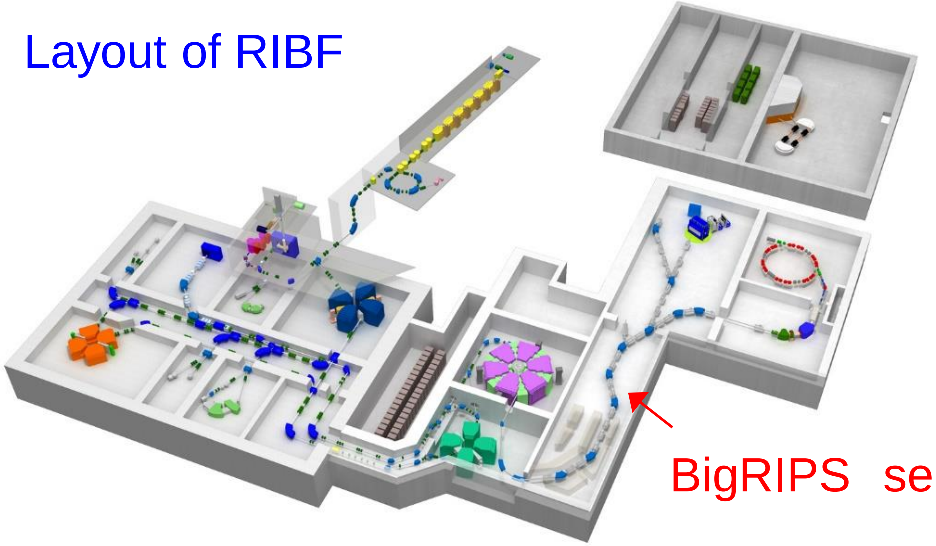
Neutron dripline search for fluorine, neon and sodium and the discovery of ^{39}Na

Conducted at RIKEN RIBF using the BigRIPS separator

Toshiyuki Kubo, RIKEN Nishina Center
for the RIKEN RIBF new isotope collaboration

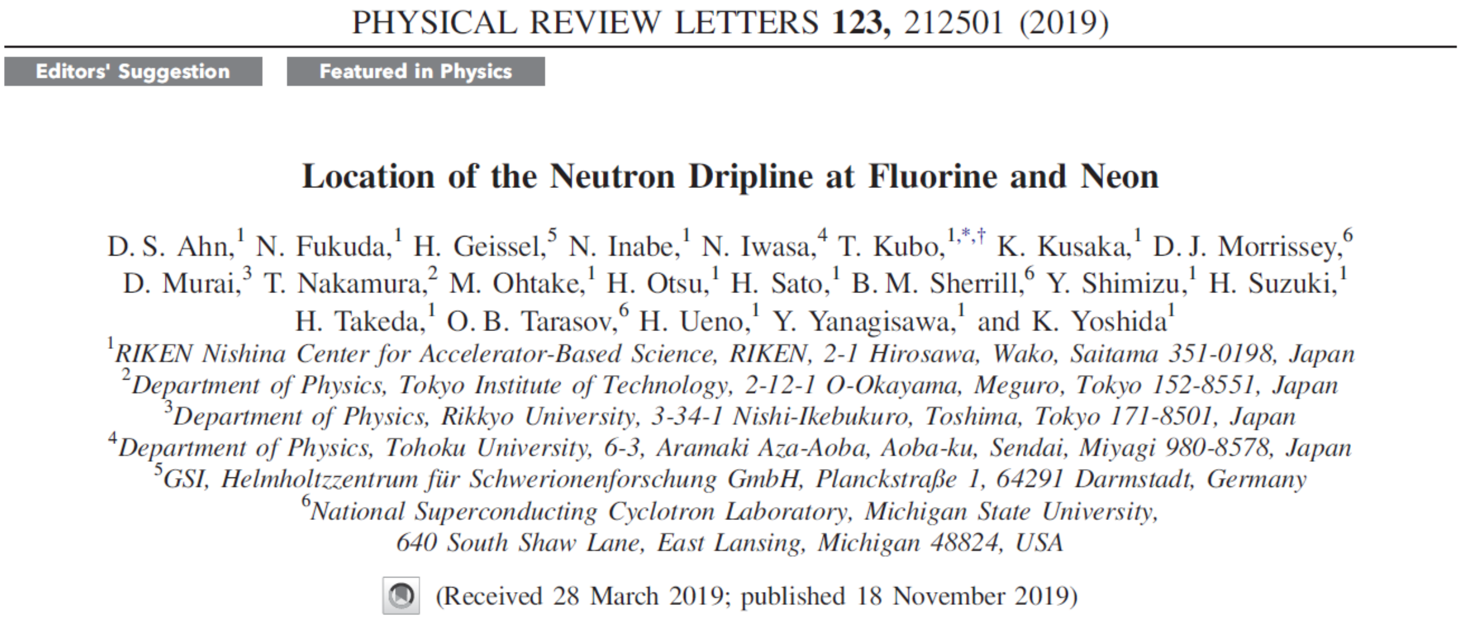
Layout of RIBF



BigRIPS separator

Invited talk presented on Feb 28 at the GSI NUSTAR annual meeting 2024, Feb 26 – March 1, 2024, GSI, Darmstadt, Germany

The present work was published in these two papers.



PHYSICAL REVIEW LETTERS **123,** 212501 (2019)

Editors' Suggestion

Featured in Physics

Location of the Neutron Dripline at Fluorine and Neon

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PHYSICAL REVIEW LETTERS **129,** 212502 (2022)

Editors' Suggestion

Featured in Physics

Discovery of ^{39}Na

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Outline of my talk

- Introduction
  - Overview of the BigRIPS separator and RI beam production at RIBF
- Determination of the neutron dripline for F and Ne * and discovery of ^{39}Na **
  - Introduction
  - Experimental method and setups
  - First experiment (determination of the neutron dripline)
  - Second experiment (discovery of ^{39}Na)
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- Summary and future perspective

Published in PRL:
* Phys. Rev. Lett. 123, 212501 (2019)
** Phys. Rev. Lett. 129, 212502 (2022)

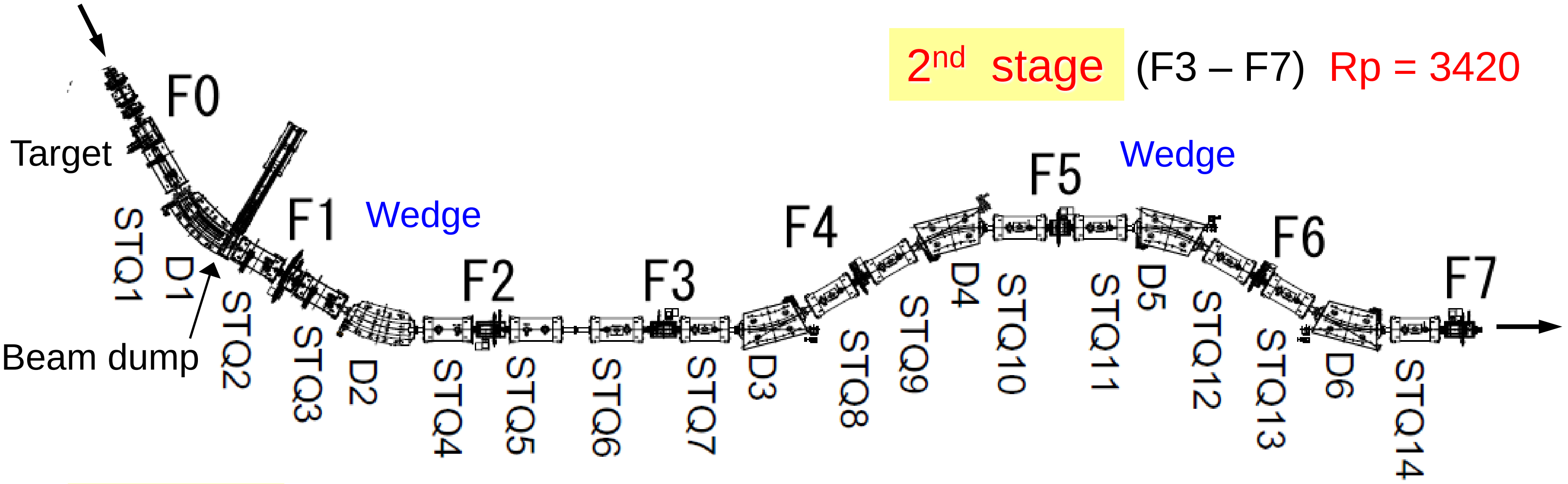
BigRIPS separator (since March 2007)

Two-stage separator characterized by:

- Large acceptances
  - → efficient RI beam production
- High momentum resolution at 2nd stage
  - → excellent particle identification (PID)

$\Delta\theta = 80$ mr
$\Delta\phi = 100$ mr
$\Delta p/p = 6$ %
$B\rho = 9$ Tm
L = 78.2 m

E = 345 MeV/u



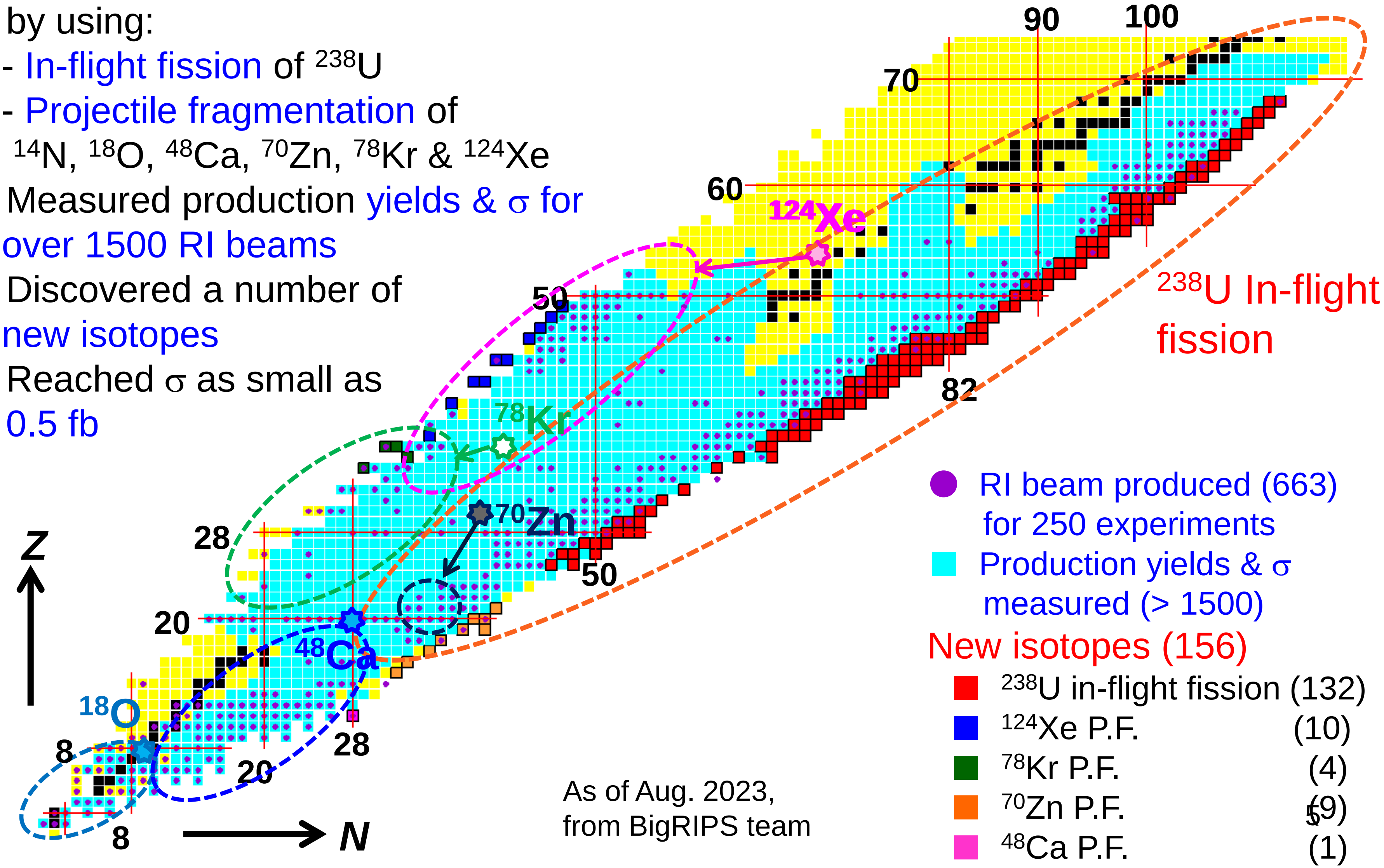
2nd stage (F3 – F7) Rp = 3420

1st stage (F0 – F2) Rp = 1270

STQ1-14: large-aperture superconducting quadrupole triplets D1-D6: dipoles F1-F7: focuses

RI beams produced at BigRIPS (May 2007 – Aug. 2023)

- We have produced a total of 663 RI beams and delivered to 250 experiments.
- by using:
  - In-flight fission of ^{238}U
  - Projectile fragmentation of ^{14}N, ^{18}O, ^{48}Ca, ^{70}Zn, ^{78}Kr & ^{124}Xe
- Measured production yields & σ for over 1500 RI beams
- Discovered a number of new isotopes
- Reached σ as small as 0.5 fb



● RI beam produced (663) for 250 experiments

■ Production yields & σ measured (> 1500)

New isotopes (156)

- 🟥 ^{238}U in-flight fission (132)
- 🟦 ^{124}Xe P.F. (10)
- 🟩 ^{78}Kr P.F. (4)
- 🟧 ^{70}Zn P.F. (9)
- 🟪 ^{48}Ca P.F. (1)

As of Aug. 2023,
from BigRIPS team

Primary beam intensities at RIKEN RIBF

Maximum beam intensities achieved so far

^{48}Ca: 737 pnA (12.2 kW)
^{70}Zn: 824 pnA (19.9 kW) → highest!
^{78}Kr: 691 pnA (18.6 kW)
^{124}Xe: 173 pnA (7.4 kW)
^{238}U: 117 pnA (9.6 kW)

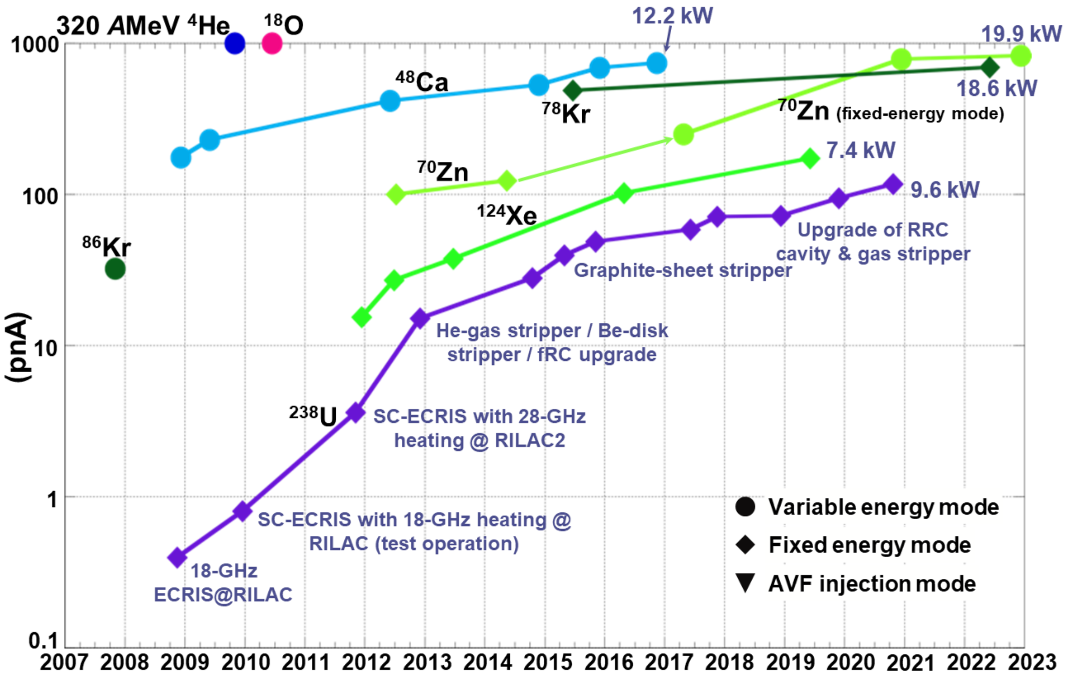
Reaching the goal intensity of 1000 pnA

E = 345 MeV/u

As of 2023

1 pnA (particle nA) = 6.24 x 10^{9} particles/s

History of beam intensities at RIBF



Beam energies of the beams without explicitly indicated are 345 AMeV.

Goal intensity 1000 pnA

From RIBF Accelerator Group (Courtesy of N. Fukunishi)

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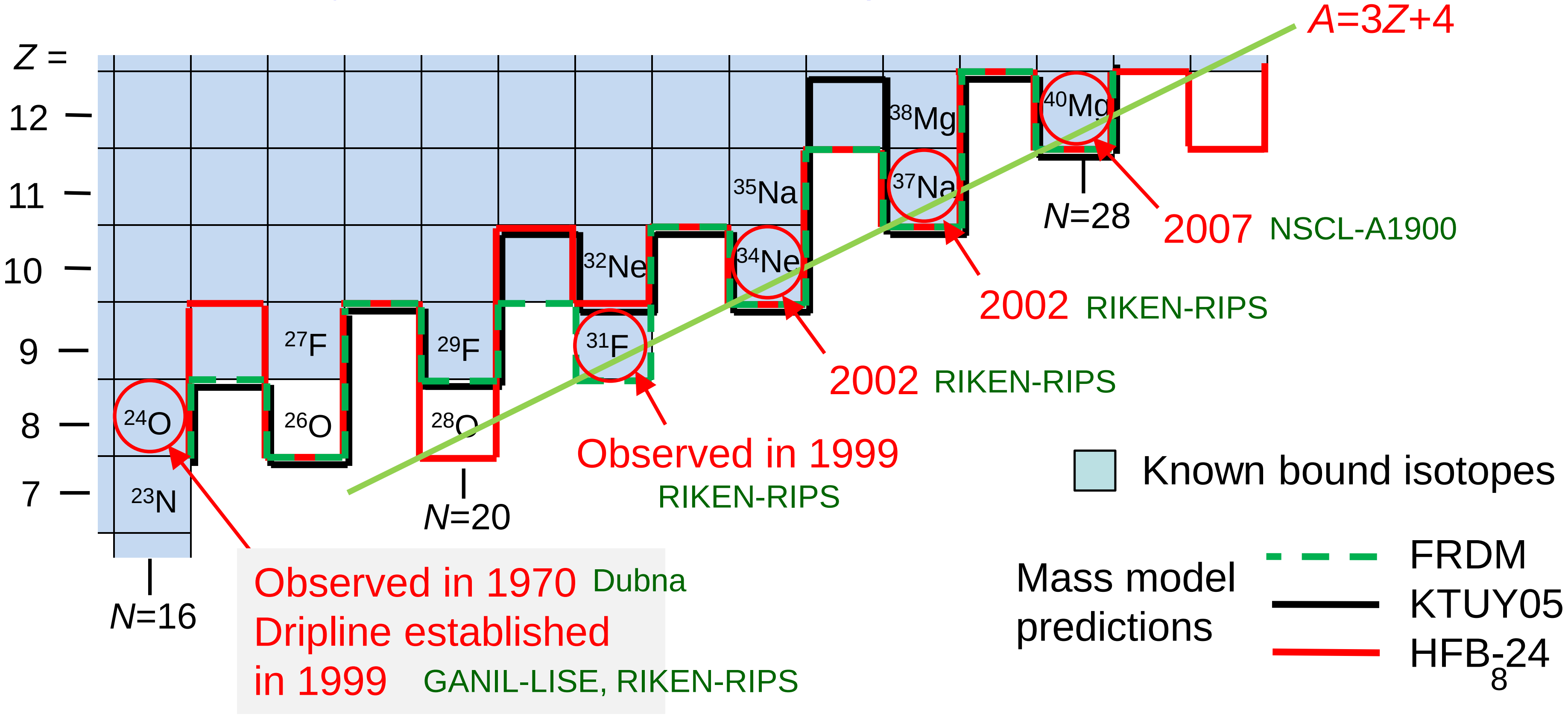
Situations of the neutron dripline before this work

- Known isotopes were up to ^{31}F, ^{34}Ne, ^{37}Na, and ^{40}Mg, all having $A = 3Z + 4$.
- Neutron dripline was determined only up to oxygen ($Z = 8$), which is ^{24}O established in 1999.
- New isotopes beyond the $A = 3Z + 4$ line were not searched last 20 years for F to Na and their dripline was not known.



Observed in 1970 Dubna
Dripline established in 1999 GANIL-LISE, RIKEN-RIPS

Observed in 1999 RIKEN-RIPS

2002 RIKEN-RIPS

2002 RIKEN-RIPS

2007 NSCL-A1900

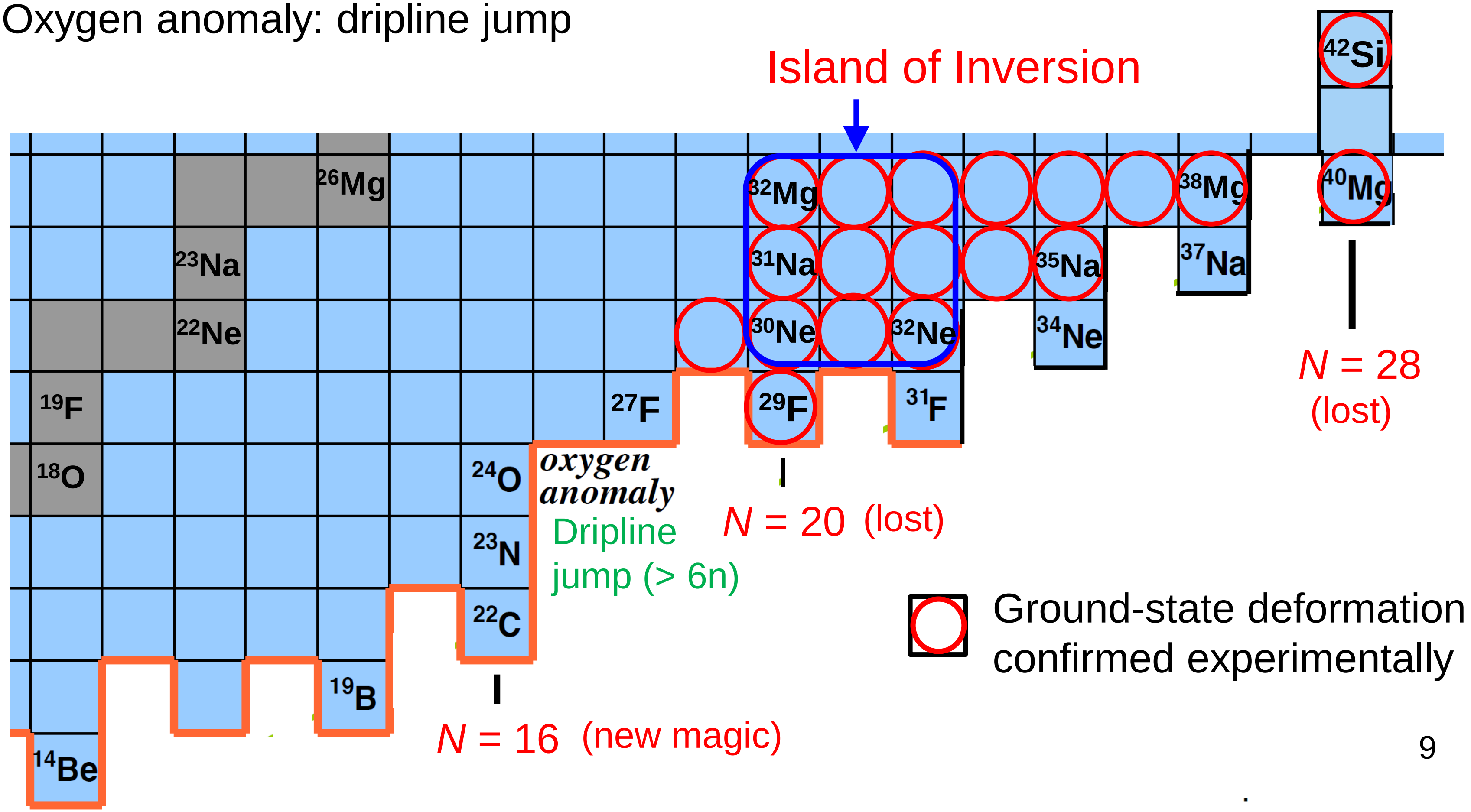
🟦 Known bound isotopes

Mass model predictions

- FRDM
- KTUY05
- HFB-24

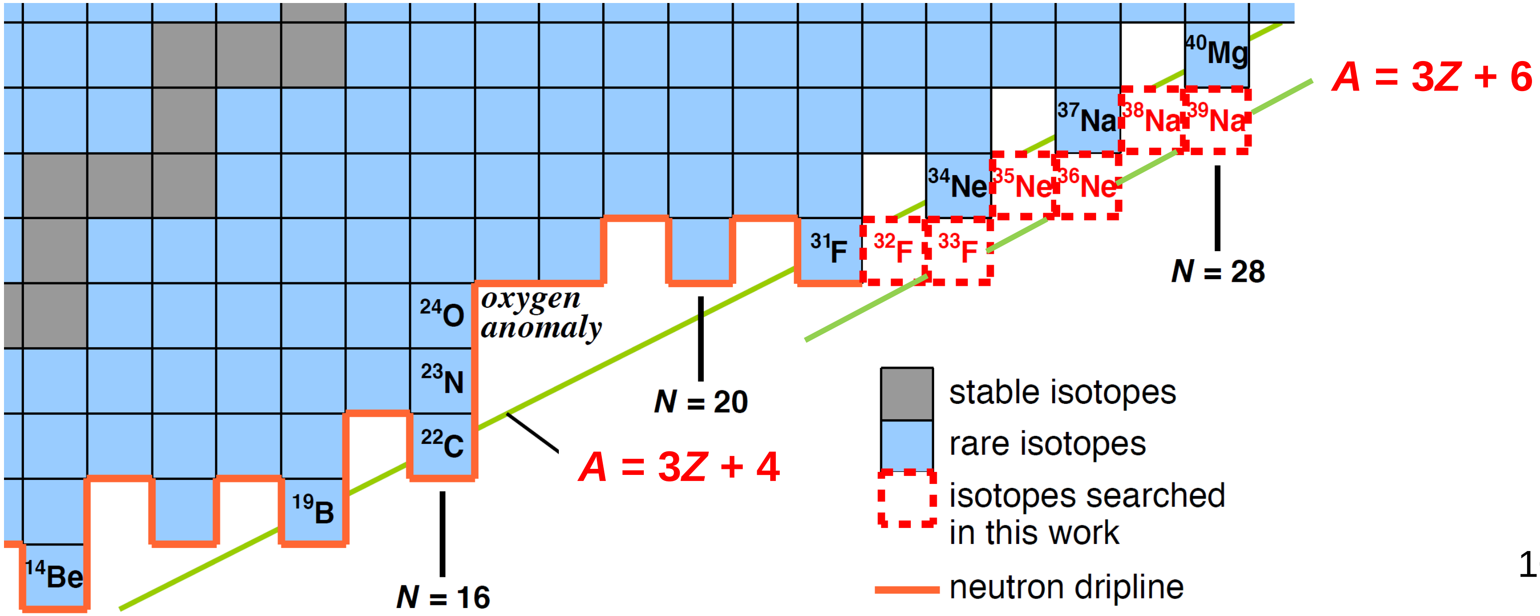
Known nuclear structure before this work

- Island of Inversion (Z = 10 – 12 and N = 20 – 22) is shown below.
- Red circles indicate isotopes whose deformation was experimentally confirmed.
- Magicity is lost at N = 20 and 28, causing the deformation of these isotopes.
- The nuclear structure of ^{31}F, ^{34}Ne, and ^{37}Na was not yet studied.
- New magic number N = 16
- Oxygen anomaly: dripline jump



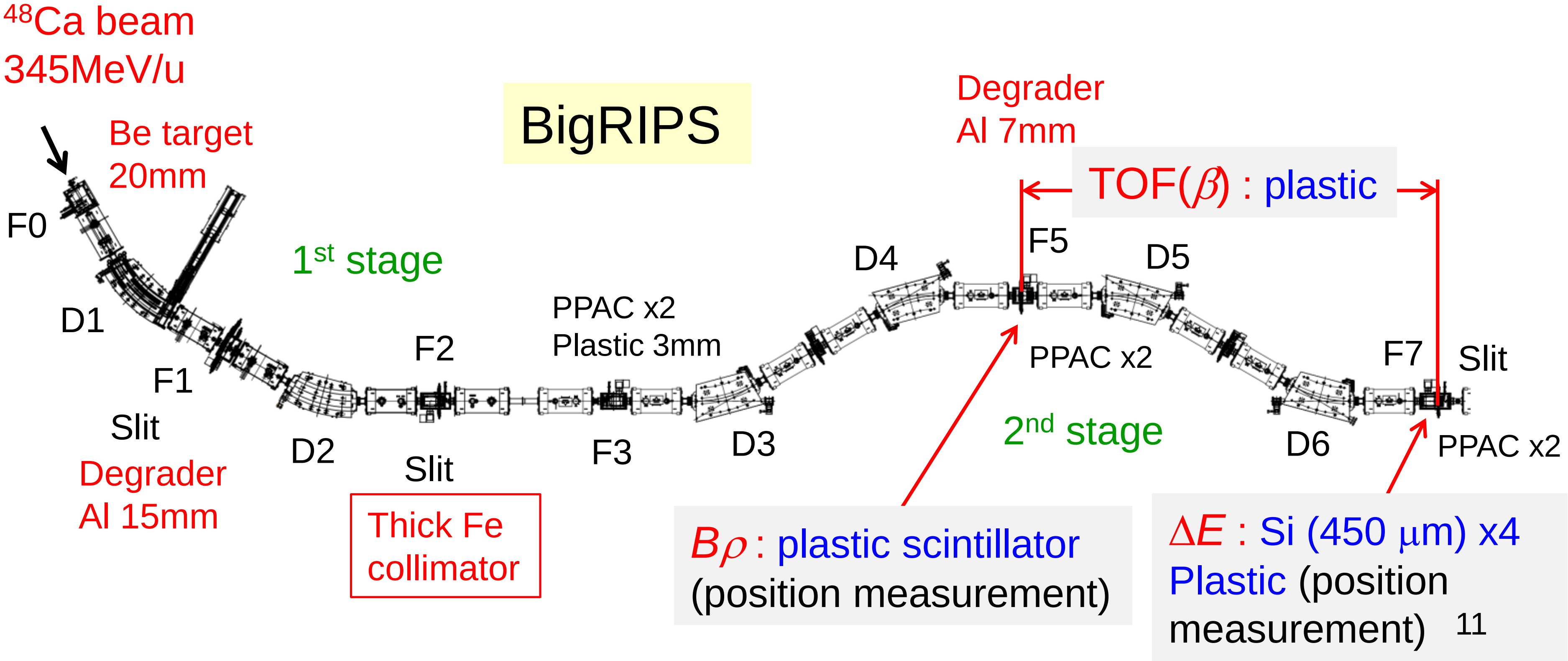
Outline of this work

- We conducted search for extremely neutron-rich new isotopes ^{32,33}F, ^{35,36}Ne and ^{38,39}Na that are located beyond the $A = 3Z + 4$ line as shown below.
- We performed the experiment twice.
- In the first experiment, we determined the neutron dripline of F and Ne to be ^{31}F and ^{34}Ne, respectively.
- In the second experiment, we discovered an extremely neutron-rich isotope ^{39}Na with $N = 28$ and established its particle stability.
- We discussed the underlying nuclear structure, such the magicity loss at N = 28 for Na and resulting nuclear deformation, and the role of deformation in determining the location of dripline.



Experimental setups at BigRIPS

- Isotopes were produced by projectile fragmentation of an intense ^{48}Ca beam at 345 MeV/u, and separated and identified in flight.
- PID relied on TOF, $B\rho$ and ΔE measurements through which Z and A/Z of fragments are deduced.
- Only the latter half of 2nd stage (F5 to F7) was used for PID, because we were concerned about high counting rates upstream.



^{48}Ca beam
345MeV/u

Be target
20mm

Degrader
Al 15mm

Thick Fe
collimator

Degrader
Al 7mm

TOF(β) : plastic

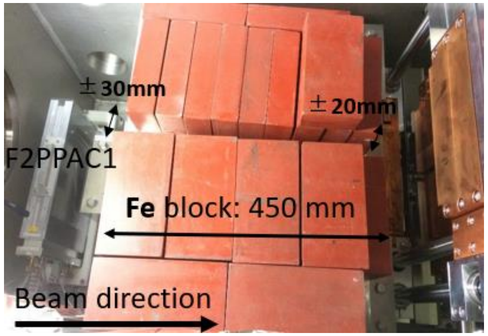
$B\rho$: plastic scintillator
(position measurement)

ΔE : Si (450 μm) x4
Plastic (position measurement)

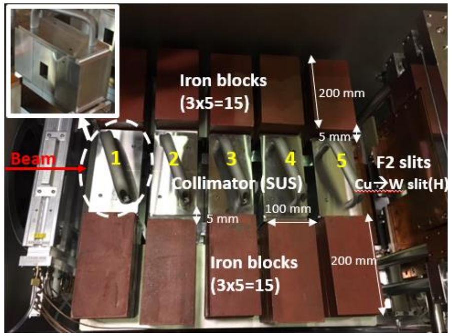
Background reduction and removal we made to achieve background free PID

- We reduced light charged particle backgrounds, such as tritons, using a thick Fe collimator placed at the end of 1st stage (F2).

1st exp.

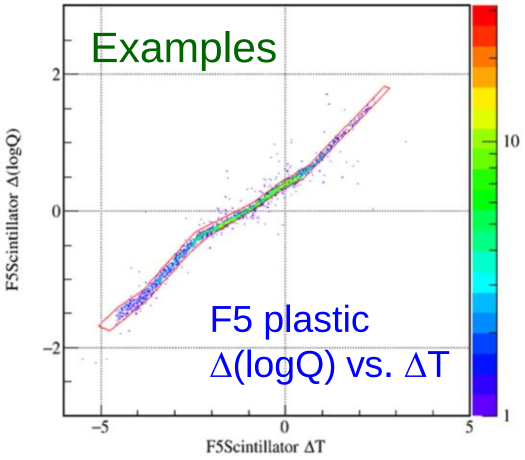


45 cm thick Fe collimator at F2

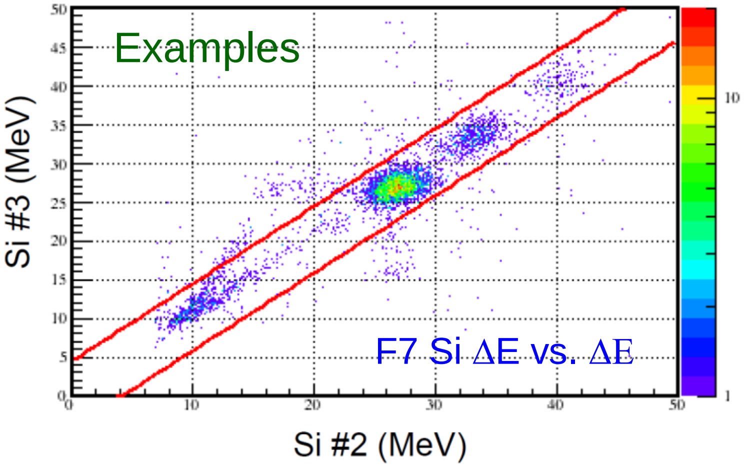


2nd exp. (more sophisticated)

- We thoroughly removed inconsistent events by checking various correlation plots of detector signals in data analysis


Examples

F5 plastic Δ(logQ) vs. ΔT


Examples

F7 Si ΔE vs. ΔE

BigRIPS settings in the first experiment

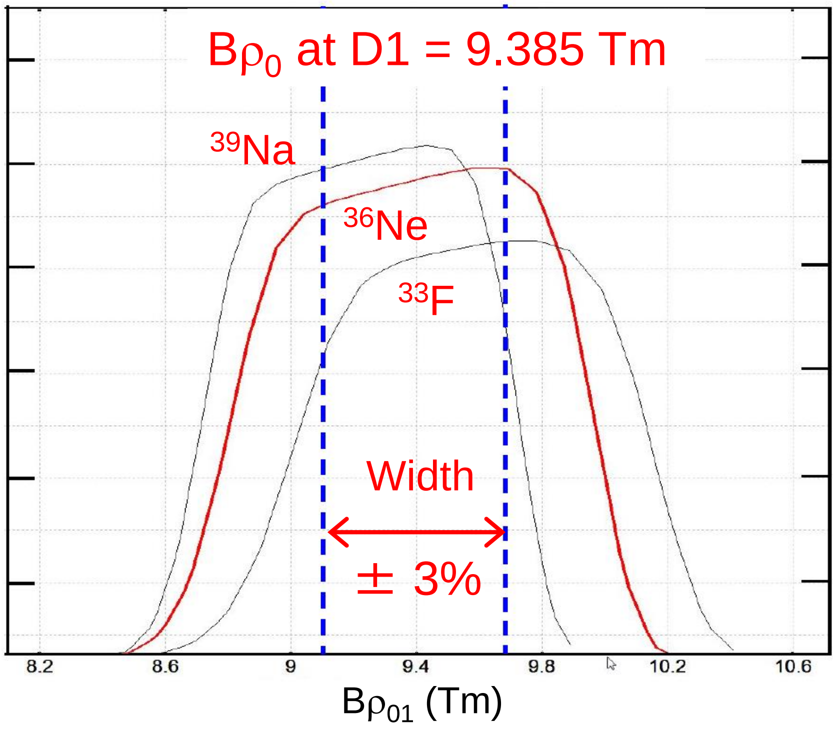
Settings	^{33}F	^{36}Ne+^{39}Na
Tuned for	^{33}F	Middle of ^{36}Ne & ^{39}Na
Beam	^{48}Ca 345 MeV/u	^{48}Ca 345 MeV/u
Target	Be 20 mm	Be 20 mm
Beam dump	±125 mm	±125 mm
$B\rho$ before F1	9.385 Tm	9.385 Tm
$B\rho$ after F1	8.804 Tm	8.721 Tm
F1 degrader	Al 15 mm 18.66 mr	Al 15 mm 18.66 mr
F5 degrader	Al 7 mm 5.969 mr	Al 7 mm 5.969 m
$\Delta p/p$	±3%	±3%
F2 slit	±15mm(H) ±10mm(V)	±15mm(H) ±10mm(V)
F7 slit	±20 mm	±20 mm

- We ran two settings.
- One is tuned for ^{33}F and the other one is tuned for the middle of ^{36}Ne and ^{39}Na.
- These two settings are the same except for the $B\rho$ settings after the first dispersive focus F1.

$B\rho$ setting at F1 and isotope separation at F2

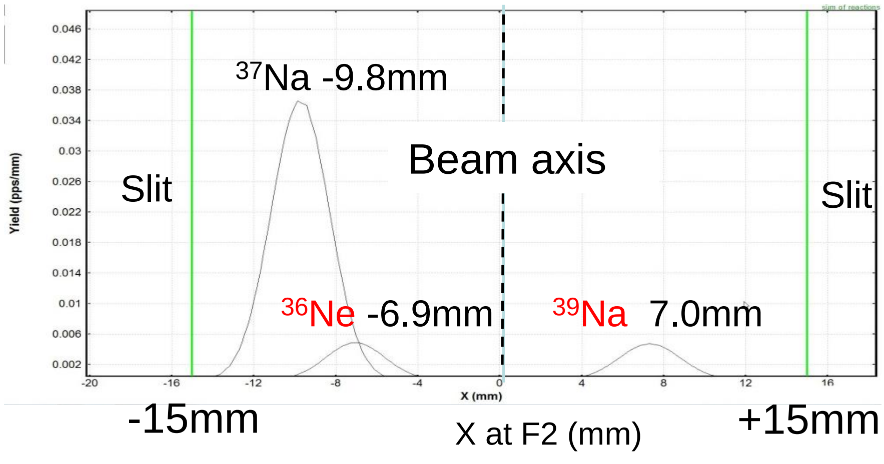
Simulated by LISE^{++} code

Momentum distribution and $B\rho$ setting at F1



Horizontal position spectrum at F2

^{36}Ne+^{39}Na setting

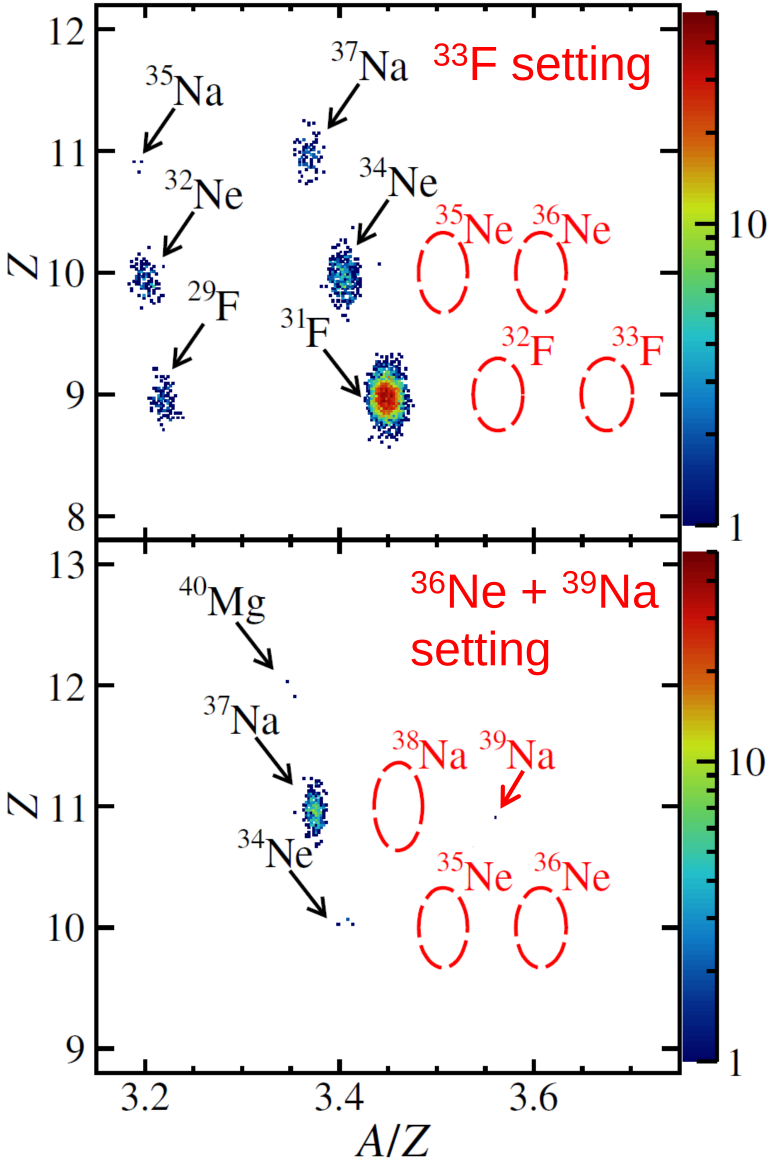


Good transmission for the targeted isotopes

From N. Inabe

Results of the first experiment: *Z* vs *A*/*Z* PID plot

Very clean background free PID was achieved !



- ^{48}Ca beam intensity was as high as ~450 pnA.

- ^{33}F setting: 1.4×10^{17} ions in 14 h

  No events for ^{32}F and ^{33}F!
  No events for ^{35}Ne and ^{36}Ne!

  c.f. ^{31}F: 3938 events
  ^{34}Ne: 115 events

- ^{36}Ne+^{39}Na setting: 7.8×10^{16} ions in 7.8h

  No events for ^{35}Ne and ^{36}Ne!
  No events for ^{38}Na!
  Amazingly 1 events for ^{39}Na!

  c.f. ^{34}Ne: 4 events
  ^{37}Na: 363 events

How we determined the neutron dripline from the non-observation of ^{32,33}F and ^{35,36}Ne

- For this purpose, we evaluated the confidence level (CL) for non-existence.
- The CL was calculated from the zero-event probability which was obtained using their expected yields and Poisson probability distribution as follows:

$$P(k|\lambda) = \lambda^k e^{-\lambda}/k! \xrightarrow[k=0]{} P(0|\lambda) = e^{-\lambda} \longrightarrow \mathrm{CL} = 1 - P(0|\lambda)$$

Poisson distribution
λ : expected yield
k : number of events

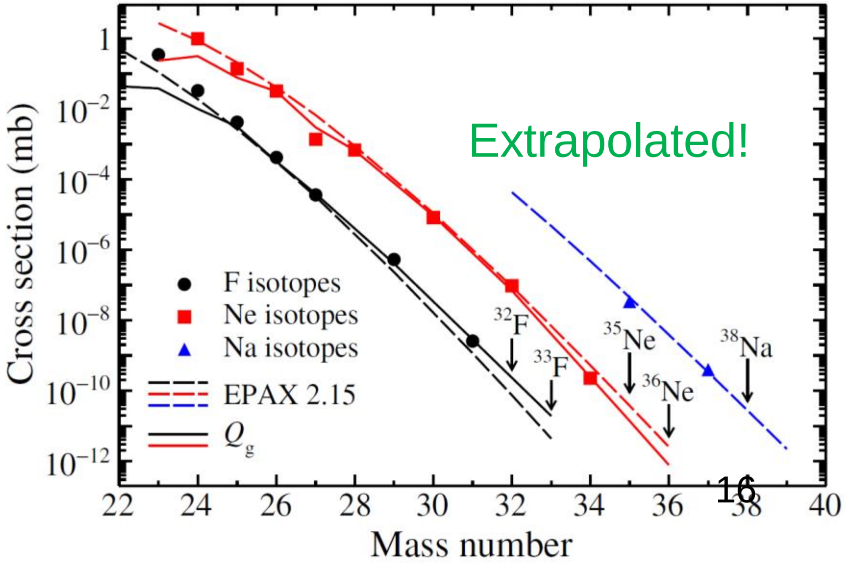
Event zero

Zero-event probability

Confidence level for non-existence

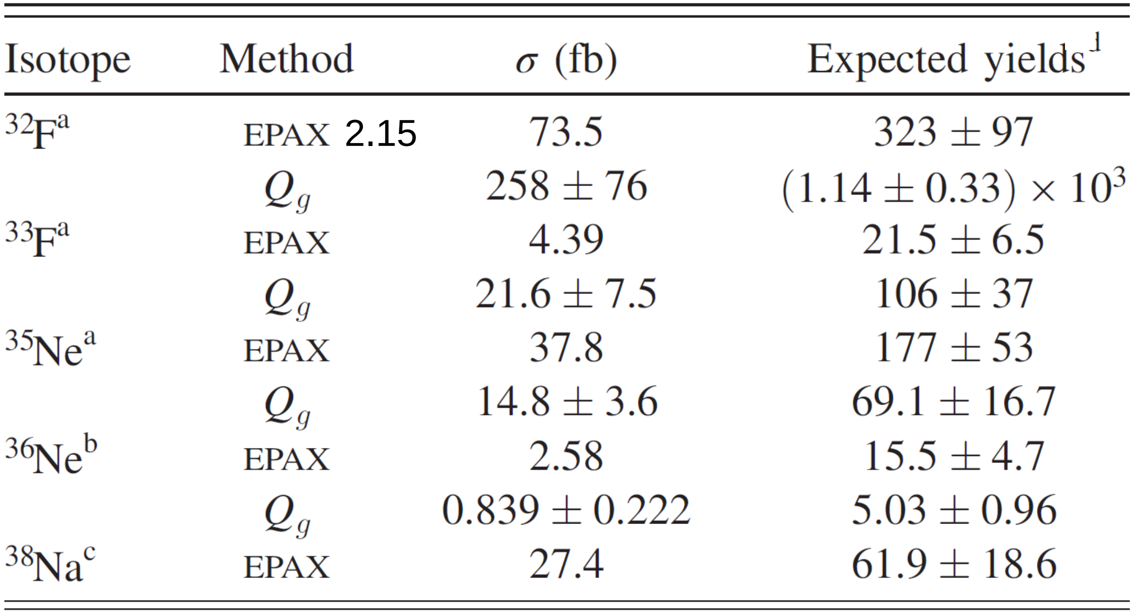
- The expected yields of non-observed isotopes were estimated by extrapolation of cross sections.
- For this purpose, we performed systematic cross section measurements and extrapolated the cross sections using the EPAX formula and the Qg systematics fit as shown in the figure.

Systematic cross section measurements along with predictions



Summary of the confidence level (CL) evaluation and conclusion of the first experiment

- The obtained CL values are quite high.
- We concluded that the unobserved isotopes ^{32,33}F, ^{35,36}Ne and ^{38}Na are unbound with high confidences.
- This allowed us to determine the neutron dripline of F and Ne to be ^{31}F and ^{34}Ne, respectively.



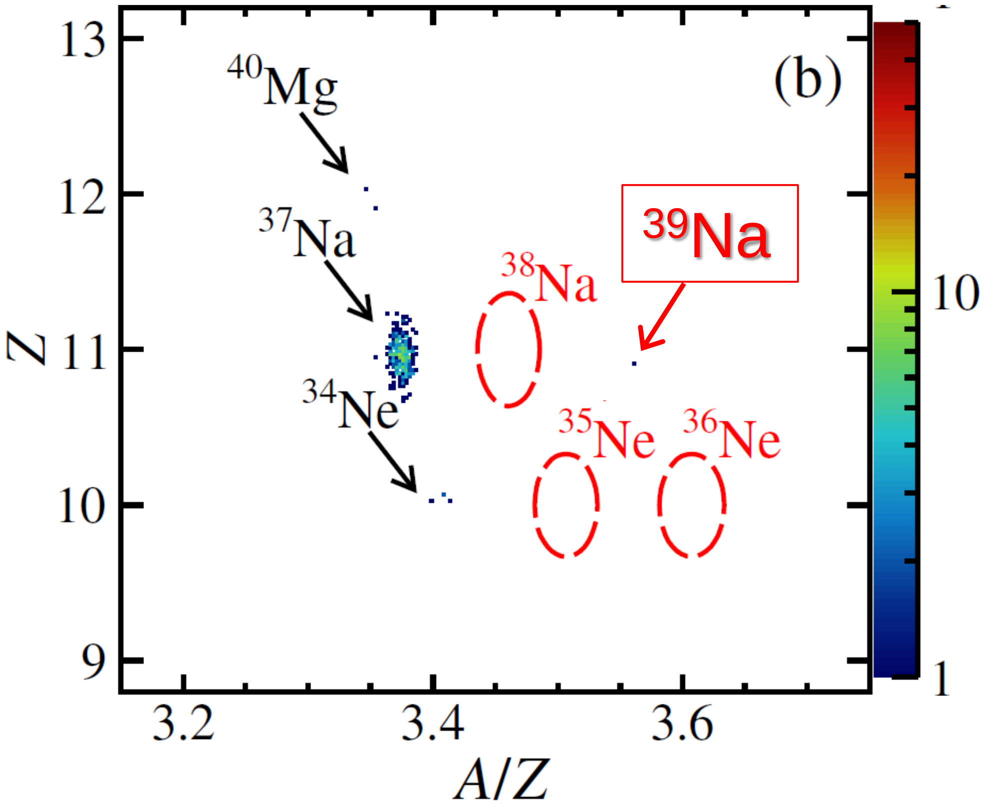
Isotope	Method	σ (fb)	Expected yields[d]	CL (=1-P)
^{32}F[a]	EPAX 2.15	73.5	323 ± 97	≈1
	Q_g	258 ± 76	$(1.14 \pm 0.33) \times 10^3$	≈1
^{33}F[a]	EPAX	4.39	21.5 ± 6.5	$1 - 3\text{x}10^{-10}$
	Q_g	21.6 ± 7.5	106 ± 37	≈1
^{35}Ne[a]	EPAX	37.8	177 ± 53	≈1
	Q_g	14.8 ± 3.6	69.1 ± 16.7	≈1
^{36}Ne[b]	EPAX	2.58	15.5 ± 4.7	$1 - 2\text{x}10^{-7}$
	Q_g	0.839 ± 0.222	5.03 ± 0.96	$99.3\ \%\ ^{+0.4\%}_{-1.0\%}$
^{38}Na[c]	EPAX	27.4	61.9 ± 18.6	≈1

→ Improved by 2nd experiment

a ^{33}F setting. b Total of the ^{33}F and ^{36}Ne+^{39}Na settings. c ^{36}Ne+^{39}Na setting.

1 event observed for ^{39}Na!

- We were very much excited about this one event for ^{39}Na, because the sodium dripline may extend to the further neutron-rich side.
- We decided to revisit the search for ^{39}Na in the second experiment!



Nishina center gave us more beam time later !

BigRIPS settings in the second experiment

Settings	^{39}Na	^{36}Ne
Tuned for	^{39}Na	^{36}Ne
Beam	^{48}Ca 345 MeV/u	^{48}Ca 345 MeV/u
Target	Be 20 mm	Be 20 mm
Beam dump	±125 mm	±125 mm
$B\rho$ before F1	9.155 Tm	9.408 Tm
$B\rho$ after F1	8.439 Tm	8.770 Tm
F1 degrader	Al 15 mm 18.66 mr	Al 15 mm 18.66 mr
F5 degrader	Al 7 mm 5.969 mr	Al 7 mm 5.969 mr
$\Delta p/p$	±3%	±3%
F2 slit	±8.3mm(H) ±20mm(V)	±8.3mm(H) ±20mm(V)
F7 slit	±20 mm	±20 mm

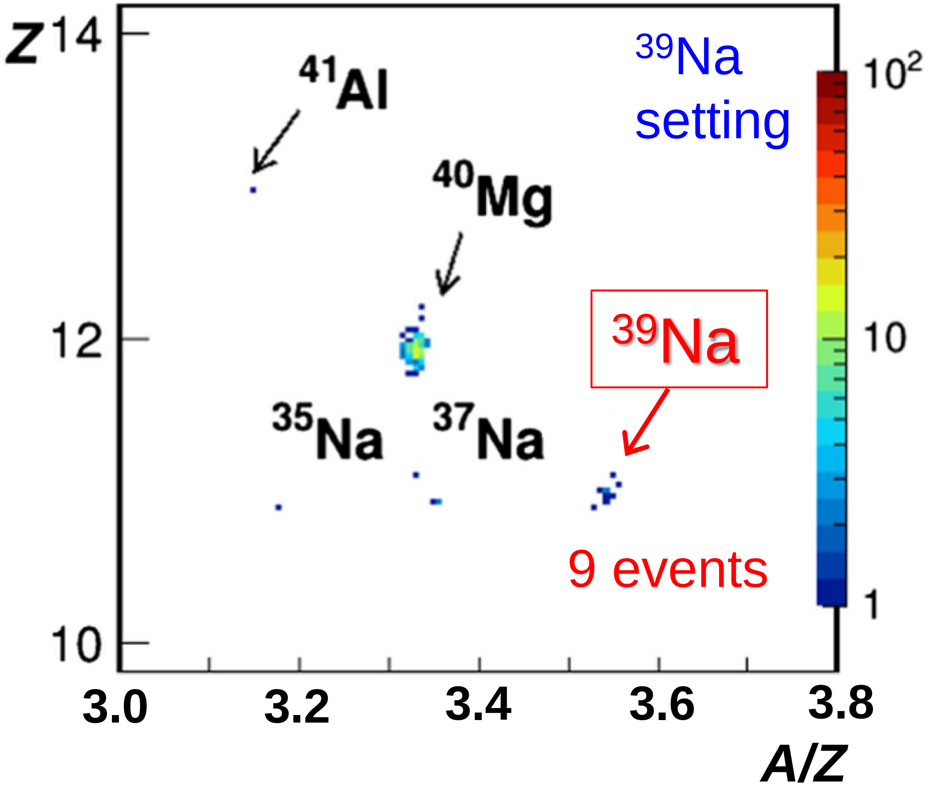
- We ran two settings, in which we revisited the search for ^{39}Na and the production of ^{36}Ne.
- $B\rho$ settings were fully optimized for the transmission of ^{39}Na and ^{36}Ne as a central particle in each setting.
- Otherwise the second experiment was essentially the same as the first experiment.

Results of the search for ^{39}Na in the 2nd experiment

We revisited the search with optimized $B\rho$ setting, longer running time and increased beam intensity.

Very clean background free PID again!

Z vs A/Z PID plot



- ^{48}Ca beam intensity was as high as ~540 pnA.
- ^{39}Na setting: 5.25×10^{17} ions in 46.1 h

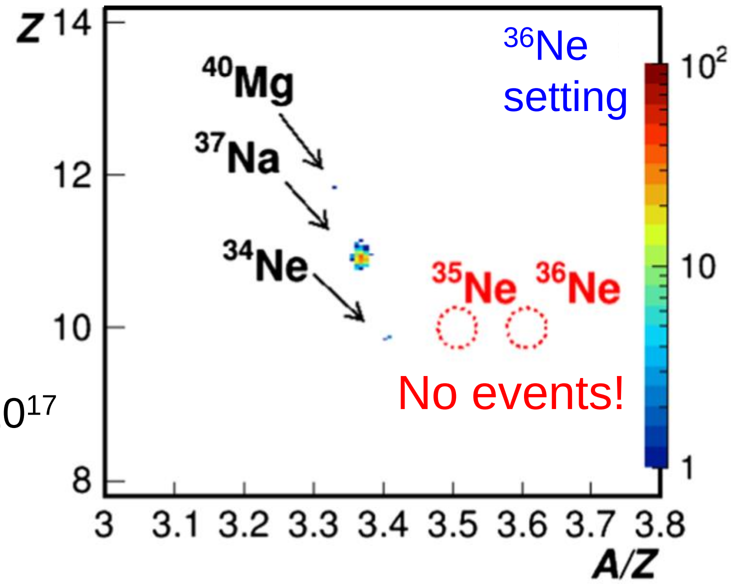
We clearly observed 9 events for ^{39}Na and established its particle stability!

Production σ as small as 0.5 fb !

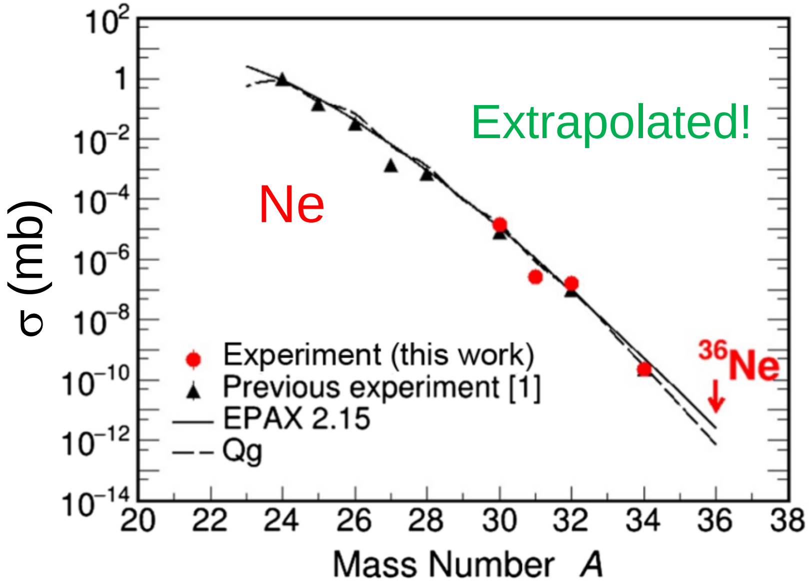
- It is amazing that the Na dripline extends further to the neutron-rich side!

Results of the production of ^{36}Ne in the 2nd experiment

We observed no events again. CL for the non-existence of ^{36}Ne was significantly improved. We obtained more confidence for the location of Ne neutron dripline: ^{34}Ne.



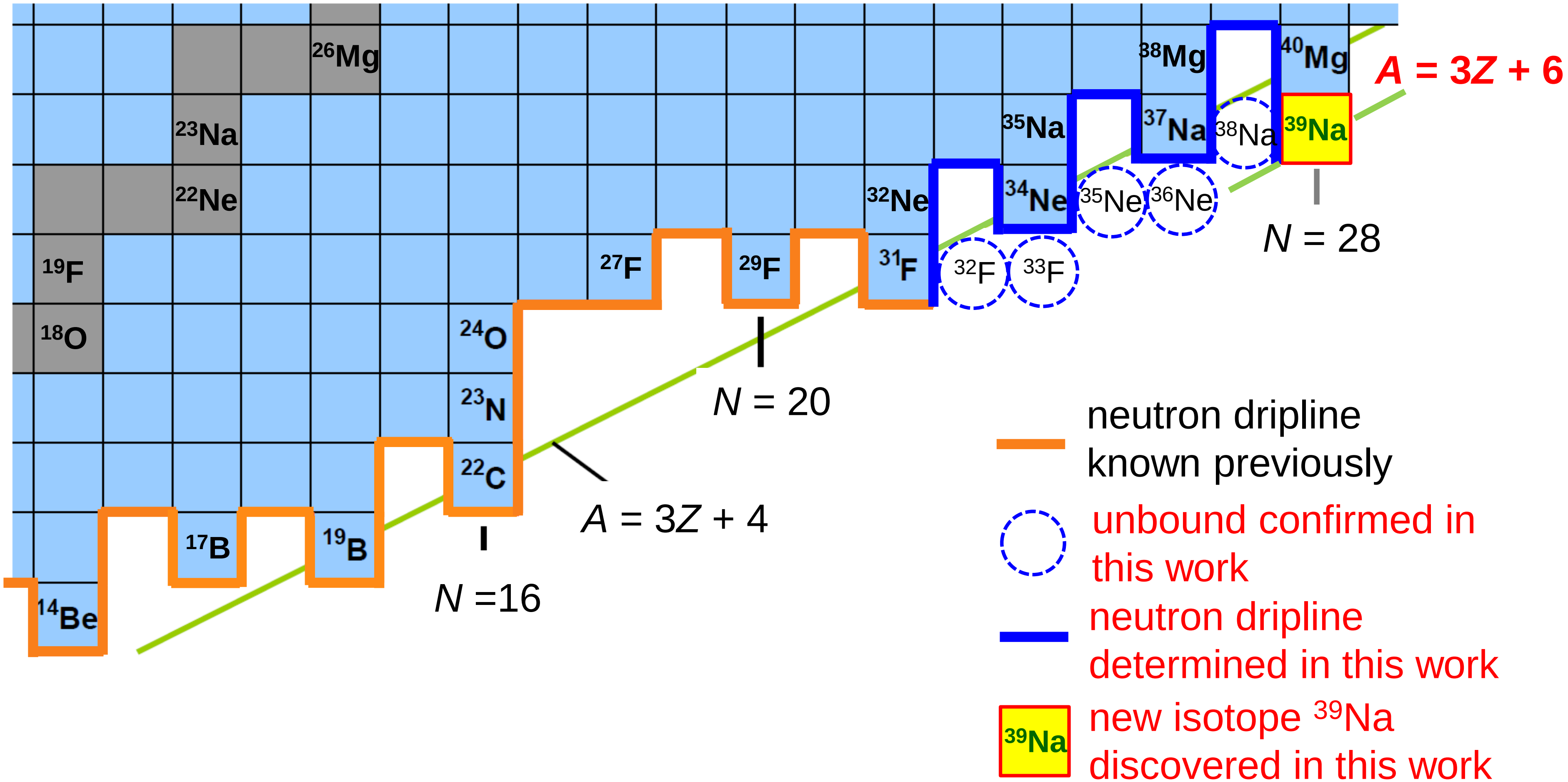
3.09x10^{17} ions in 25.3 h



Isotopes	Method	σ(fb)	Expected yields	CL (= 1–P)
^{36}Ne	EPAX 2.15	2.58	25.8	≈1
	Qg (2nd exp.)	0.74±0.24	7.39±2.40	$99.938\ \%^{+0.056\%}_{-0.619\%}$
	Qg (1st exp.)	0.84±0.22	5.03±0.96	$99.3\ \%^{+0.4\%}_{-1.0\%}$
	Qg total			$99.9996\ \%^{+0.0004\%}_{-0.005\%}$

←

Summary of the present experimental results



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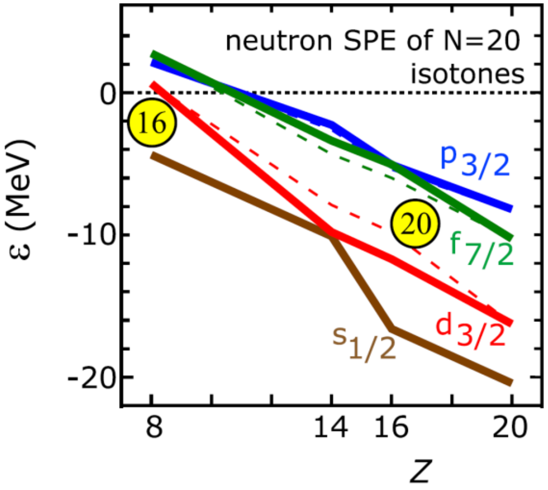
** Phys. Rev. Lett. 129, 212502 (2022)

Nuclear structure and nuclear binding far from stability

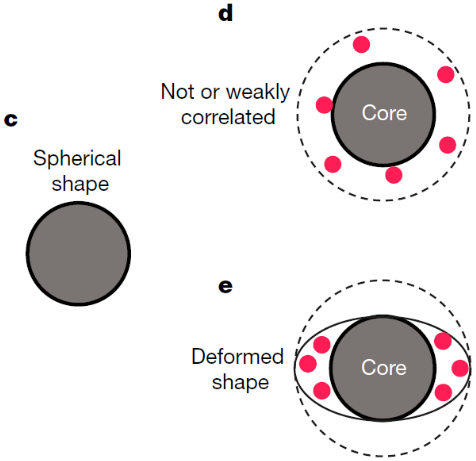
- Location of neutron dripline or nuclear binding near the limit of existence is determined reflecting details of underlying nuclear structure.
- So they could provide a key to understanding the structure at extremely neutron-rich conditions.
- In the region far from stability, nuclear force causes evolution of nuclear shell property, which results in loss of magic numbers (or emergence of new magic numbers), as shown in the right figure.

Shell evolution



From T. Otsuka, Phys. Scr. T152 (2013) 014007

- Magicity loss causes nuclear deformation. (Jahn-Teller effect)
- Nuclear deformation generates more binding energies, because valence nucleons are closely configured with strong correlations, as illustrated in this picture.



From Otsuka group’s Nature paper

N. Tsunoda, *et al.*, *Nature (London)* 587, 66 (2020)

Deformation induces more stability!

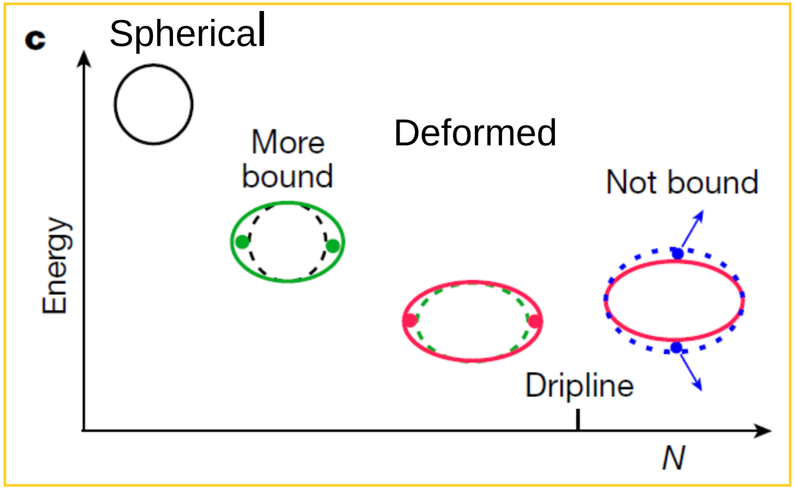
Implications of the present results on underlying nuclear structure

- First, nuclear deformation, which induces more binding, plays a key role in determining the location of neutron dripline in the present region.

Illustrates how deformation determines the dripline.

This role of deformation was predicted by the recent large-scale shell model calculation by Otsuka group.

N. Tsunoda, *et al.*, *Nature (London)* 587, 66 (2020)



Binding energy vs. *N* or deformation

From Otsuka group's Nature paper

- Second, the newly established particle stability of ^{39}Na suggests the occurrence of nuclear deformation. ^{39}Na could be bound because its ground state is deformed. This implies that the N = 28 magicity is lost for Na, like the case of ^{40}Mg.

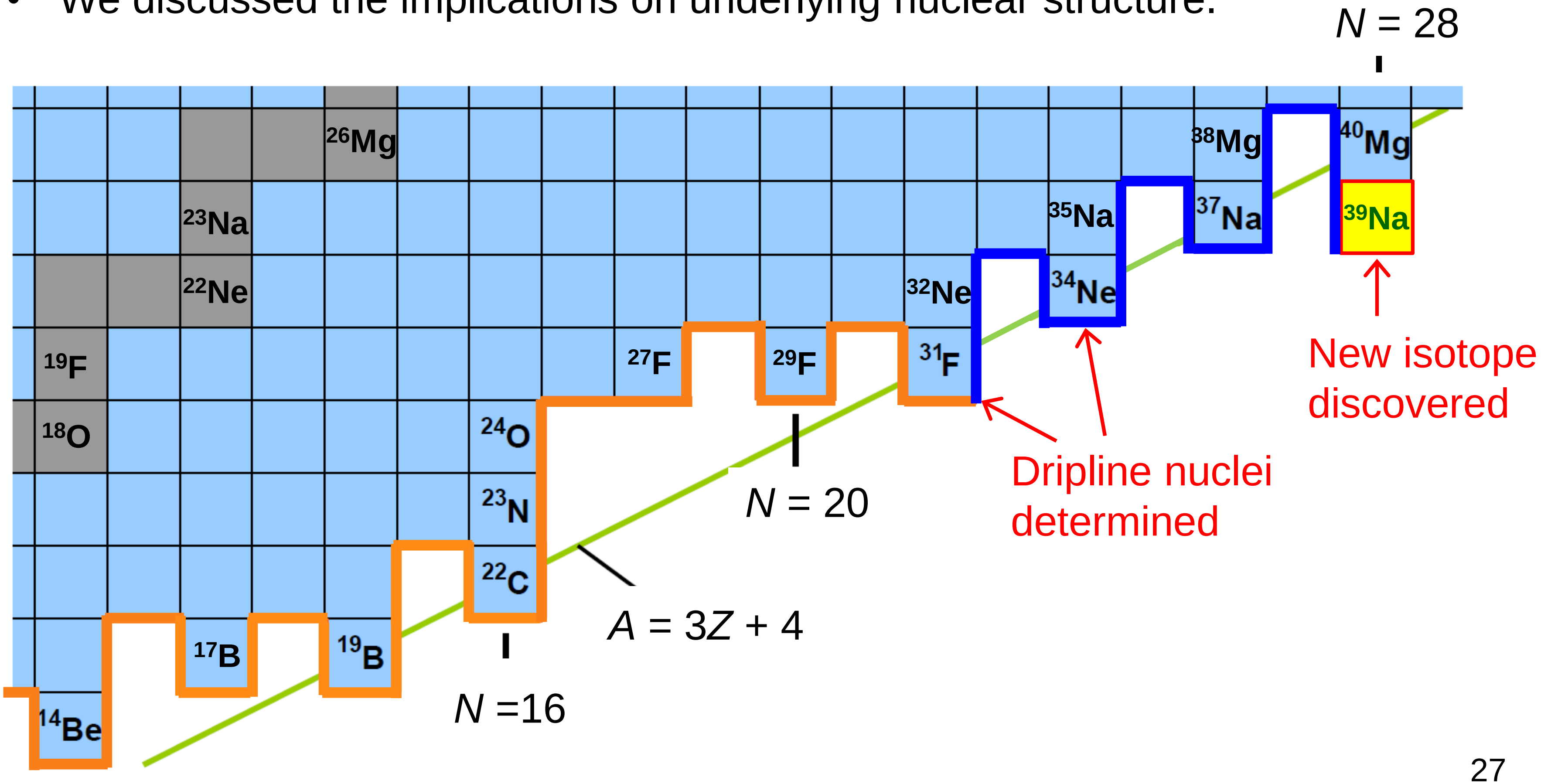
Outline of my talk

- Introduction
  Overview of the BigRIPS separator and RI beam production at RIBF
- Determination of the neutron dripline for F and Ne * and discovery of ^{39}Na **
  Introduction
  Experimental method and setups
  First experiment (determination of the neutron dripline)
  Second experiment (discovery of ^{39}Na)
  Discussion on underlying nuclear structure
- Summary and future perspective

Published in PRL:
* Phys. Rev. Lett. 123, 212501 (2019)
** Phys. Rev. Lett. 129, 212502 (2022)

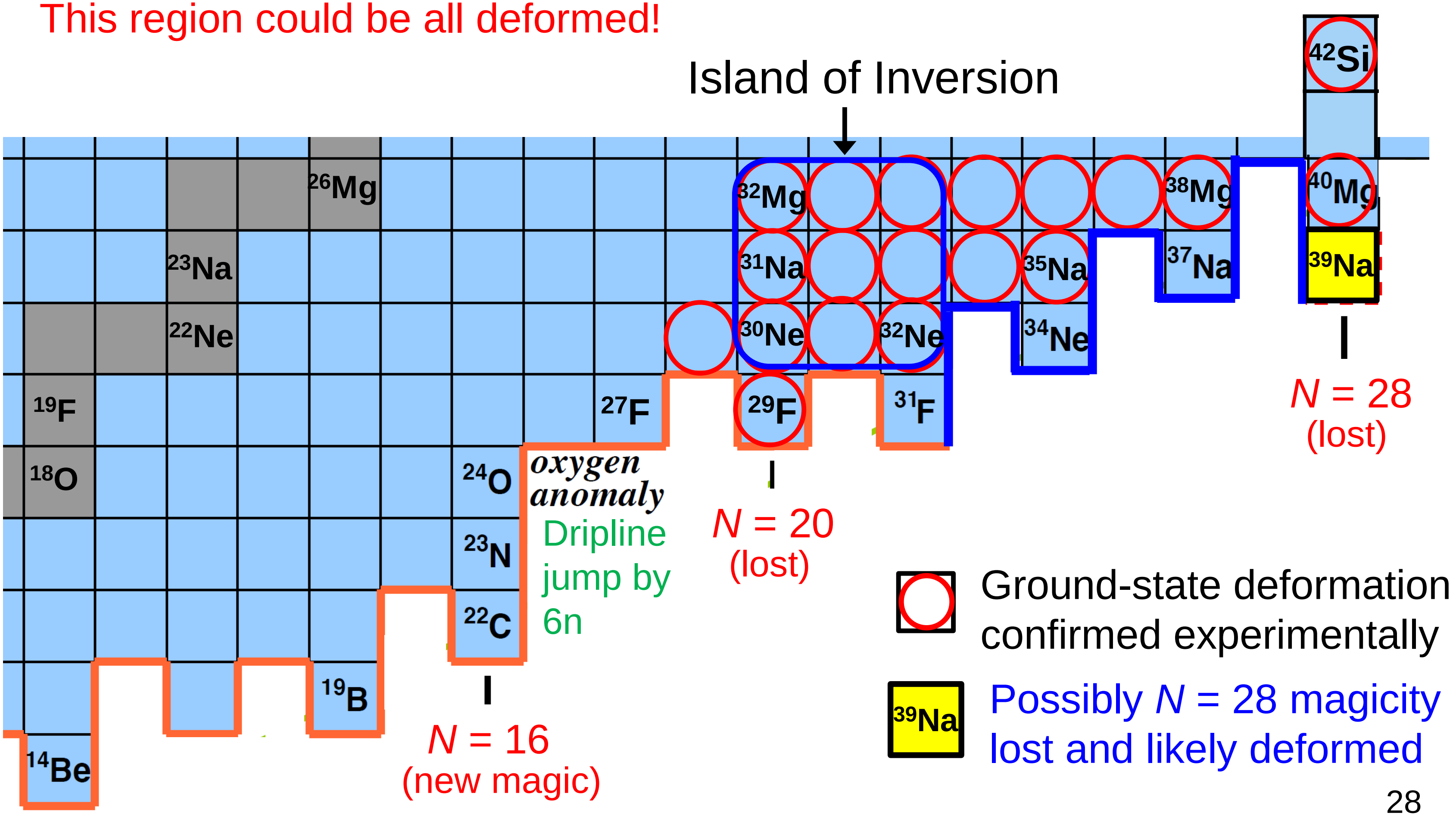
Summary

- We reported the determination of the neutron dripline for F and Ne and the discovery of ^{39}Na as summarized below.
- The location of the neutron dripline was extended up to Z = 10 for the first time in nearly 20 years. So was the existence limit of neutron-rich Na isotopes.
- We discussed the implications on underlying nuclear structure.



Summary of nuclear structure in the present region

- Magicity loss at *N* = 20 and 28 causes the deformation in this region.
- The deformation plays a key role in determining the neutron dripline.
- ^{39}Na could be bound because its ground state is deformed.
- Possibly *N* = 28 magicity is also lost for Na and ^{39}Na is likely deformed.
- This region could be all deformed!

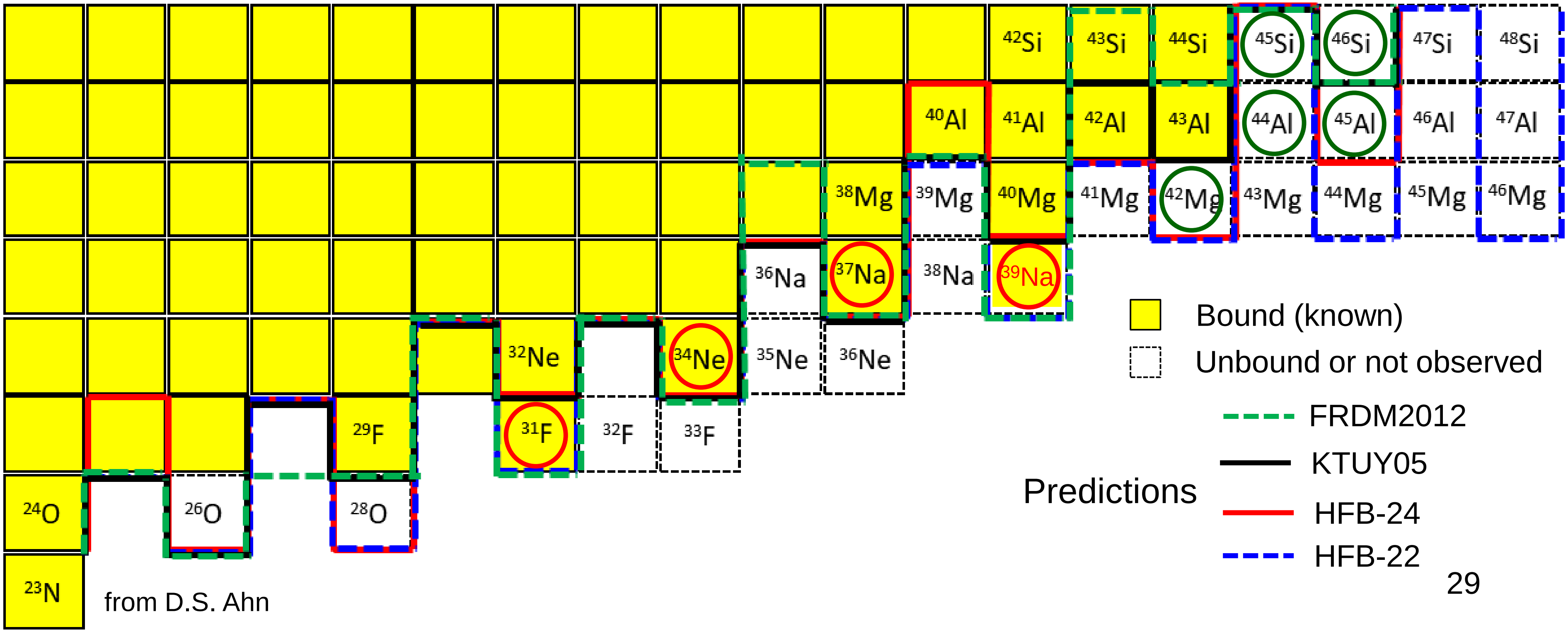


Future perspective

What to do next may include:

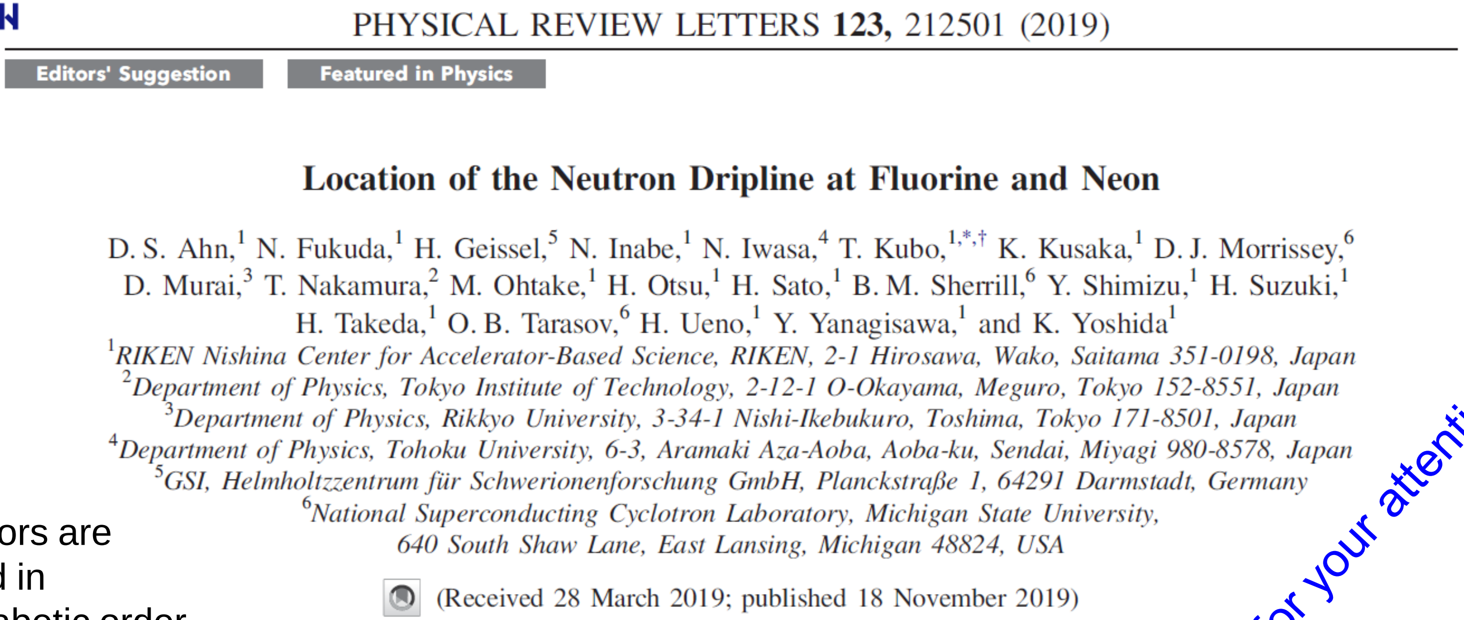
- Experimental studies on the nuclear structure of ^{31}F, ^{34}Ne, ^{37}Na and ^{39}Na.
- Search for new isotopes for the next elements above Na (such as ^{42}Mg, ^{45}Al, and ^{46}Si).
- Determination of the neutron dripline at Na (search for ^{41}Na).

These will be important challenges for new-generation facilities including GSI FAIR!



from D.S. Ahn

List of collaborators



PHYSICAL REVIEW LETTERS **123,** 212501 (2019)

Editors' Suggestion **Featured in Physics**

Location of the Neutron Dripline at Fluorine and Neon

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(Received 28 March 2019; published 18 November 2019)

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listed in
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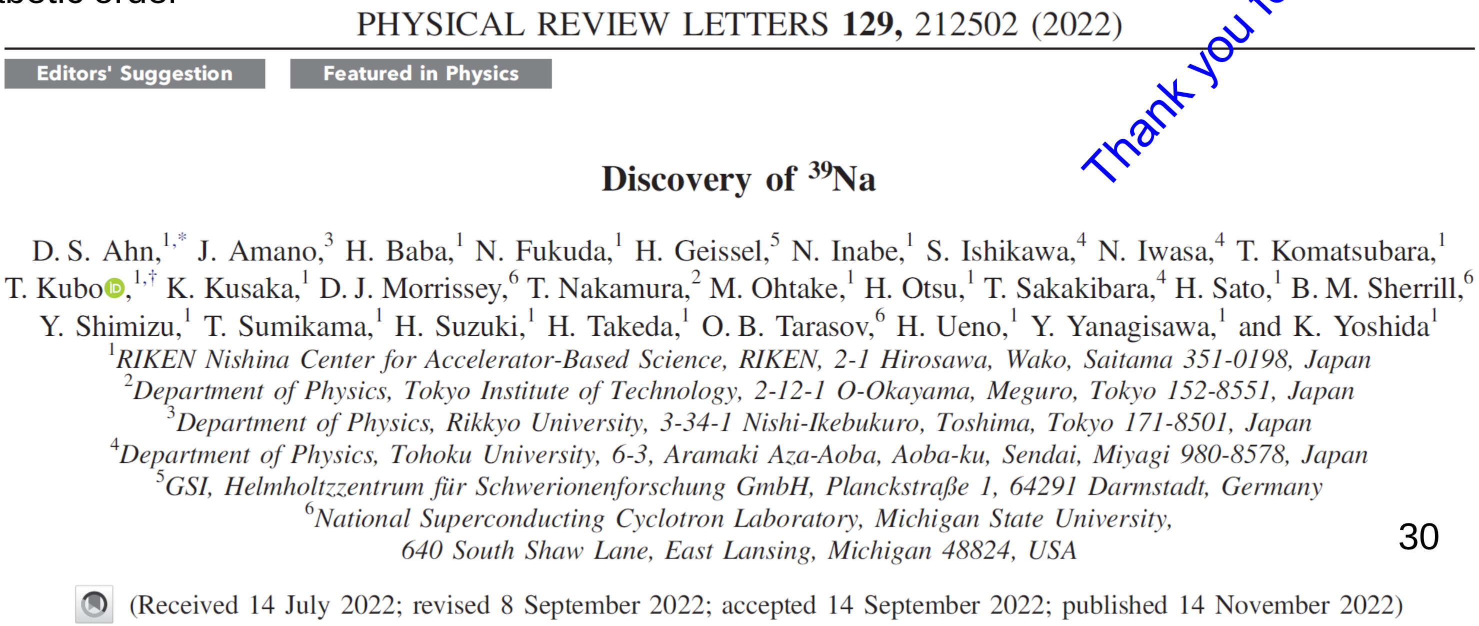

PHYSICAL REVIEW LETTERS **129,** 212502 (2022)

Editors' Suggestion **Featured in Physics**

Discovery of ^{39}Na

D. S. Ahn,[1,*] J. Amano,[3] H. Baba,[1] N. Fukuda,[1] H. Geissel,[5] N. Inabe,[1] S. Ishikawa,[4] N. Iwasa,[4] T. Komatsubara,[1] T. Kubo,[1,†] K. Kusaka,[1] D. J. Morrissey,[6] T. Nakamura,[2] M. Ohtake,[1] H. Otsu,[1] T. Sakakibara,[4] H. Sato,[1] B. M. Sherrill,[6] Y. Shimizu,[1] T. Sumikama,[1] H. Suzuki,[1] H. Takeda,[1] O. B. Tarasov,[6] H. Ueno,[1] Y. Yanagisawa,[1] and K. Yoshida[1]

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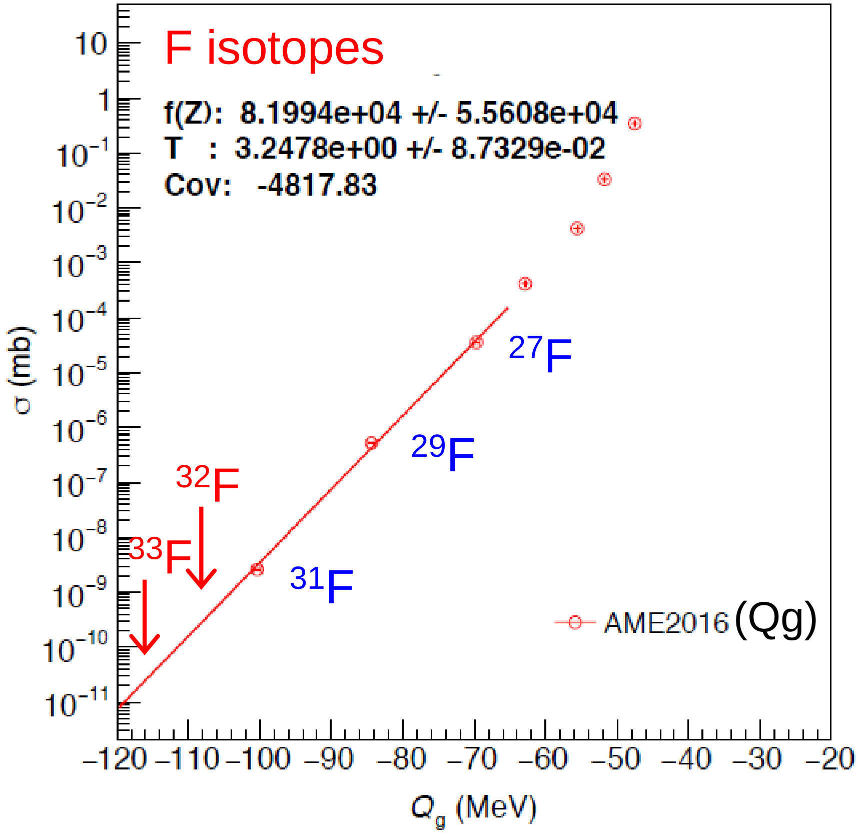
Thank you for your attention !

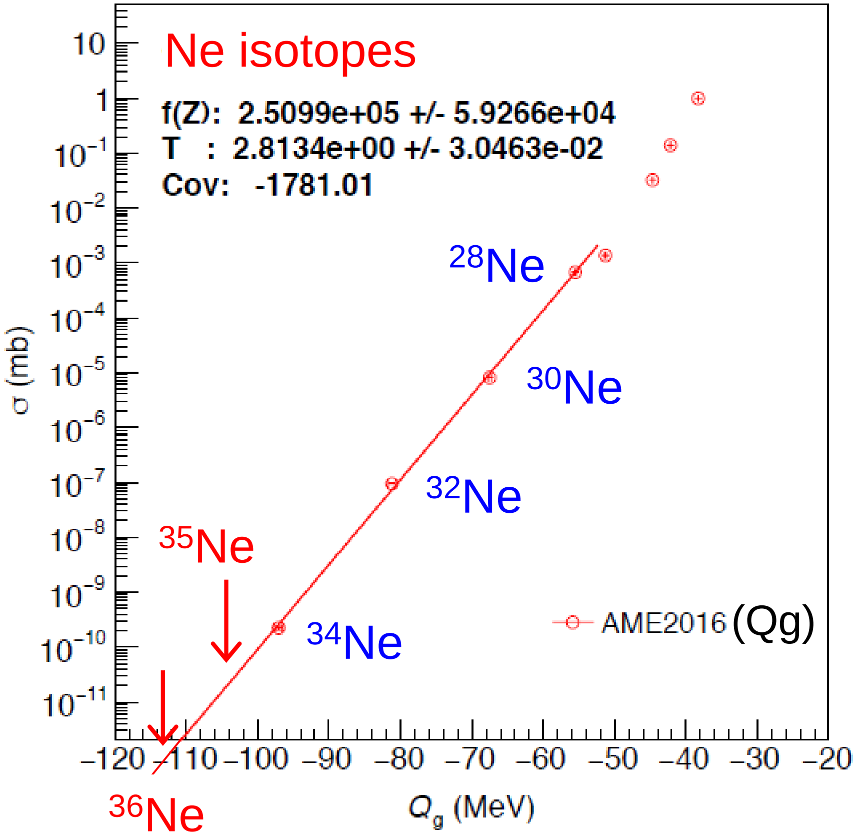
Q_g systematics fit and extrapolation of cross sections

$\sigma(Z,A) = f(Z)\exp(Q_g/T)$, $Q_g = \Delta Mp - \Delta Mf$, T : temperature parameter

Good for the region far from stability. See O. Tarasov et al., PRL102, 2009.



Assume $S_{1n}=0$, $S_{2n}=0$ for ^{32}F and ^{33}F.

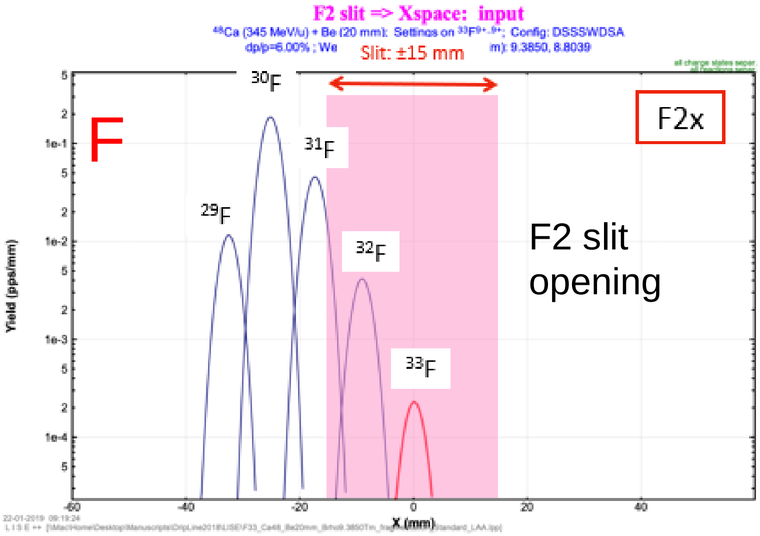


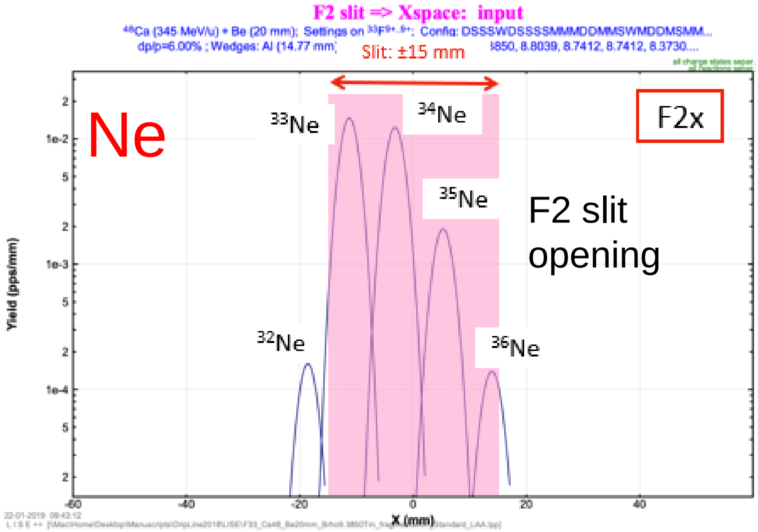
Assume $S_{1n}=0$, $S_{2n}=0$ for ^{35}Ne and ^{36}Ne.

Some details of horizontal position spectrum at F2

All the targeted isotopes (^{32,33}F, ^{35,36}Ne and ^{38,39}Na) are inside the slit opening.

^{33}F setting



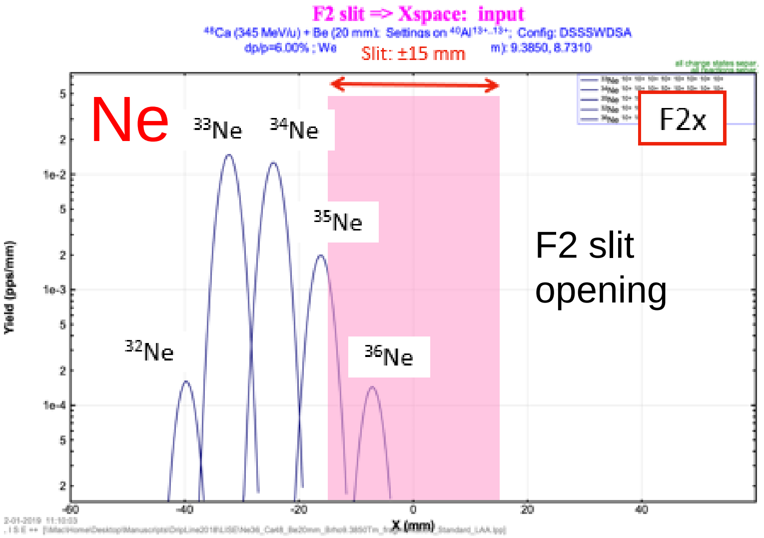


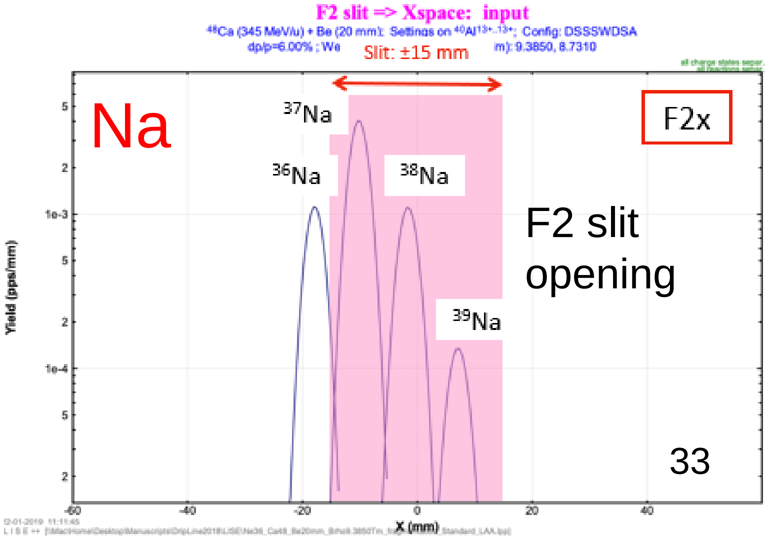
LISE^{++} simulation

F2 slit: ±15mm

From D.S. Ahn

^{36}Ne+^{39}Na setting



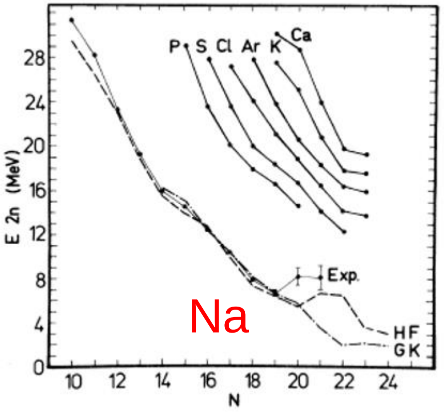


Experiments to study structure of exotic nuclei in this region

- Mass (S_{2n}): specific behaviors for magic or deformed.
- Interaction cross sections (σ_I): enhanced if deformation or halo exists.
- In-beam γ ray spectroscopy using secondary reactions: being deformed or spherical is reflected by excitation energies of 2+, 4+ states for even-even nuclei (similarly for odd nuclei).
- Cross section and momentum distribution in nucleon removal reactions: reflects existence of a deformed halo structure
- Invariant mass spectroscopy:

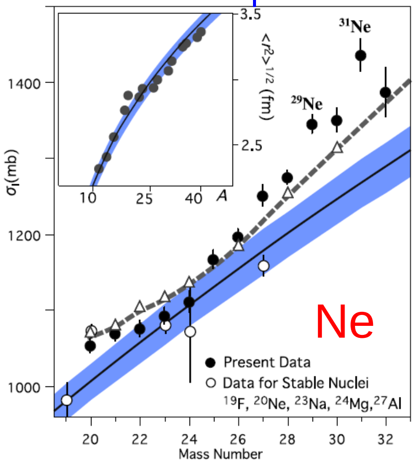
Examples

S_{2n}



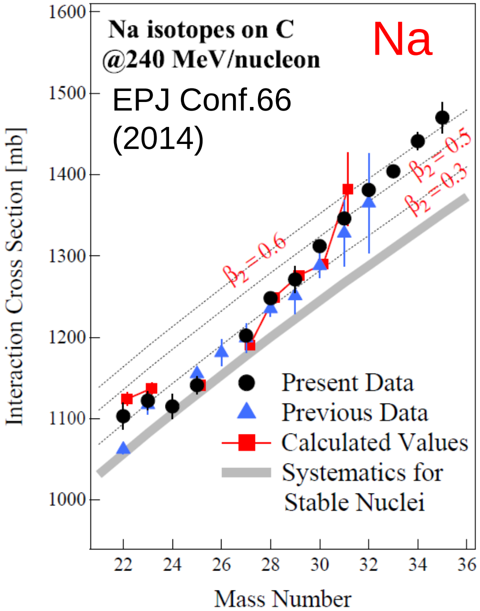
PRC 12, 644(1975)

σ_I



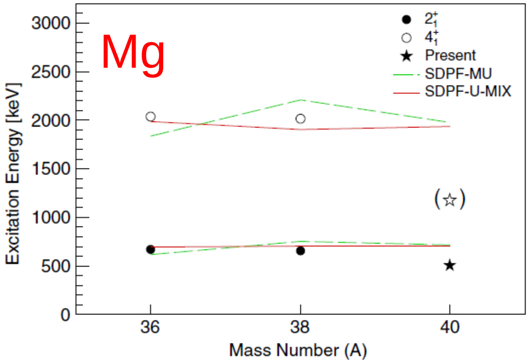
PLB 707, 357 (2012)

σ_I



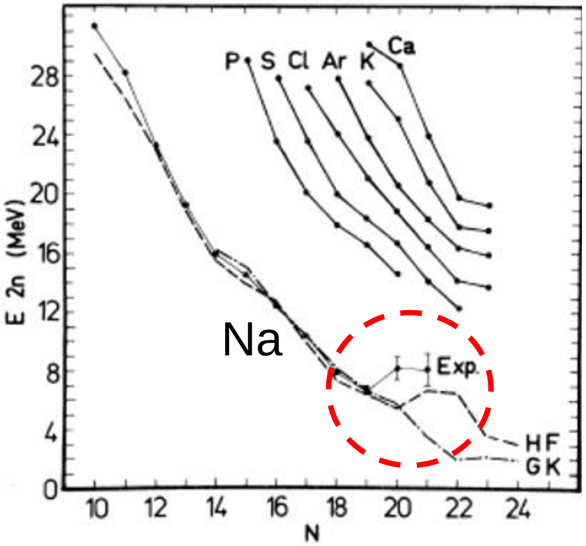
EPJ Conf.66 (2014)

Ex of 2^+, 4^+

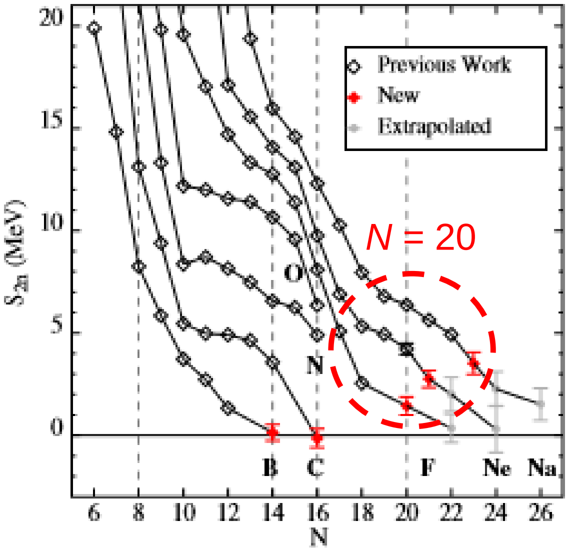


PRL 122, 052501 (2019)

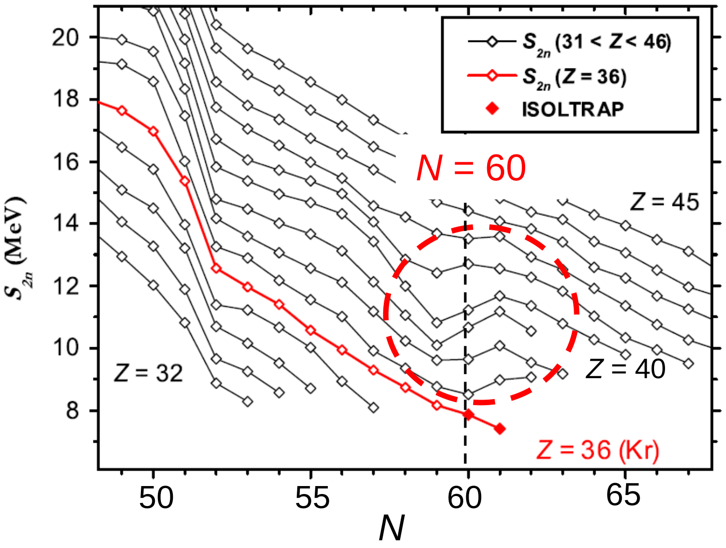
Trend plots of 2n-separation energy that exhibit humps caused by g.s. deformation



C. Thibault et al.,
PRC 12, 644 (1975)



L. Gaudefroy et al., PRL
109, 202503 (2012)



S. Naimi et al., PRL
105, 032502 (2010)