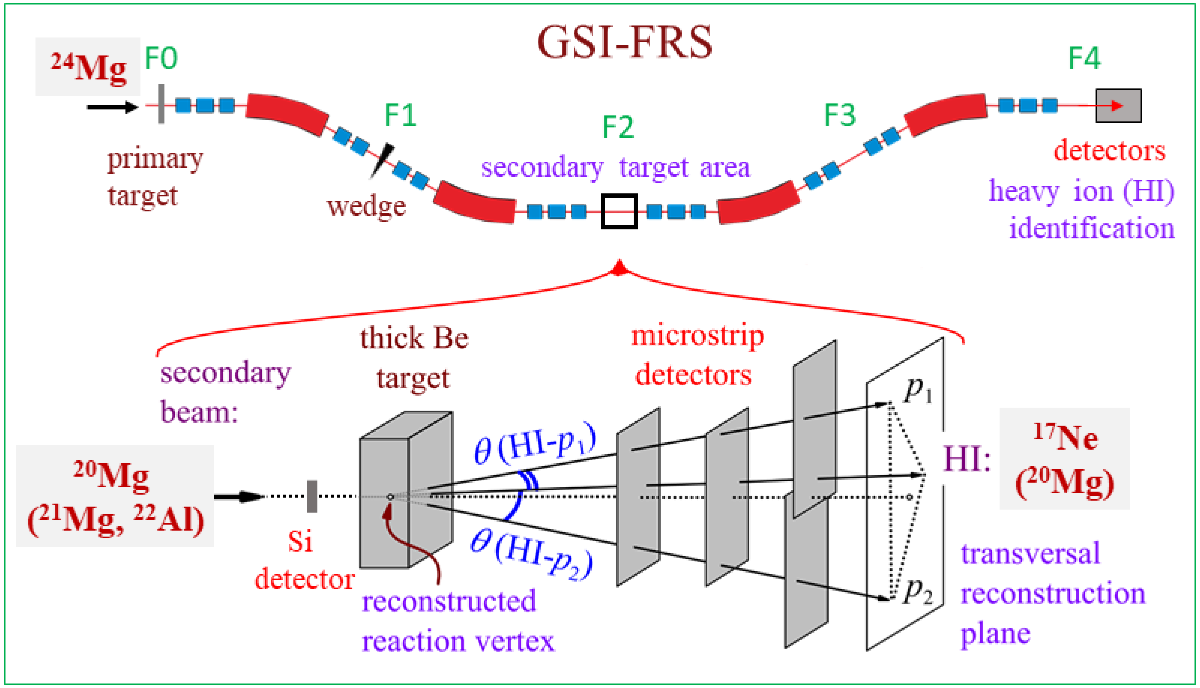

**Each peak corresponds to the decay of one state**

Talk by Dr. Ivan Mukha



I. Mukha, K. Sümmerer, L. Acosta *et al.*, PRL, 99, 182501 (2007); PRC 85, 044325 (2012)

# Experimental overview

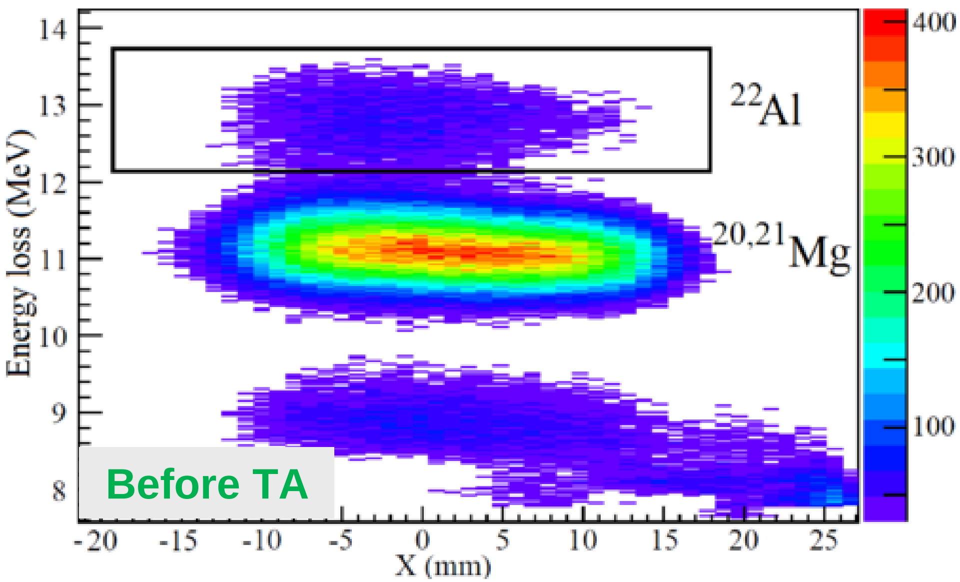


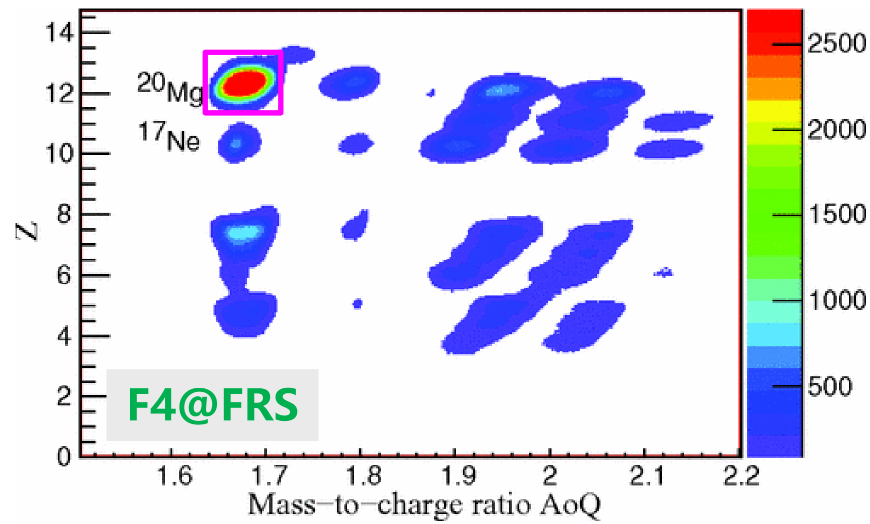

- Energy of $^{24}$Mg beam: 591 MeV/u
- Primary target: Be, 4 g/cm$^2$; secondary target: Be, 2 g/cm$^2$
- Microstrip detector array: measurement of trajectories of decay products

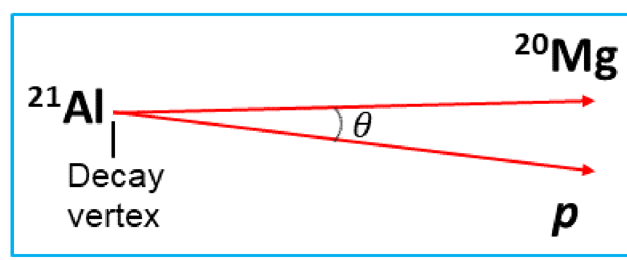
# Identification of $^{21}$Al decay events

$$^{22}\mathrm{Al} \xrightarrow{\text{neutron knockout}} {}^{21}\mathrm{Al} \xrightarrow{\text{decay}} {}^{20}\mathrm{Mg}+p$$

- **PID: B*ρ*-TOF-Δ*E* method**
  - ☞ Δ*E* → *Z*
  - ☞ B*ρ* and TOF → *A/Q*



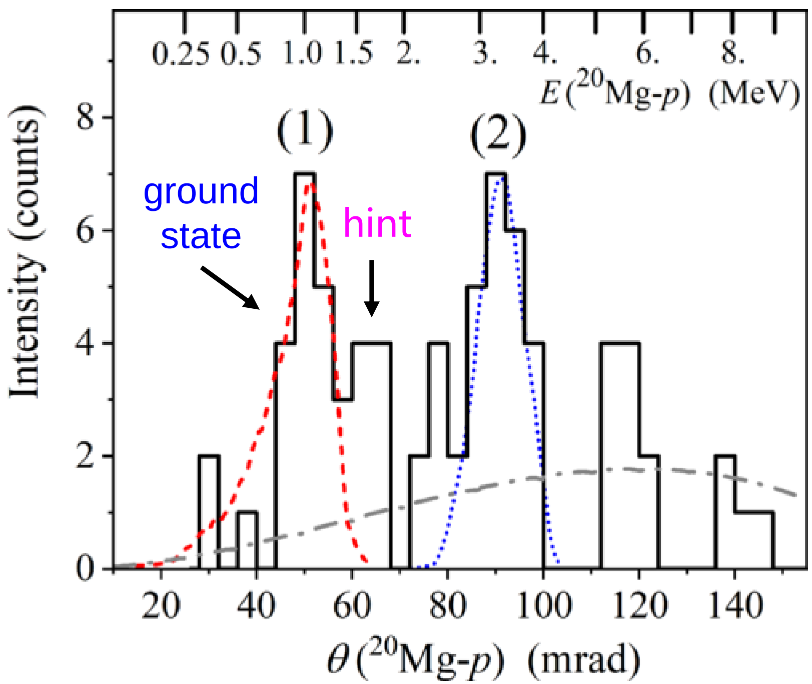



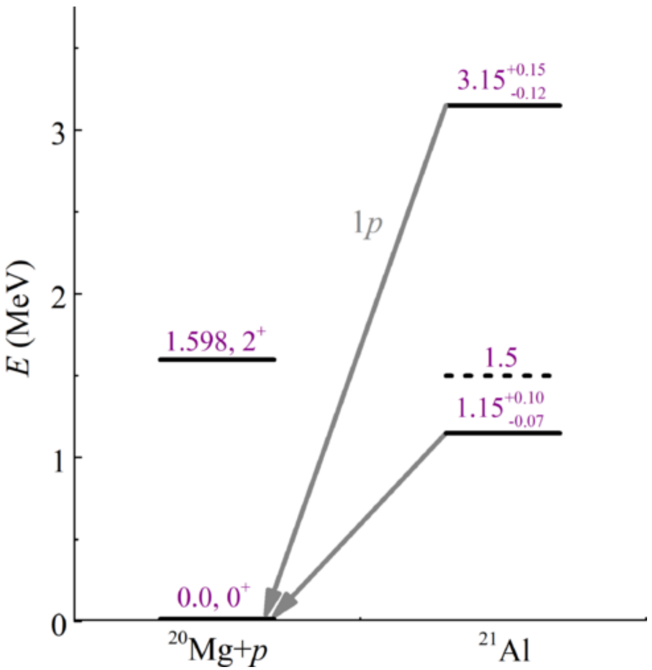





I. Mukha, K. Sümmerer, L. Acosta *et al.*, PRC 82, 054315 (2010)
D. Kostyleva, X.-D. Xu, I. Mukha *et al.*, PRC 110, L031301 (2024)

# Observation and spectroscopy of $^{21}$Al



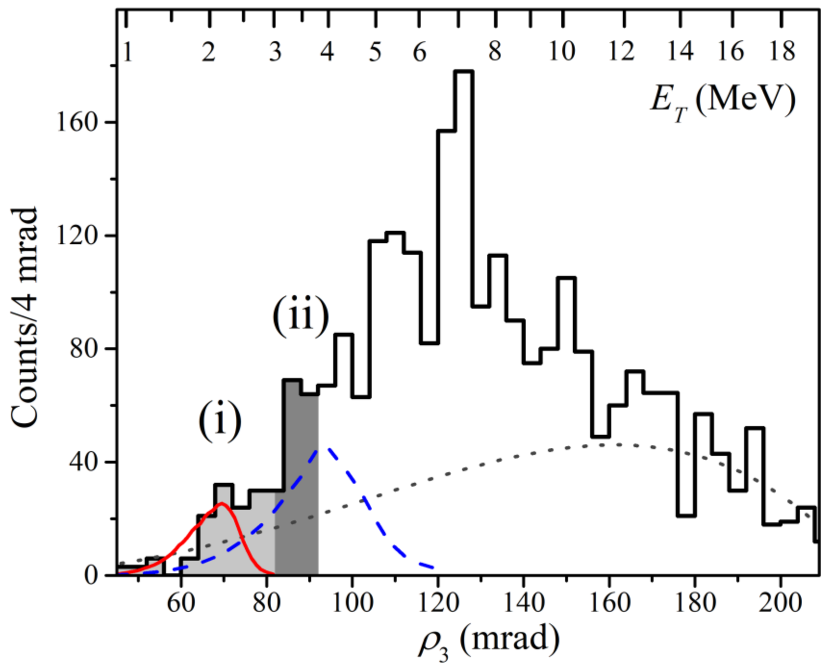



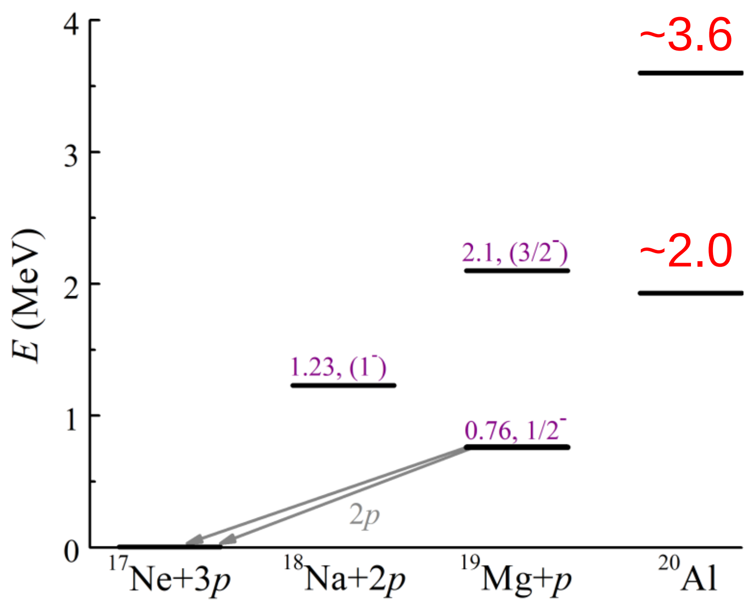

- Prominent peaks (1) and (2): observation of two states of $^{21}$Al
- The proton separation energy and mass of $^{21}$Al were determined.
- $^{21}$Al is the first Al isotope beyond the proton dripline.

D. Kostyleva, X.-D. Xu, I. Mukha *et al*., PRC 110, L031301 (2024)

# First observation of 3$p$ decay of $^{20}$Al

- **Production and decay of $^{20}$Al** $^{20}\mathrm{Mg} \xrightarrow{\text{charge exchange}} {}^{20}\mathrm{Al} \xrightarrow{\text{decay}} {}^{17}\mathrm{Ne}+p_1+p_2+p_3$
- **$^{17}$Ne-proton angular correlation** $\rho_3 = \sqrt{\theta^2_{p_1-{}^{17}\mathrm{Ne}} + \theta^2_{p_2-{}^{17}\mathrm{Ne}} + \theta^2_{p_3-{}^{17}\mathrm{Ne}}} \sim \sqrt{Q_{3p}}$

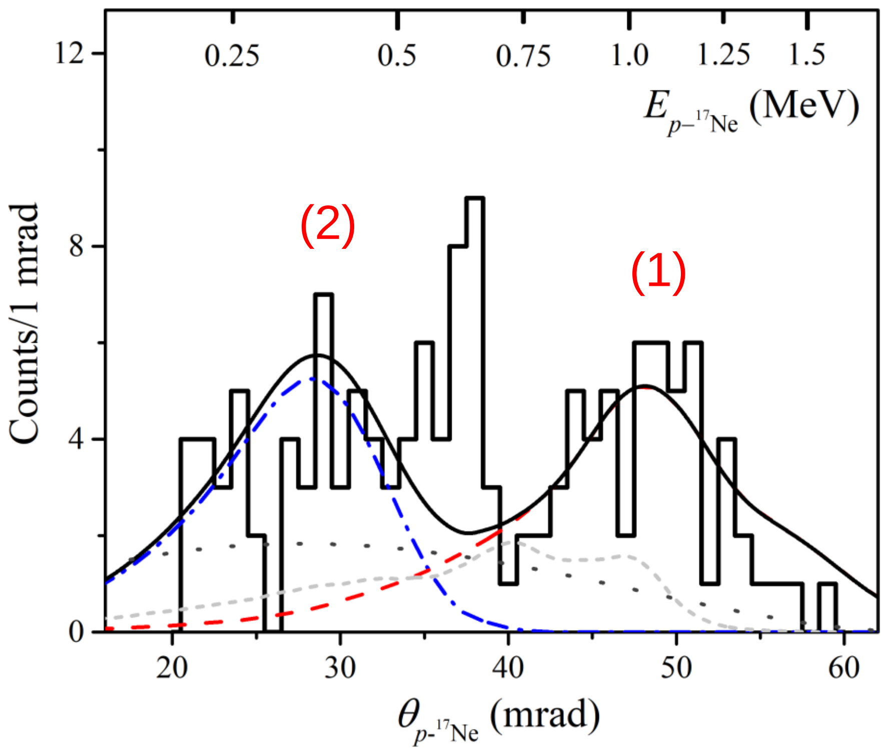


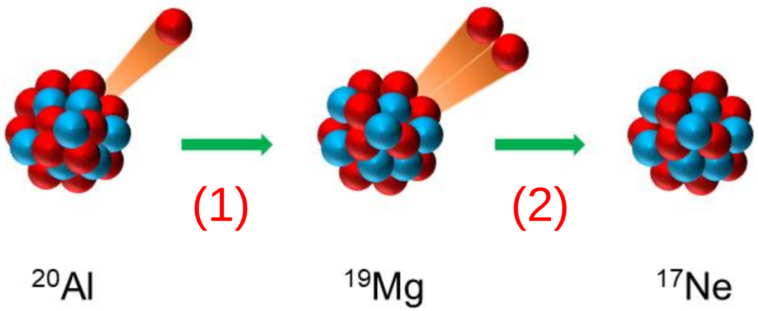

X.-D. Xu, I. Mukha, J. G. Li *et al.*, PRL 135, 022502 (2025)

**What is the decay mechanism?**

# Decay mechanism of $^{20}$Al ground state




**sequential 1*p*-2*p* emission**

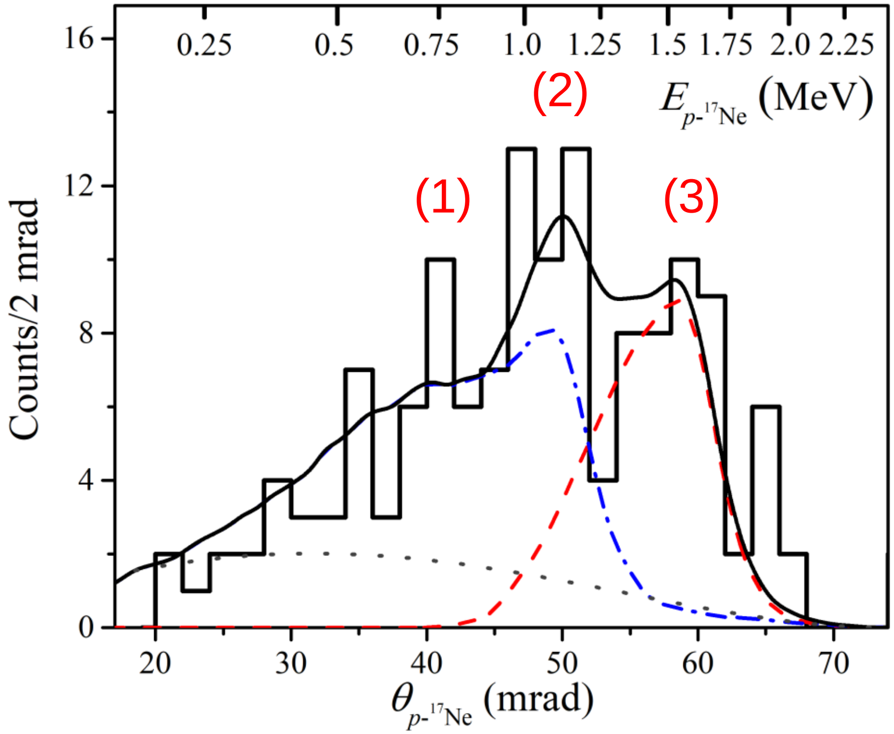


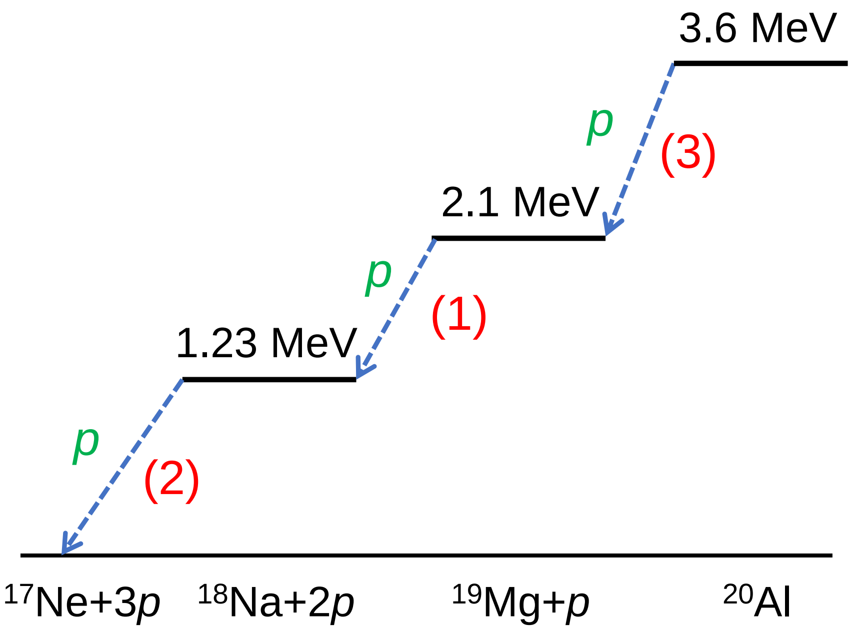

1. one-proton decay with $Q_p$= 1.17 MeV
2. simultaneous 2*p* emission with $Q_{2p}$=0.76 MeV

**First observed case of "daughter" 2*p* radioactivity following 1*p* decay of the parent state**

X.-D. Xu, I. Mukha, J. G. Li *et al.*, PRL 135, 022502 (2025)

# Decay mechanism of the 3.6-MeV state

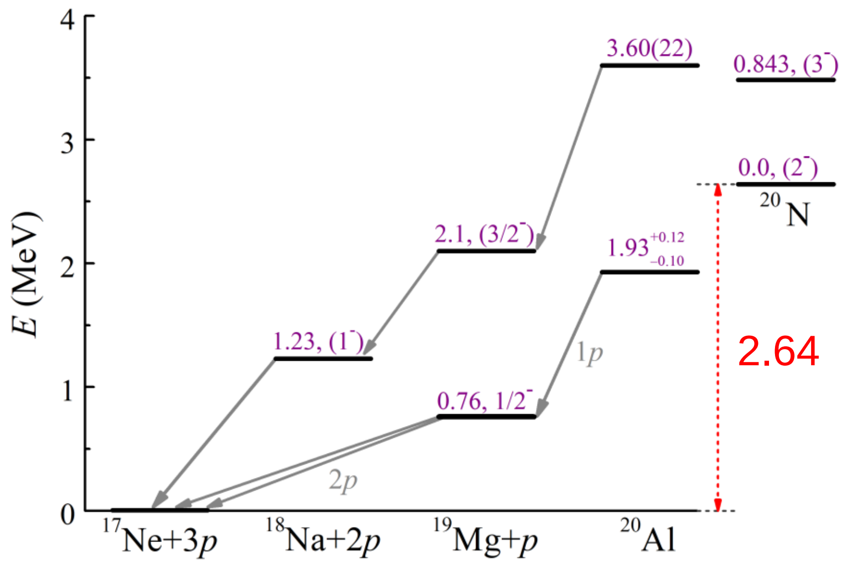


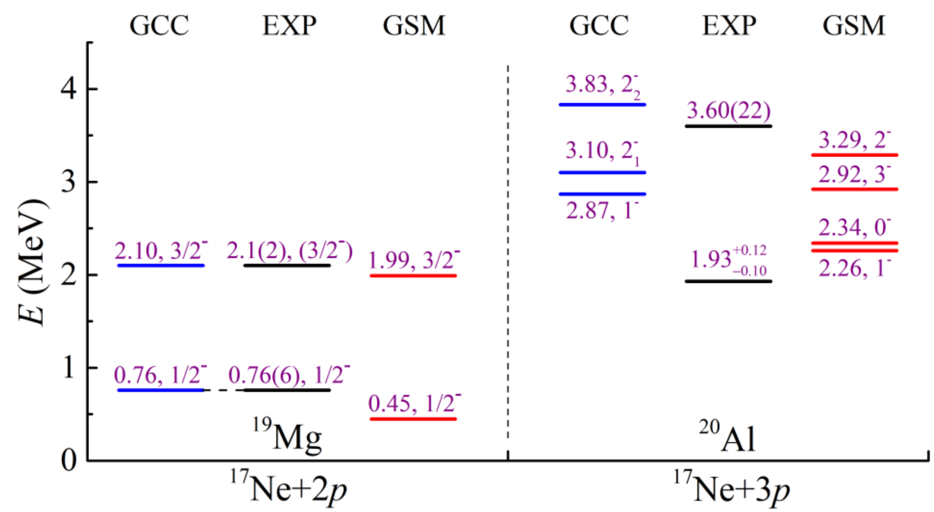




**The 3.6-MeV state decays by sequential proton emission.**

X.-D. Xu, I. Mukha, J. G. Li *et al.*, PRL 135, 022502 (2025)

# Isospin symmetry breaking in $^{20}$Al and $^{20}$N



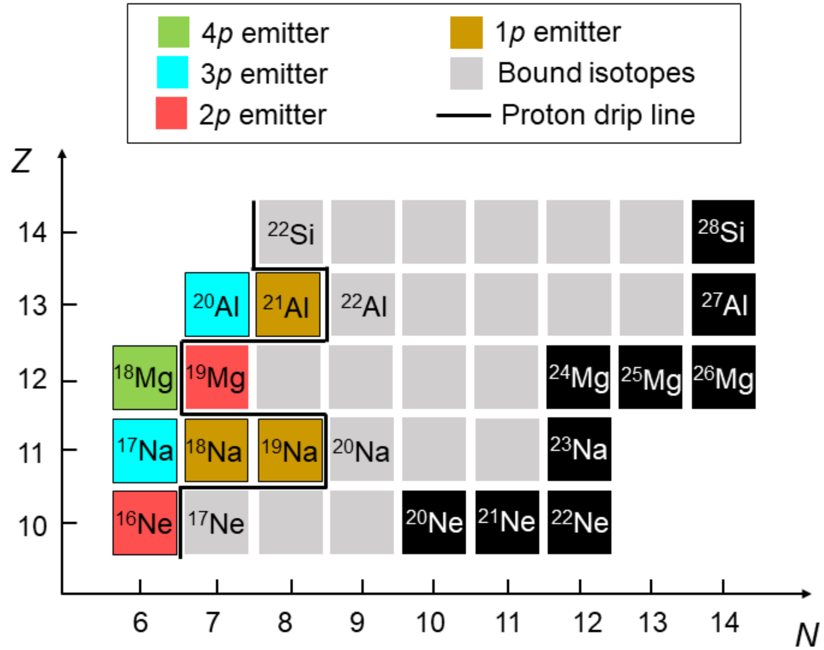

- $Q_{3p}$($^{20}$Al)=$1.93^{+0.12}_{-0.10}$ MeV: significantly smaller than the predictions inferred from the isospin symmetry by employing the $S_n$ of $^{20}$Al's mirror partner $^{20}$N
  → Possible isospin symmetry breaking in $^{20}$Al–$^{20}$N
- Both GSM and GCC model predict that the spin-parity of the $^{20}$Al g.s. is $1^-$, which differs from the spin-parity of the $^{20}$N g.s., ($2^-$).
  → Further evidence of the isospin symmetry violation



X.-D. Xu, I. Mukha, J. G. Li *et al.*, PRL 135, 022502 (2025)

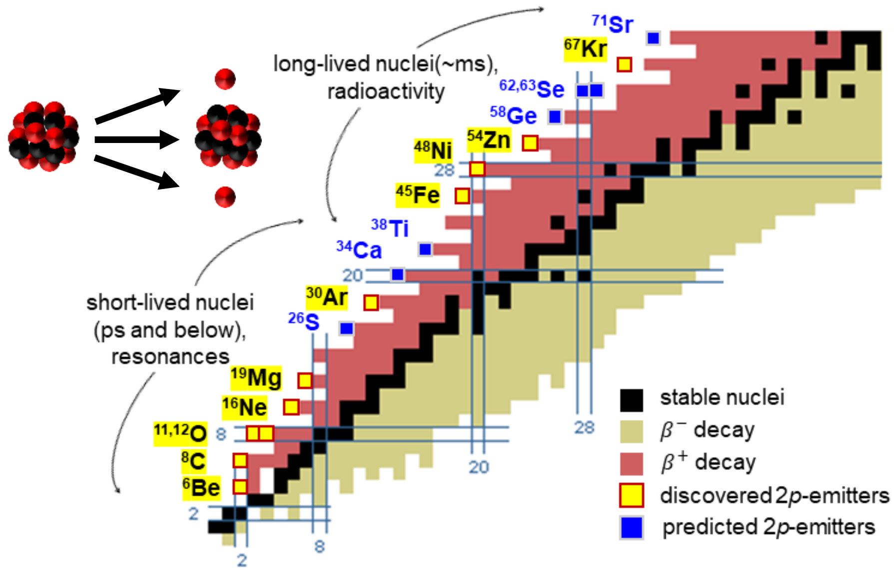
# Summary

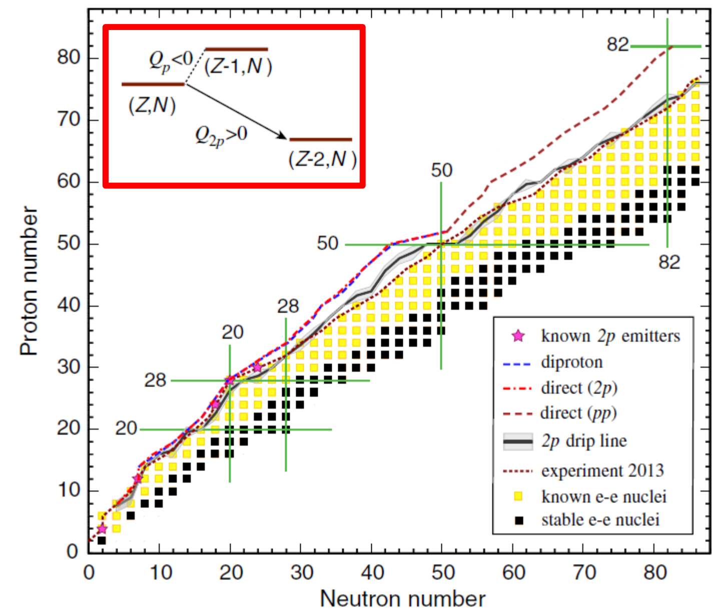
- Observation and spectroscopy of $^{21}$Al
  - ✓ $^{21}$Al: the first Al isotope beyond the proton dripline
  - ✓ The mass and proton separation energy of $^{21}$Al were determined.
  - ✓ The decay scheme of observed states in $^{21}$Al were constructed.




- Discovery of three-proton emitter $^{20}$Al
  - ✓ Observation of the lightest Al isotope $^{20}$Al
  - ✓ First discovered case of “daughter” 2*p* radioactivity
  - ✓ Possible isospin symmetry breaking in the mirror pair $^{20}$Al–$^{20}$N

# Two-proton radioactivity landscape



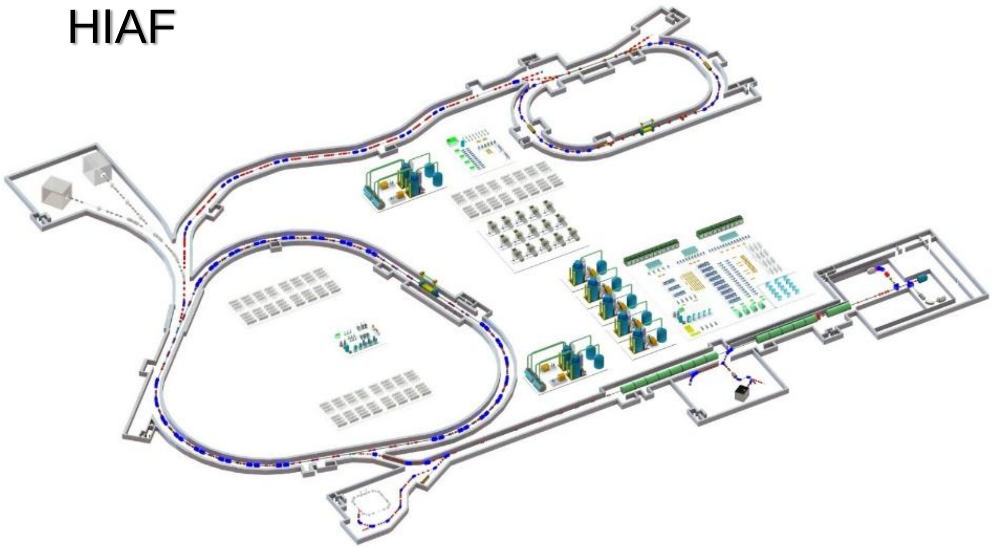




Almost all elements between Ar and Pb have 2$p$ decaying isotopes! **$^{19}$Mg, $^{45}$Fe, $^{48}$Ni, $^{54}$Zn**, $^{26}$S, $^{34}$Ca, $^{57,58}$Ge, $^{62,63}$Se, **$^{67}$Kr**, $^{71}$Sr, $^{102,103}$Te, $^{73}$Zr, $^{77}$Mo, $^{81}$Ru, $^{85}$Pd, $^{113}$Ce, $^{117}$Nd, $^{121}$Sm, $^{125,126}$Gd, $^{130}$Dy, $^{133\text{-}135}$Er, $^{138,139}$Yb, $^{151,152}$Os, $^{154\text{-}156}$Pt, $^{158,159}$Hg,$^{109,110}$Ba, $^{114}$Ce, $^{127}$Gd, $^{131}$Dy, $^{144,145}$Hf, $^{147\text{-}149}$W

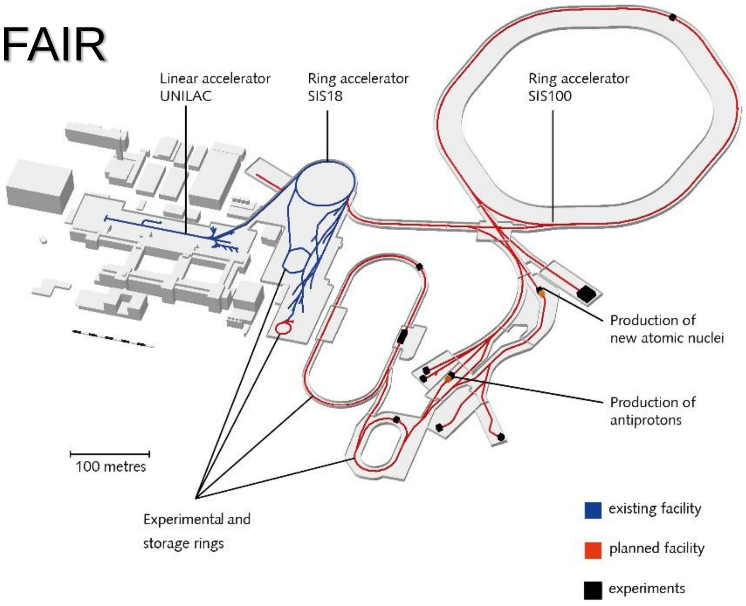

L. V. Grigorenko and M. V. Zhukov, PRC 68, 054005 (2003)
E.Olsen, M. Pfützner, N. Birge *et al.*, PRL 110, 222501 (2013)

# In-flight decay study at advanced RIB facilities

HIAF



FAIR




X. H. Zhou *et al.*, AAPPS Bull. 32, 35 (2022)

https://www.gsi.de/en/researchaccelerators/fair

High energy
High intensity

ideal condition

In-flight decay with particle emission
(2*p*, 4*p*, 2*n*, 4*n*…)

# Acknowledgments

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**Thank you for your attention!**