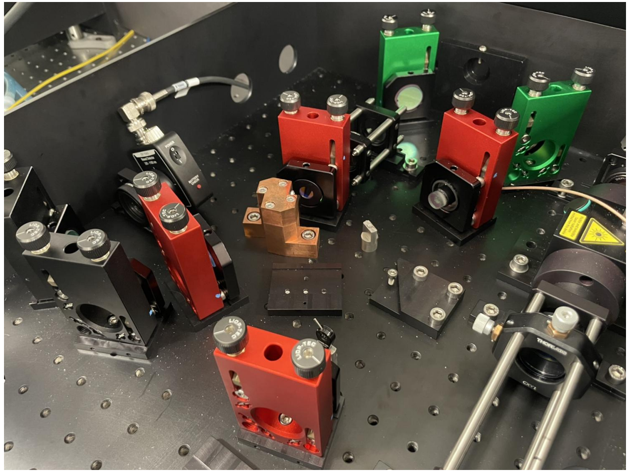
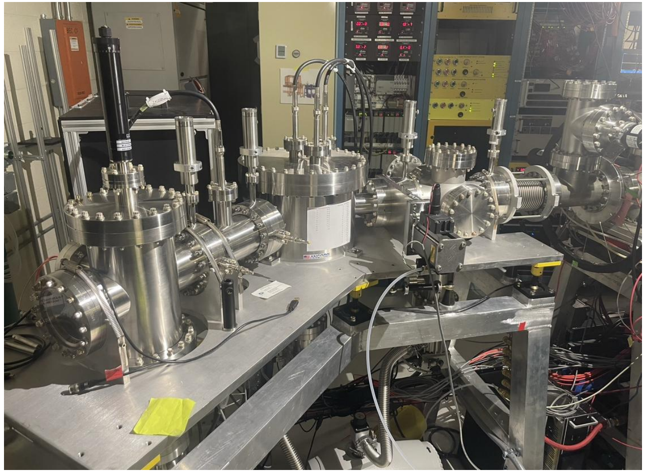
Laser spectroscopy of aluminium isotopes at the limits of existence at FRIB

Massachusetts
Institute of
Technology

Shane Wilkins — MIT Department of Physics

ISOLDE Workshop and Users Meeting 2024 — 27th-29th December 2024

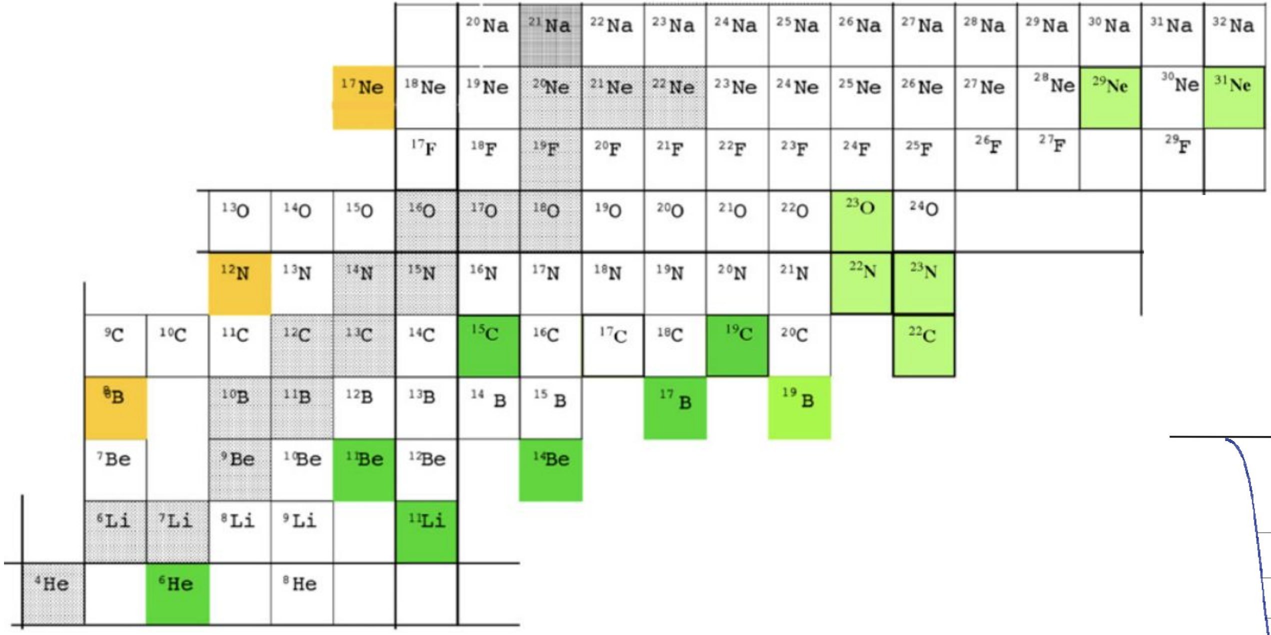


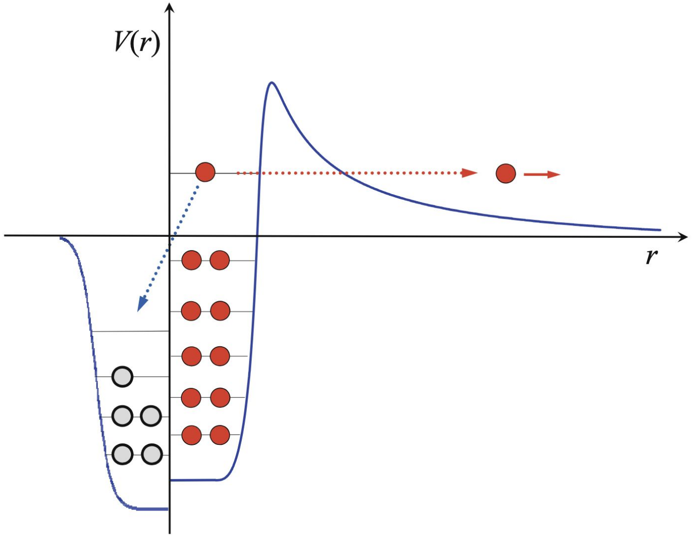


EMA lab

Rare proton halos

While there are multiple well-established neutron halos, proton halos are a more elusive phenomenon as they are more subtle in nature.

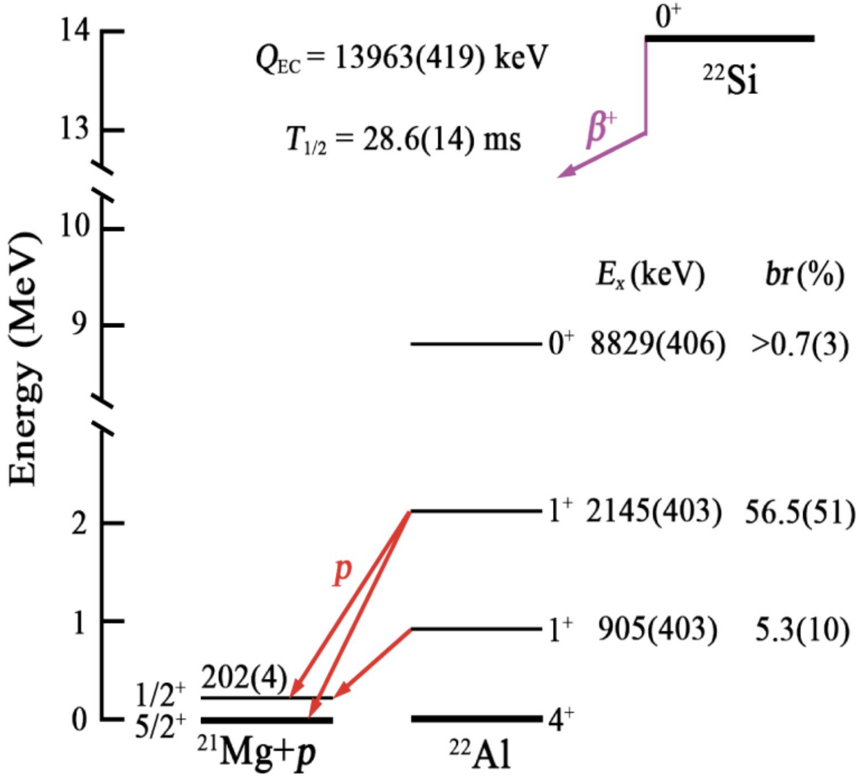


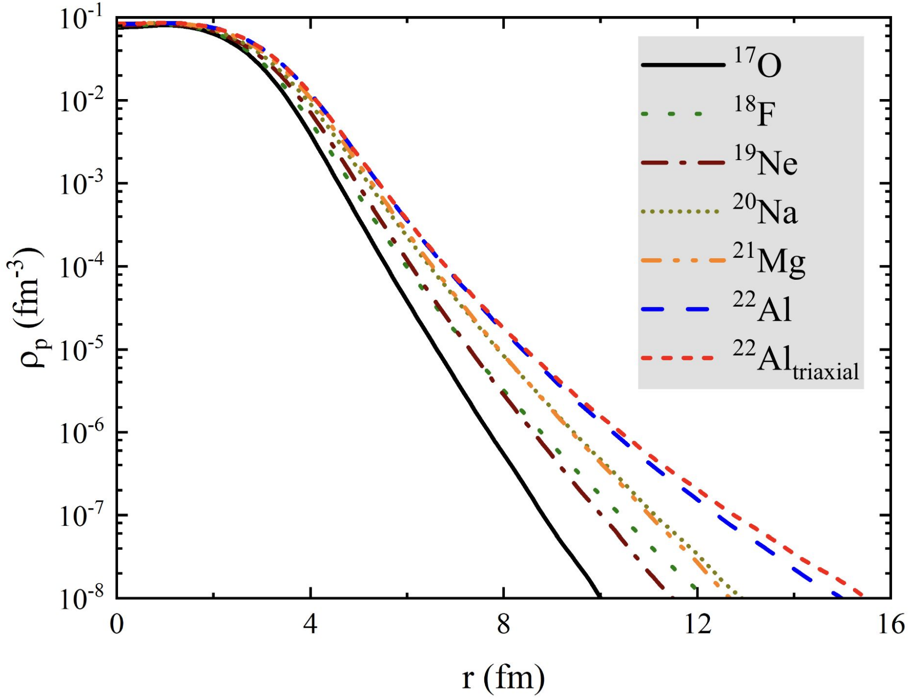


I. Tanihata *et al*., Prog. Part. Nucl. Phys. **68** 215–313 (2013), Pfützner *et al*., Nuclei Near and at the Proton Dripline (2023).

Is there a proton halo in ^{22}Al?

Decay studies suggest halo structures in ^{22}Al from observed asymmetry between ^{22}Si → ^{22}Al and ^{22}O → ^{22}F.

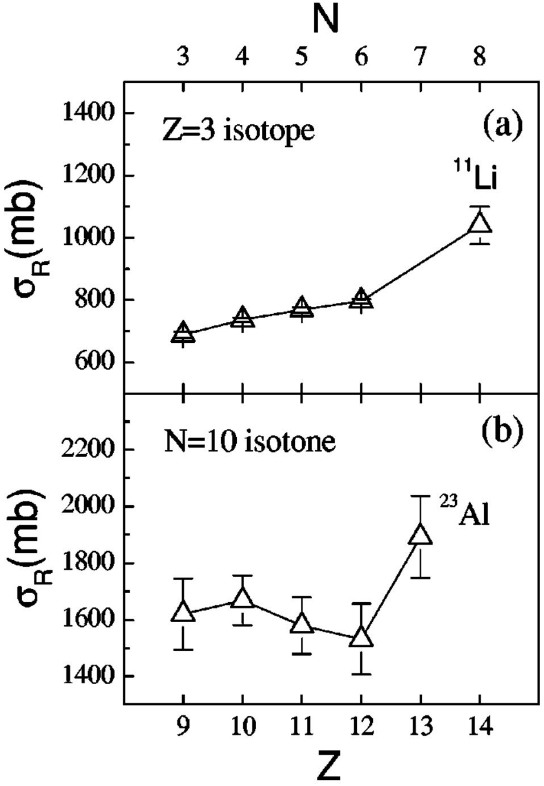


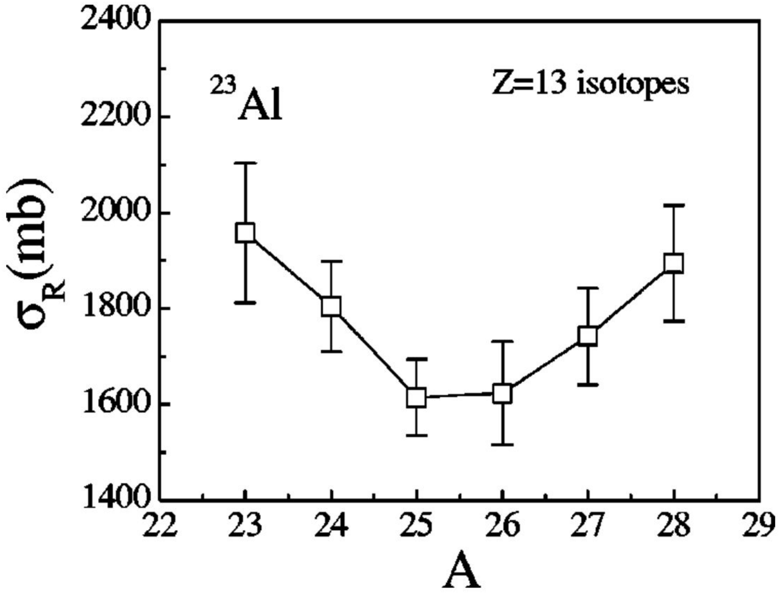


Lee *et al.*, Phys. Rev. Lett. **125** 192503 (2020), Zhang *et al.*, Phys. Rev. C **110** 014320 (2024)

Is there a proton halo in ^{22}Al?

Reaction studies suggest increased nuclear size in ^{23}Al as the dripline is approached from cross-sections.

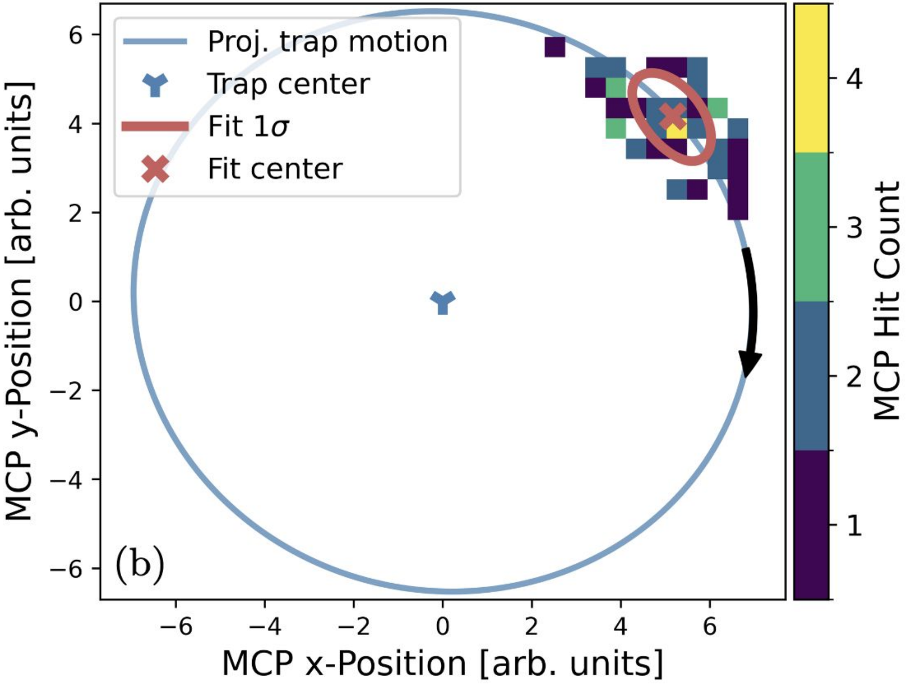


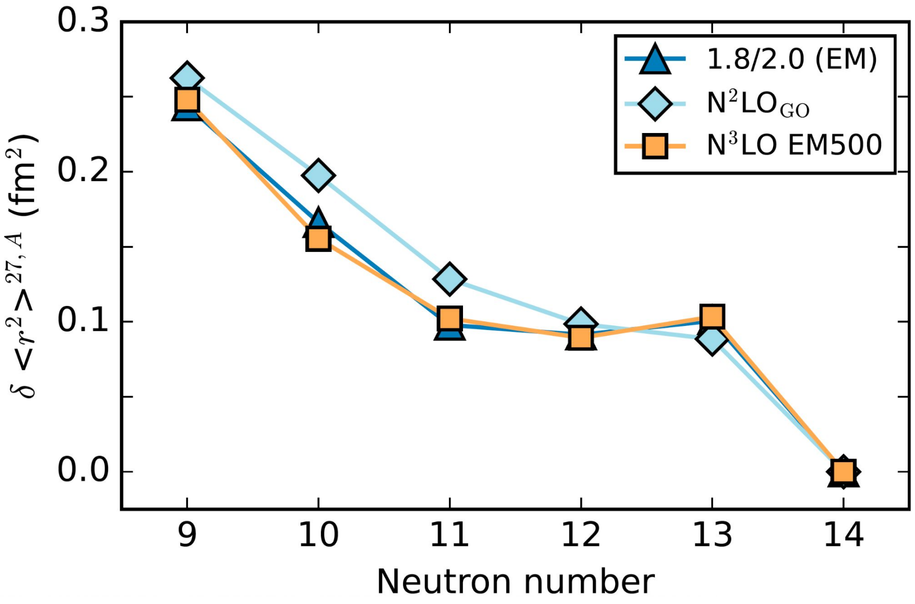


Cai *et al.*, Phys. Rev. C **65** 024610 (2002)

Is there a proton halo in ^{22}Al?

Penning trap measurements reveal exceptionally low (~100 keV) proton separation energy of ^{22}Al. *Ab initio* calculations predict rapid increase in nuclear size all the way to dripline.





Campbell *et al.*, Phys. Rev. Lett. **132** 152501 (2024), Miyagi *et al.*, Priv. Comm. (2024)

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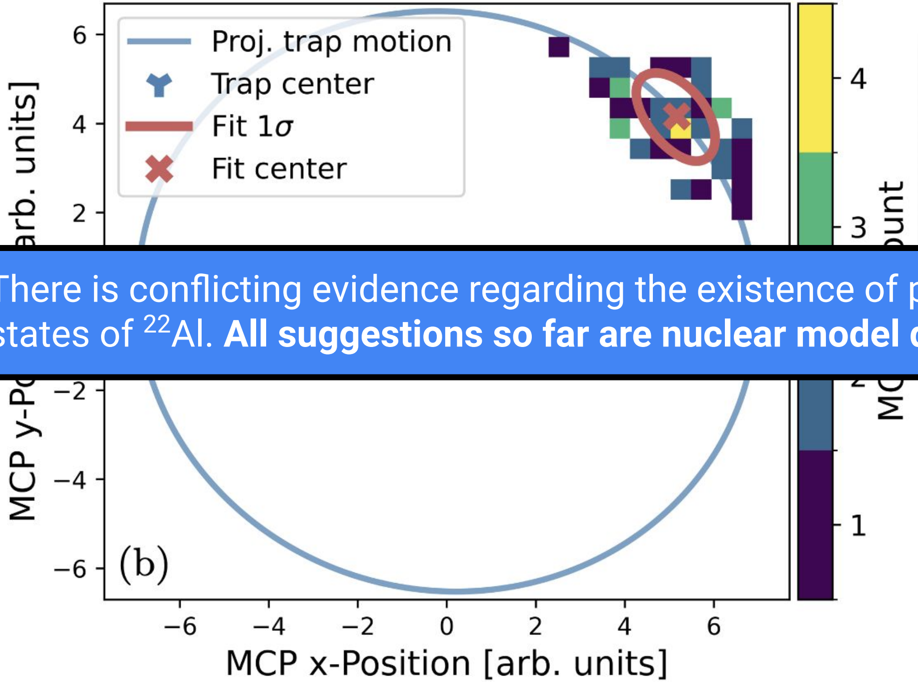
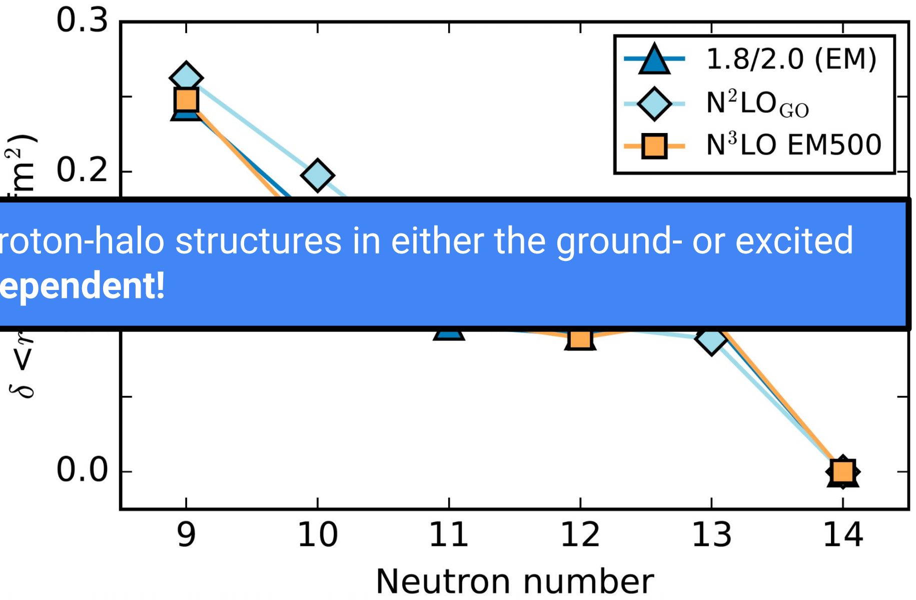




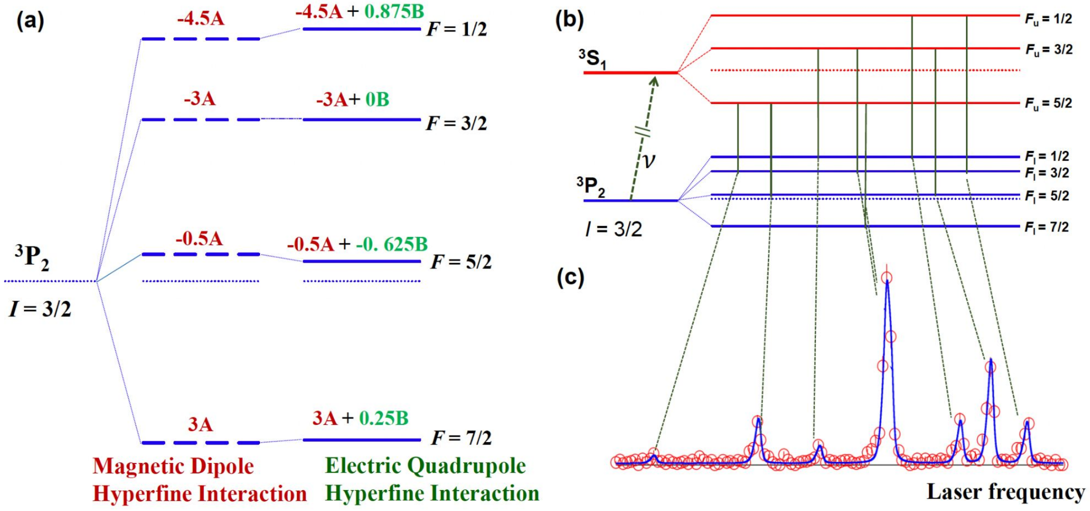
There is conflicting evidence regarding the existence of proton-halo structures in either the ground- or excited states of ^{22}Al. **All suggestions so far are nuclear model dependent!**

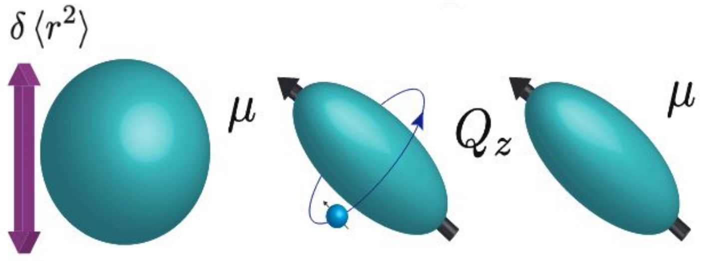
Campbell *et al.*, Phys. Rev. Lett. **132** 152501 (2024), Miyagi *et al.*, Priv. Comm. (2024)

Laser spectroscopy for nuclear structure

Laser spectroscopy is a powerful and versatile tool in investigating multiple facets of nuclear structure in a nuclear model-independent manner.

$$\Delta E_{\mathrm{hfs}}/h = \Delta E_{\mathrm{m}}/h + \Delta E_{\mathrm{e}}/h = \frac{1}{2}AK + \frac{B}{4}\frac{\frac{3}{2}K(K+1) - 2I(I+1)J(J+1)}{I(2I-1)J(2J-1)}$$

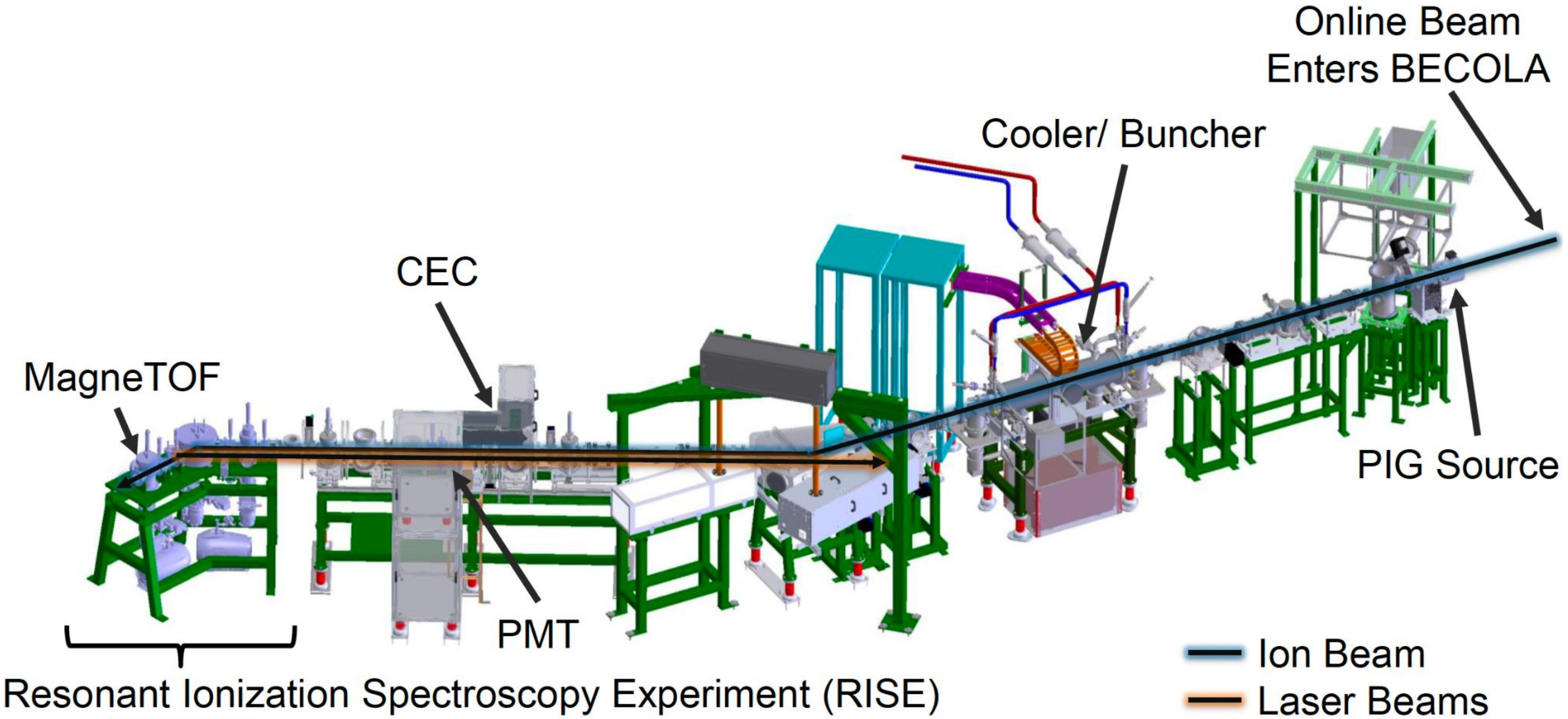




X. F. Yang, S. G. Wilkins *et al.*, Prog. Part. Nucl. Phys. **129** 104005 (2023)

Resonance Ionization Spectroscopy Experiment

Existing collinear laser spectroscopy beam line (BECOLA) extended to enable higher-sensitivity resonance ionization spectroscopy experiments.



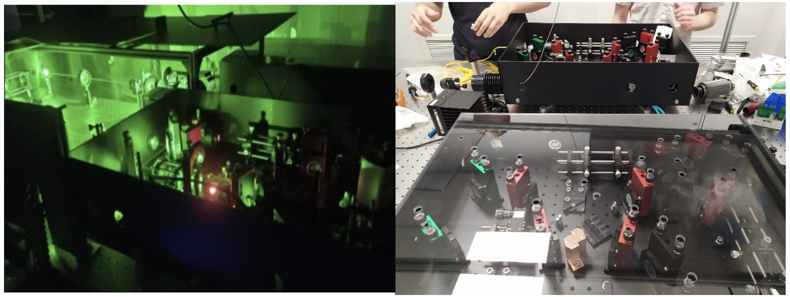
BECOLA-RISE development timeline

December 2020

Beginning of BECOLA-RISE

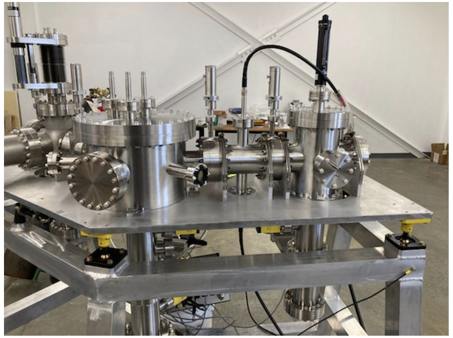
2021

Laser system built and commissioned at MIT.
RISE beamline designed and ordered.



2022

RISE beamline fully constructed.

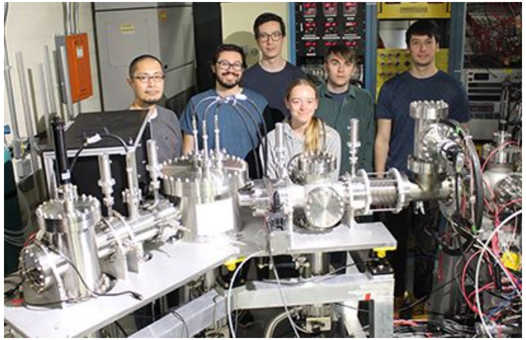


2022

RISE beamline and laser system delivered to FRIB.

2023

BECOLA-RISE successfully commissioned with spectroscopy of stable Al.

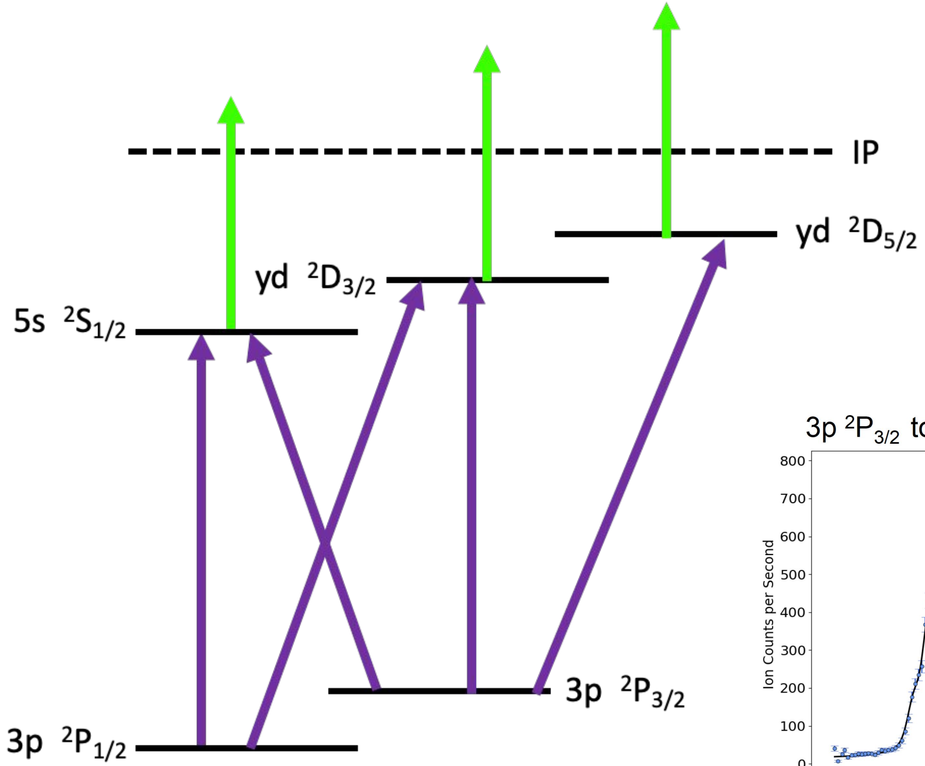


May 2024

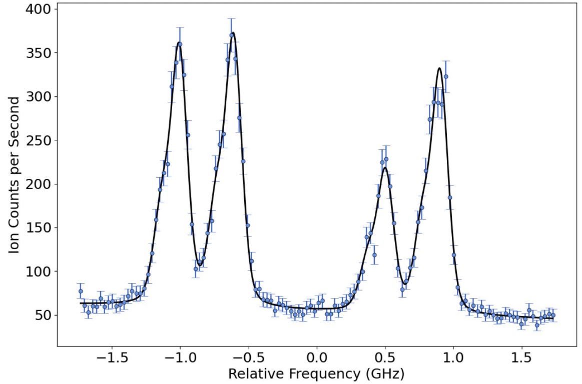
First radioactive isotope physics with $^{22-25}$Al measurements at BECOLA-RISE.

Aluminium scheme development

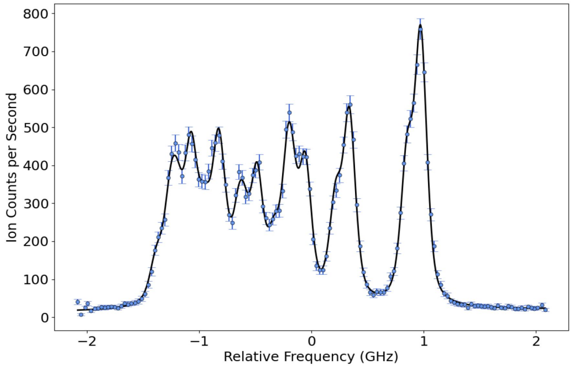
Extensive off-line development investigating 5 different transitions enabled sensitive scheme to be found.



3p $^2P_{1/2}$ to 5s $^2S_{1/2}$ ^{27}Al Sample Spectrum



3p $^2P_{3/2}$ to yd $^2D_{5/2}$ ^{27}Al Sample Spectrum



Kei Minamisono, Alejandro Ortiz-Cortes, Brooke Rickey, Adam Dockery, Skyy Pineda

Michigan State University/Facility for Rare Isotope Beams

Alex Brinson, Ronald Fernando Garcia Ruiz

Massachusetts Institute of Technology

And others!

E21015 experiment at BECOLA-RISE

Short-lived aluminium isotopes all the way to the proton dripline were measured using BECOLA-RISE at FRIB!

22Al	23Al	24Al	25Al	26Al	27Al
88.6 ms	447 ms	2.053 s	7.17 s	7.17e+5 y	STABLE 100%
ε+β+=100%	ε+β+=100%	ε+β+=100%	ε+β+=100%	ε+β+=100%	
εp=57.7%	εp=1.04%	εα=0.035%			
ε2p=1.17%		εp=1.6e-3%			

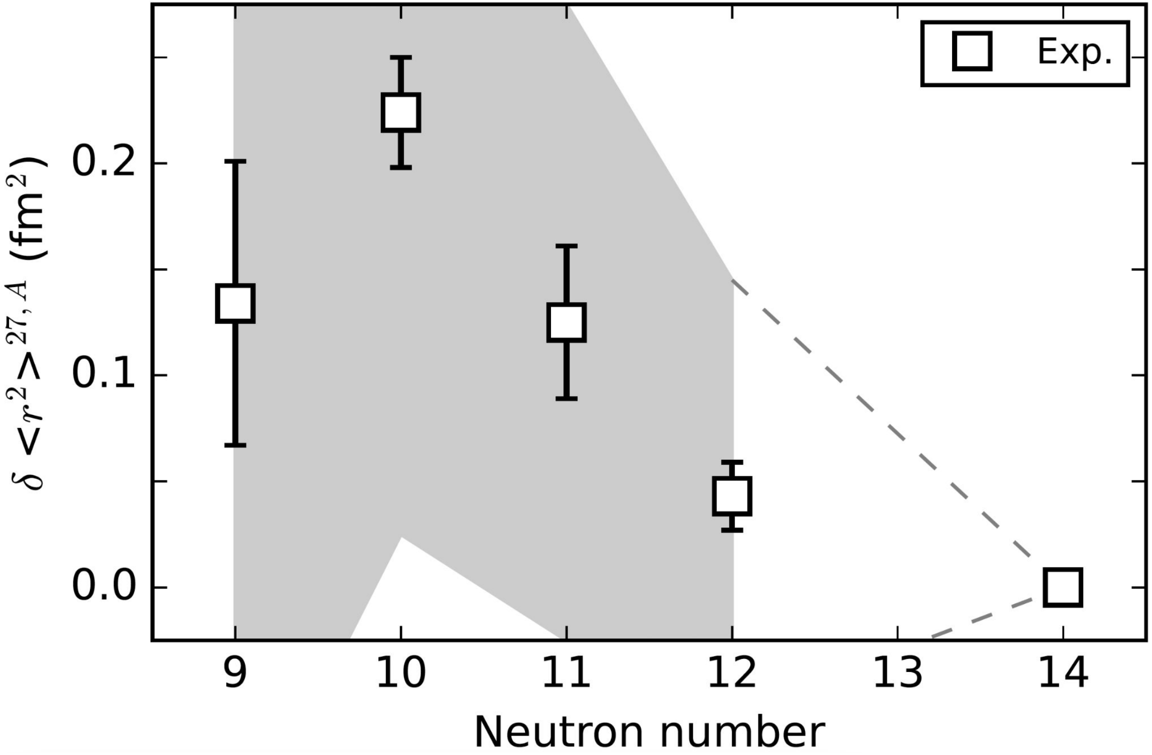
B. Rickey, Priv. Comm. (2024)

Preliminary charge radii results

Preliminary analysis of data indicates likely reduction in size of proton distribution at the limits of existence.

Brooke Rickey

Michigan State University/Facility for Rare Isotope Beams



B. Rickey, Priv. Comm. (2024)

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Massachusetts Institute of Technology

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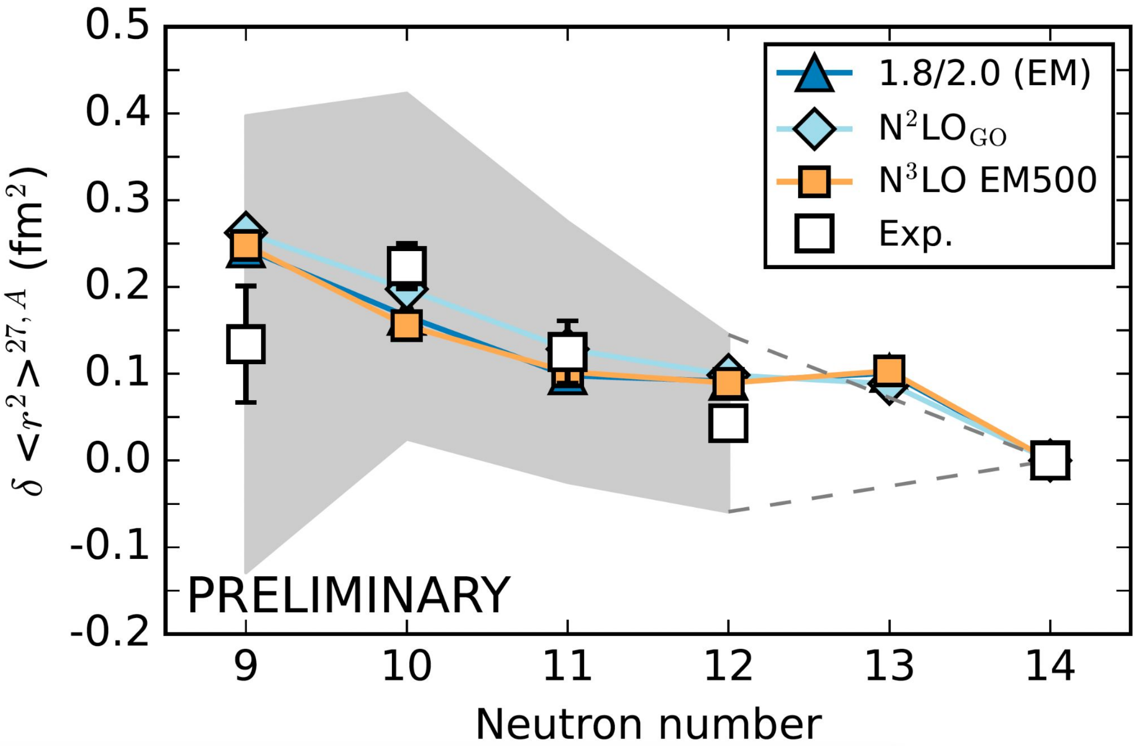


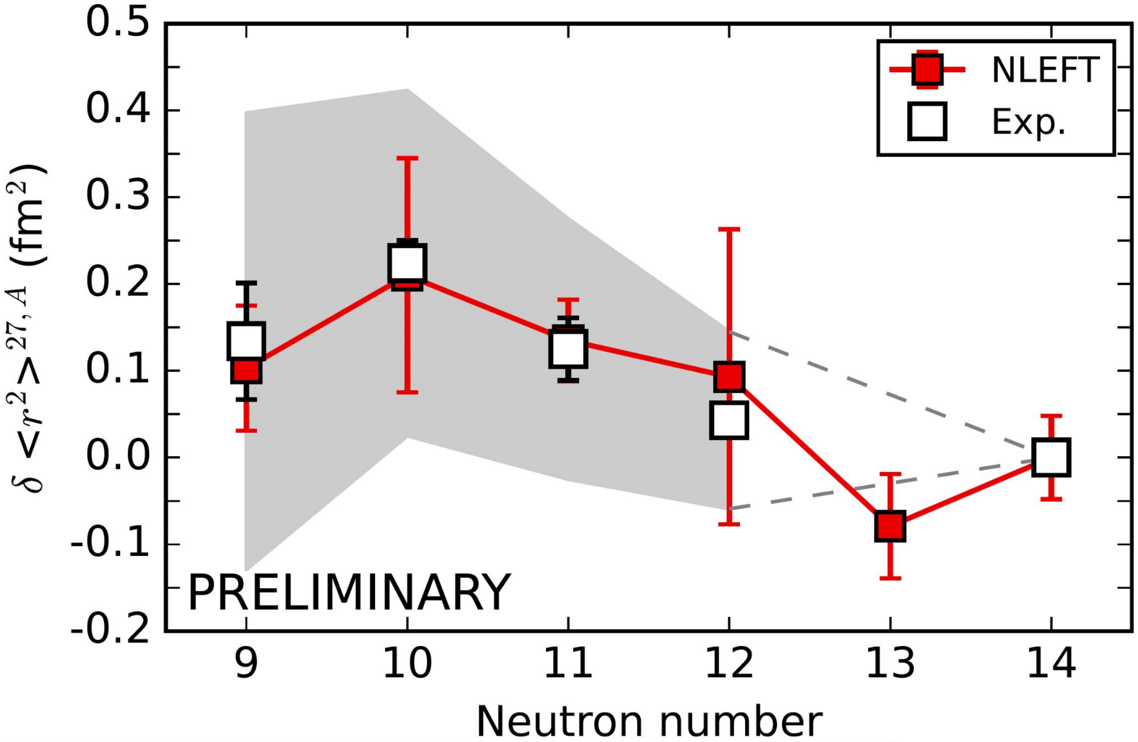
B. Rickey, Priv. Comm. (2024)

Alex Brinson

Massachusetts Institute of Technology

Nuclear lattice effective field theory calculations

Wavefunction matching technique has enabled lattice quantum Monte Carlo calculations of nuclei and nuclear matter.



Dean Lee,
Yuanzhou Ma

Michigan State University/Facility for Rare Isotope Beams

Ulf Meißner,
Shuang Zhang

University of Bonn

Serdar Elhatisari

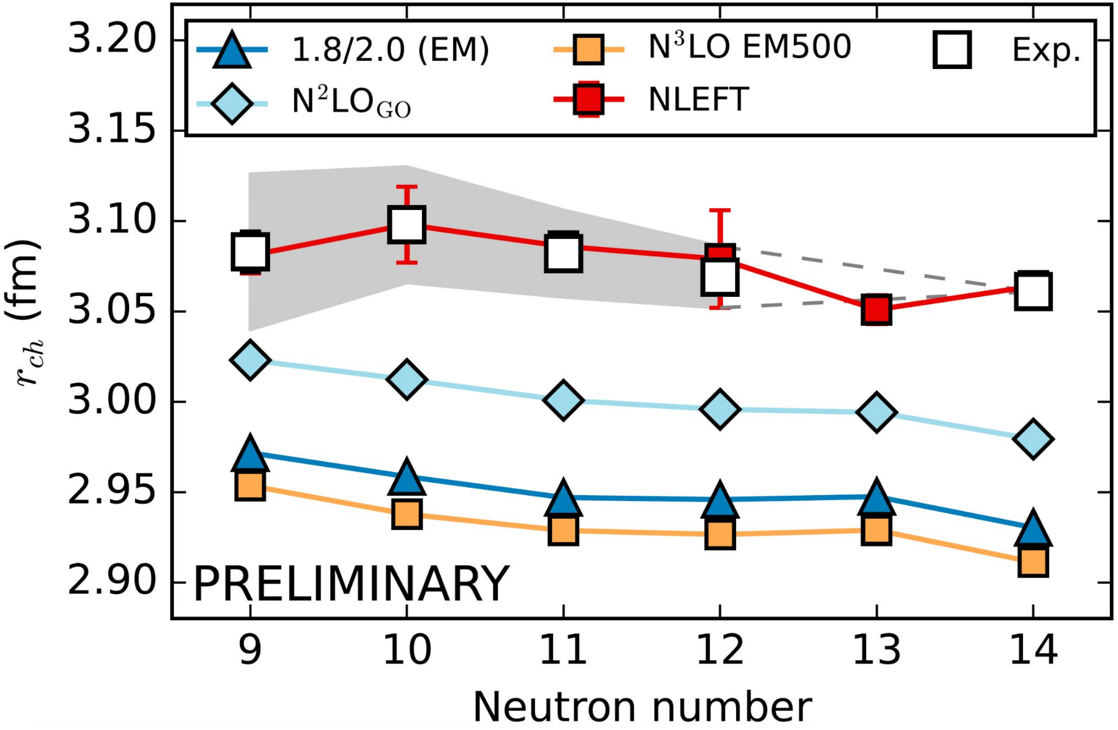
Gaziantep Islam S&T University

And others!

D. Lee, Priv. Comm. (2024), Elhatisari *et al.*, Nature **630** 59-63 (2024), König *et al.*, Phys. Rev. Lett. **132** 162502 (2023)

Nuclear lattice effective field theory calculations

NLEFT calculations both capture the relative trend in charge radii but also their absolute size, which has proven challenging for *ab initio* nuclear theories so far.



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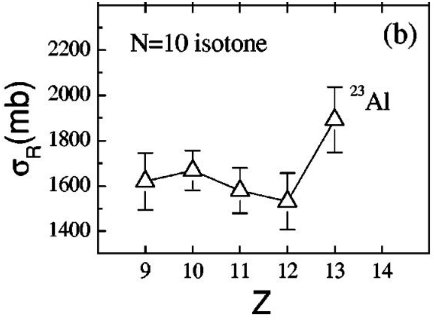
B. Rickey, Priv. Comm. (2024), D. Lee, Priv. Comm. (2024)

Approved BECOLA-RISE experiments at FRIB

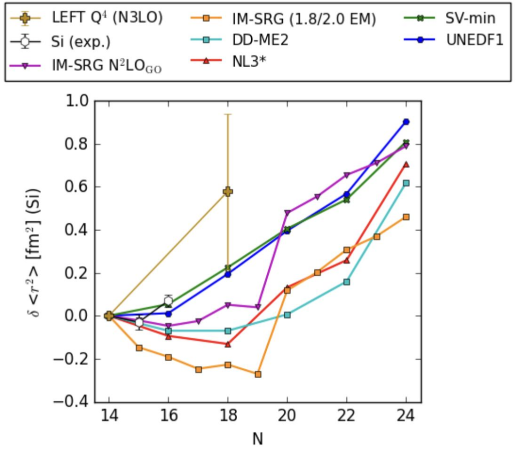
Aluminium (Z=13)
$^{22-25}$Al



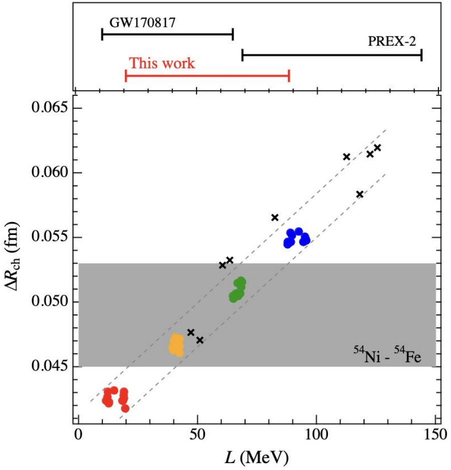
Measurement of r_{ch} for ^{22}Al → investigation of proton halo!

Silicon (Z=14)
$^{31,33-38}$Si

Properties of Si isotopes → *ab initio* nuclear theory.



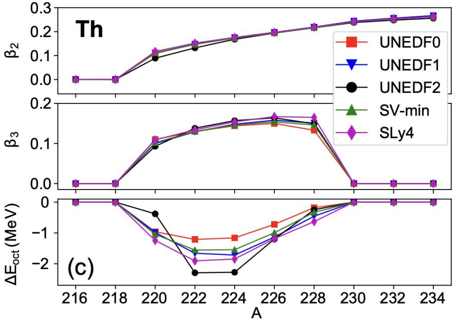
Nickel (Z=28)
^{52,53}Ni



r_{ch}(^{52}Ni) will provide powerful constraint on slope of symmetry energy (*L*) → linked to neutron stars.

Thorium (Z=90)
$^{223-226}$Th

Evolution of quadrupole and octupole deformation.



Conclusion

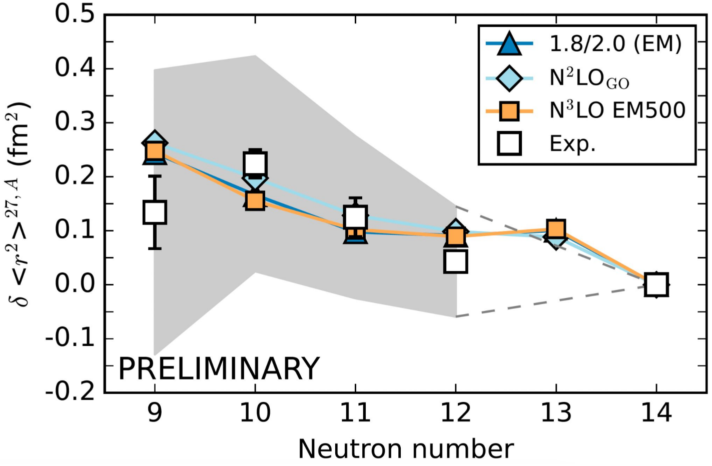
The Resonance Ionization Spectroscopy Experiment (RISE) performed its first on-line experiment at the BECOLA branch of FRIB.

Neutron-deficient aluminium isotopes all the way to the proton dripline were measured, yielding new charge radii for $^{22\text{-}25}$Al and a new magnetic moment for ^{22}Al.

Preliminary analysis indicates that the nuclear size likely decreases at the dripline for ^{22}Al, contesting the presence of a ground-state proton halo in this nucleus.

The measurements were used to confront predictions from *ab initio* nuclear theory.

Lots of experiments using the BECOLA-RISE setup will take place in the coming decade.



Acknowledgements

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LEBIT: S. Campbell, H. Erington, C. Ireland, F Maier, R. Ringle.

FRIB

TECHNISCHE UNIVERSITÄT DARMSTADT

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SC State UNIVERSITY

C. Jones, S. Papa, R. Yadav

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