Location of the Neutron Dripline at Fluorine and Neon

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Outline

- Introduction
  - Status of neutron dripline
  - Nuclear structures
  - Predictions of neutron dripline with mass models
- F/Ne dripline experiment (2014 experiment)
  : A search for $^{32,33}F$, $^{35,36}Ne$, $^{38,39}Na$ using a ^{48}Ca beam
- ^{39}Na experiment (2017 follow-up experiment)
- Summary & Future prospect

Introduction

- Status of neutron dripline
- Nuclear structures
- Predictions of neutron dripline with mass models

Where is neutron dripline?

- challenging for limit of nuclear landscape

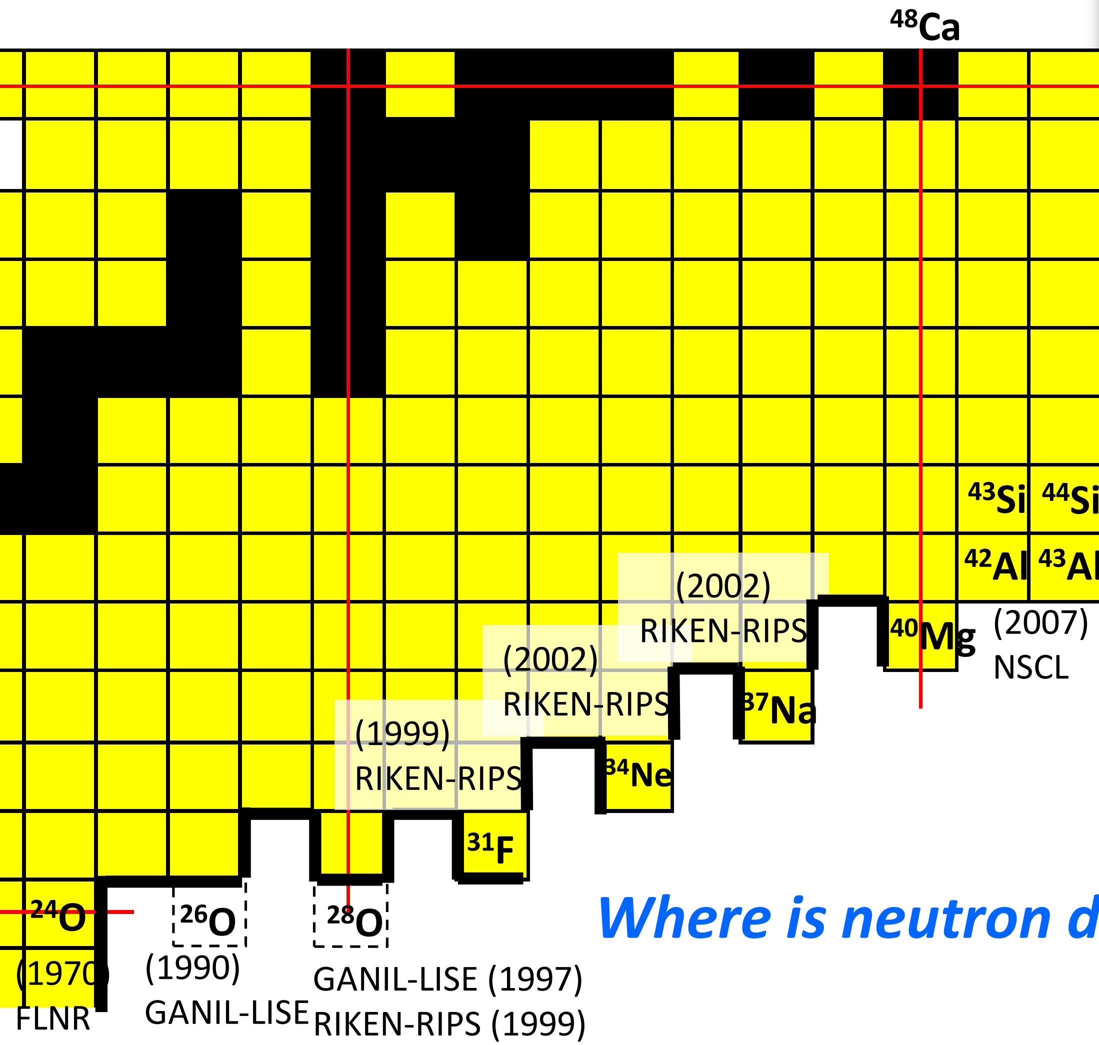
A nucleus with a set number of protons, there is a limit to how many neutrons can be added.

Neutron dripline ⟺

: limit of bound nuclei

- **Binding energy**
- **Deformation**
- **Shell evolution**
- **Nucleon-nucleon interaction**
- **Three nucleon force**
- **Tensor force**
- **Nuclear mass models**
- **…**

Status of neutron dripline



✓ ^{25,26}O :
Guillemaud-Mueller, *et al.* Phys. Rev. C41,937 (1990)

✓ ^{28}O :
O. Tarasov *et al.*, Phys. Lett. B409,64 (1997)
H. Sakurai *et al.*, Phys. Lett. B448, 180 (1999)

✓ ^{31}F :
H. Sakurai *et al.*, Phys. Lett. B448, 180 (1999)

✓ ^{34}Ne, ^{37}Na, ^{43}Si :
M. Notani *et al.*, Phys. Lett. B542,49 (2002)

✓ ^{44}Si :
O. Tarasov *et al.* Phys. Rev. C75, 064613 (2007)

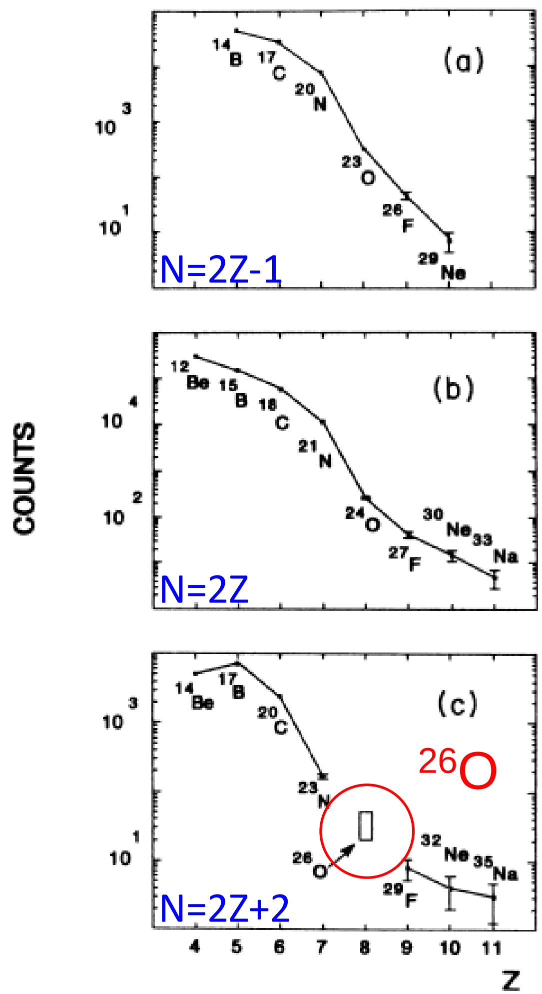
✓ ^{40}Mg, ^{42,43}Al :
T. Baumann *et al.* Nature 449, 1022 (2007)

Where is neutron dripline for Fluorine and Neon?

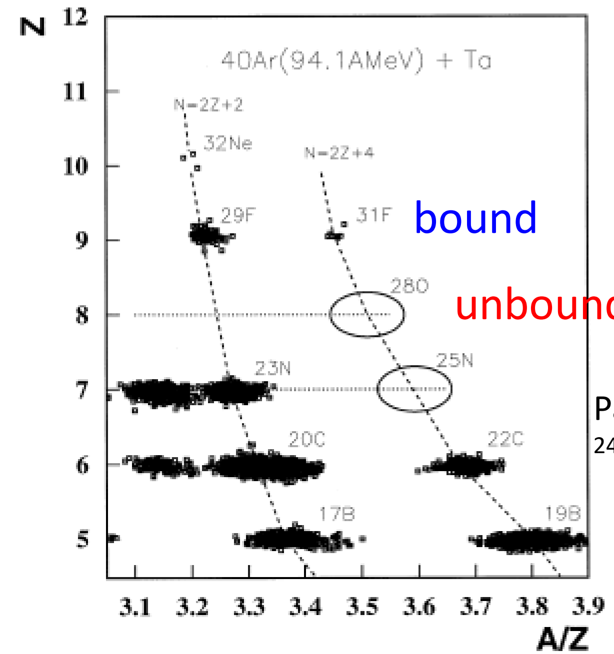
The neutron dripline has been experimentally established up to oxygen. (20 years ago)

Non-existence of ^{26}O and ^{28}O

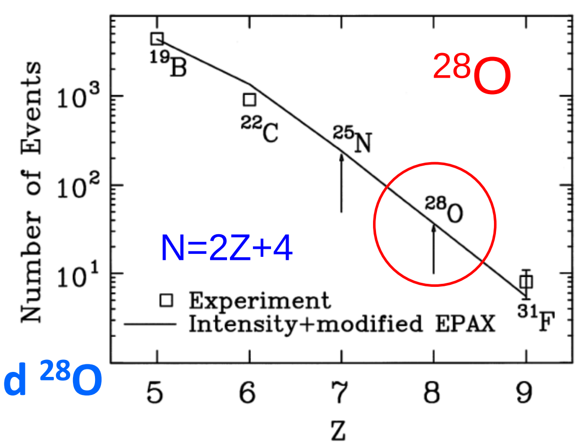
D. Guillemaud-Mueller *et al.*, PRC 41,937 (1990)



H. Sakurai *et al.*, PLB 448, 180 (1999)



Particle instability of $^{24,25}N$, $^{27,28}O$ and ^{30}F

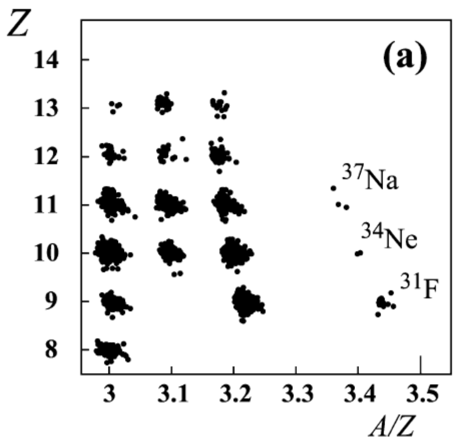


From the smooth drop and the absence of ^{26}O and ^{28}O

→ ^{26}O and ^{28}O are unbound

Neutron dripline search using a ^{48}Ca beam

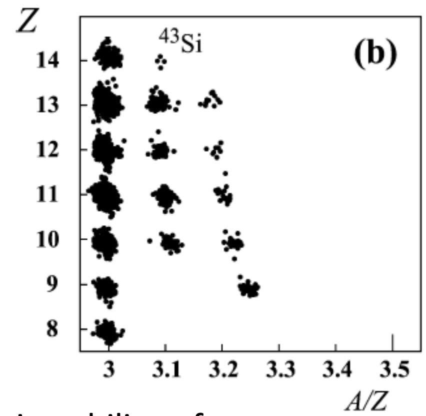
1) Discovery of ^{31}F, ^{34}Ne, ^{37}Na, ^{43}Si @RIKEN



140 pnA @RIPS,
64A MeV ^{48}Ca beam

M. Notani et al.

I = 140 pnA (max.)
Running time
= ~1 day(Ta)

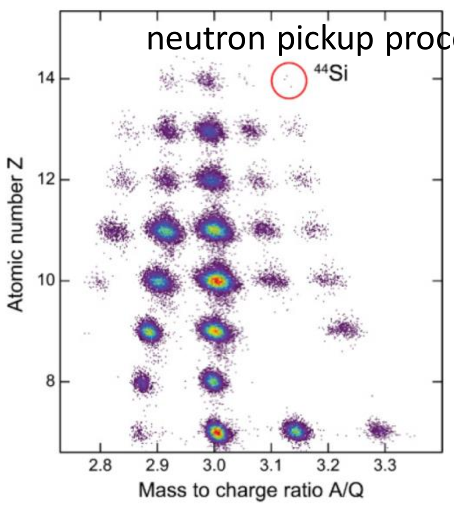


I = 140 pnA (max.)
Running time
= ~2 day(Ta)

M. Notani et al. Physics Letters B 542 (2002) 49–54
H. Sakurai et al., PLB 448, 180 (1999) → ^{31}F

Particle instability of
^{33}Ne, ^{36}Na and ^{39}Mg

2) Discovery of ^{44}Si @MSU



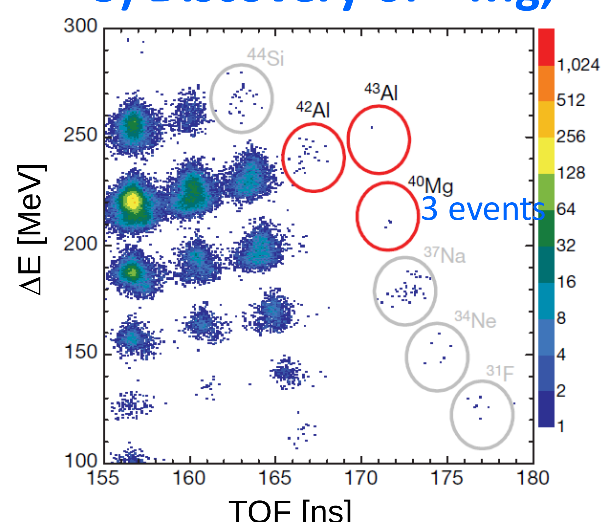
^{48}Ca + Be, W @
142 MeV/u

O. Tarasov et al.

I = 70 pnA (ave.)
Running time
= 4.3h(W) + 5.8h(Be)

O. Tarasov et al., PRC75, 064613 (2007)

3) Discovery of ^{40}Mg, ^{42,43}Al @MSU



^{48}Ca + W @
141 MeV/u

T. Baumann et al.

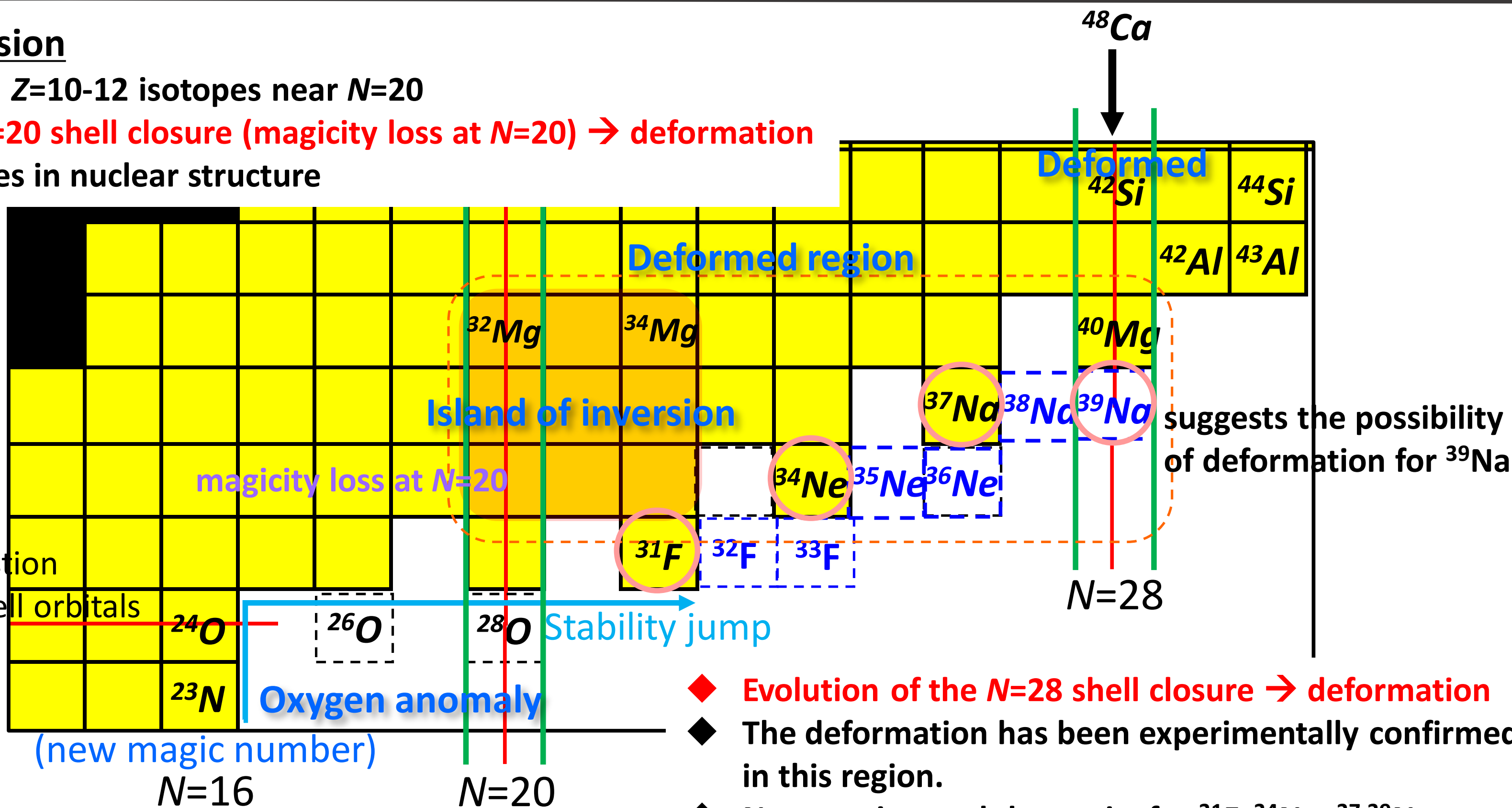
I = 80 pnA (ave.)
Running time
= 7.6 days

T. Baumann et al., nature 06213 (2007)

Evolution towards the neutron dripline

Island of inversion

- Neutron-rich *Z*=10-12 isotopes near *N*=20
- Vanishing *N*=20 shell closure (magicity loss at *N*=20) → deformation
- Rapid changes in nuclear structure



- Evolution of the *N*=28 shell closure → deformation
- The deformation has been experimentally confirmed in this region.
- No experimental data exist for ^{31}F, ^{34}Ne, $^{37,39}Na$.

Experimental methods to study the structure of neutron-rich exotic nuclei

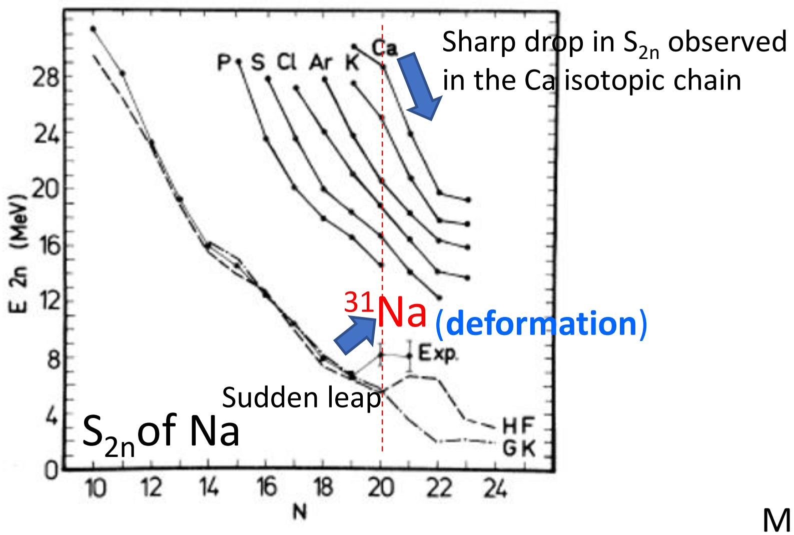
- Direct mass measurement [S_{2n}]
- 1n(or 2n) removal cross section and momentum distribution
- Interaction cross sections [σ_I]
- Excitation energy of 2+ and 4+ states in even-even nuclei (Observation of ground-state rotational bands in odd-even nuclei)

The location of the dripline is strongly affected by the nuclear structure.

Mass measurement, 1n(2n) removal reactions

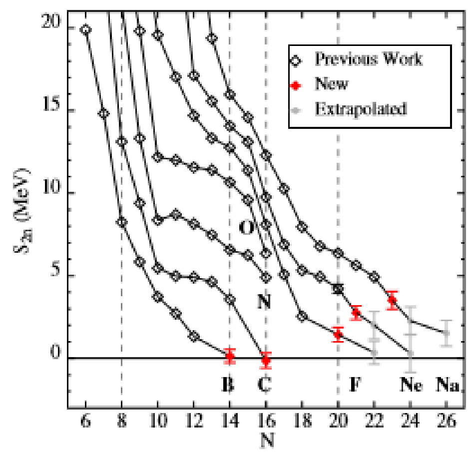
■ Direct mass measurement: specific behaviors for magic or deformed

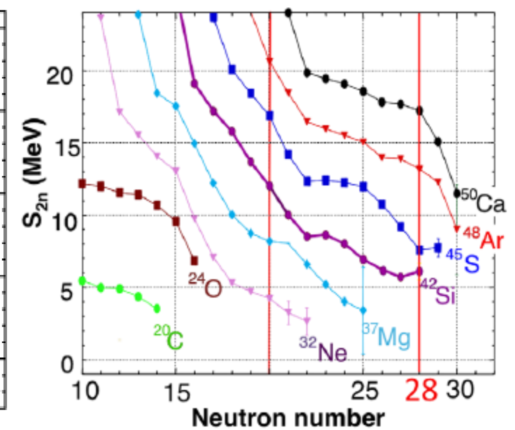
C. Thibault et al., Phys. Rev. C 12, 644(1975)



L. Gaudefroy et al., Phys. Rev. Lett. 109, 202503(2012)

O. Sorlin et al., Phys. Scr. T152 (2013) 014003





Mass measurement of ^{19}B, ^{22}C, ^{29}F, ^{31}Ne, ^{34}Na (^{42}Si: deformation)

Not measured yet for ^{31}F, ^{34}Ne, ^{37,39}Na.

■ 1n(or 2n) removal cross section and momentum distribution

: existence of a deformed halo structure

T. Nakamura et al., Phys. Rev. Lett. 103, 262501(2009) :^{31}Ne

T. Nakamura et al., Phys. Rev. Lett. 112, 142501(2014) :^{31}Ne

N. Kobayashi et al., Phys. Rev. Lett. 112, 242501(2014) :^{37}Mg

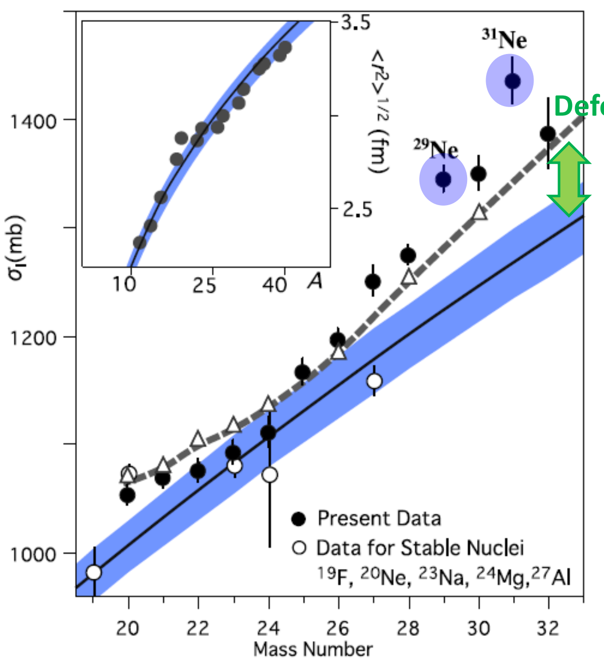
N. Kobayashi et al., Phys. Rev. C 93, 014613(2016) :^{29}Ne

Interaction cross sections

Enhanced if deformation or halo exist

■ ^{29}Ne and ^{31}Ne

M. Takechi *et al.*, PLB 707, 357 (2012)

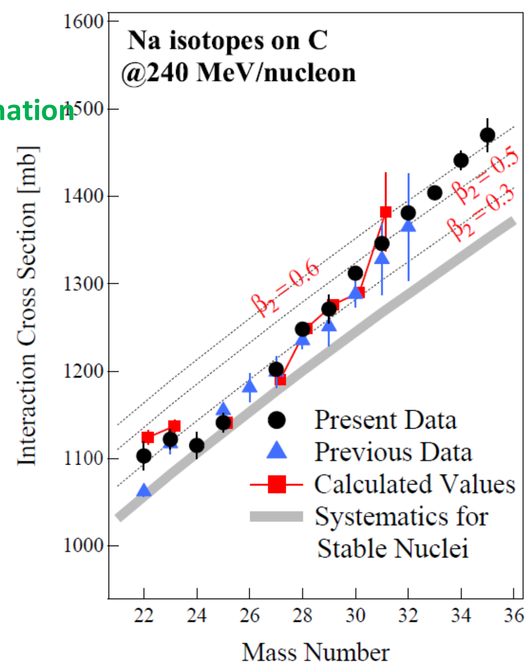


→ Large enhancements of σ_I for ^{29}Ne and ^{31}Ne

^{29}Ne, ^{31}Ne : deformed halo

■ $^{22-35}$Na

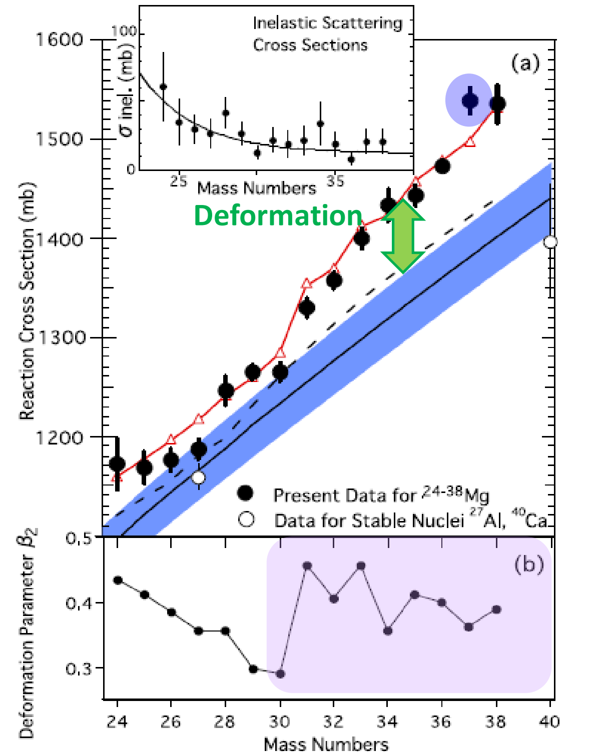
T. Suzuki *et al.*, EPJ Conf.66 (2014)



→ Deformation tends to be larger for Na isotopes with larger mass numbers

■ ^{37}Mg

M. Takechi *et al.*, PRC 90, 061305(R) (2014)



→ Deformation keeps large up to N=28.

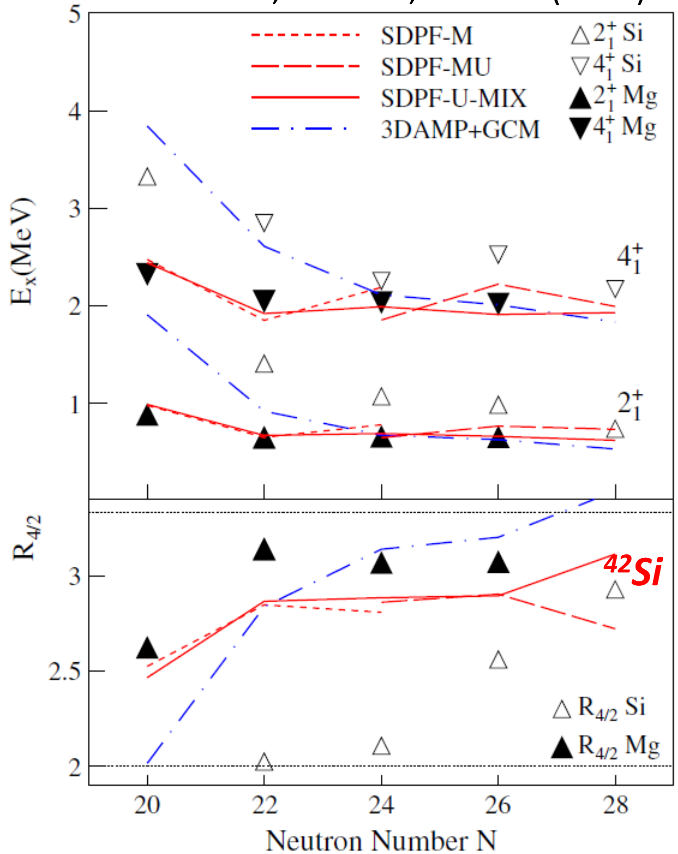
^{37}Mg: deformed halo

Excitation energy of 2+ and 4+ states in even-even nuclei

■ *N*=22,24,26 ^{34,36,38}Mg isotopes and ^{42}Si(*N*=28)

P. Doornenbal *et al.*, PRL 111, 212502 (2013)

S. Takeuchi *et al.*, PRL 109, 182501 (2012)



Collectivity: B(E2) ∝ β^2

Shell gap: E_x/B(E2)

Shape: $R_{4/2}$=E(4+)/E(2+)

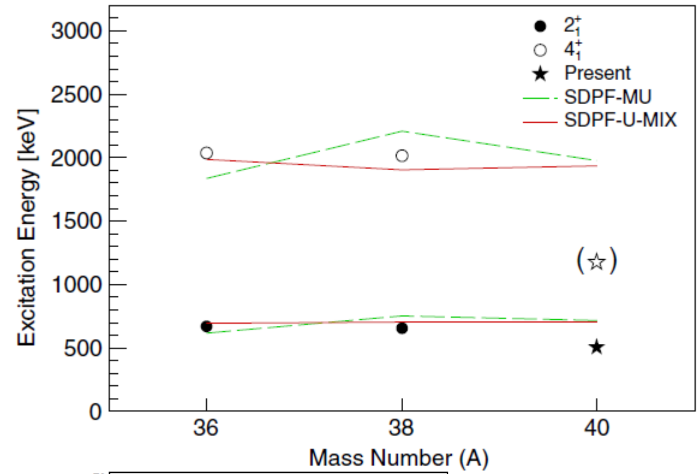
~1.8 (spherical)

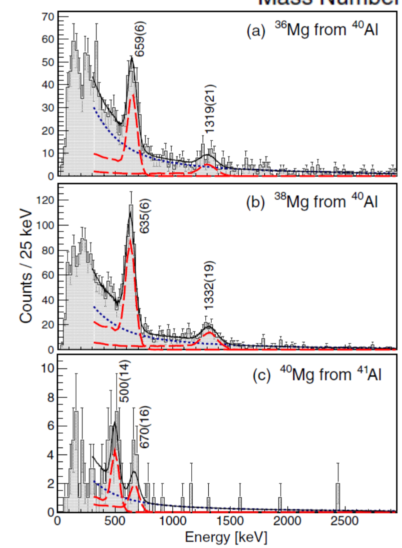
~3.3 (deformed)

Deformation extending from the *N*=20 to the *N*=28

■ *N*=28 ^{40}Mg isotopes

H. L. Crawford *et al.*, PRL 122, 052501 (2019)





There are currently no model predictions for a second low-lying state in ^{40}Mg.

[Other references]

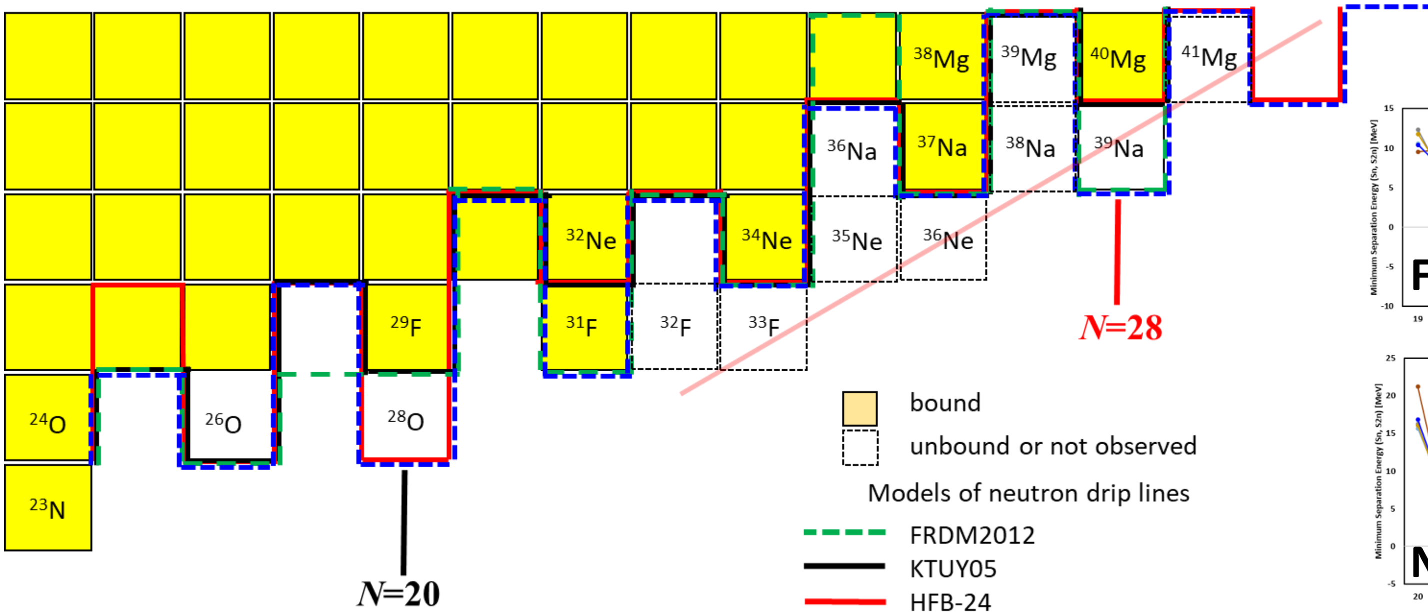
- **F**: P. Doornenbal et al., Phys. Rev. C 95, 041301(R) (2017)
- **Ne**: P. Doornenbal et al., Phys. Rev. Lett. 103, 032501(2009)
- **Na**: P. Doornenbal *et al.*, PTEP 2014, 053D01
  → Energy level systematics of the odd–even nuclei

Prediction of neutron dripline

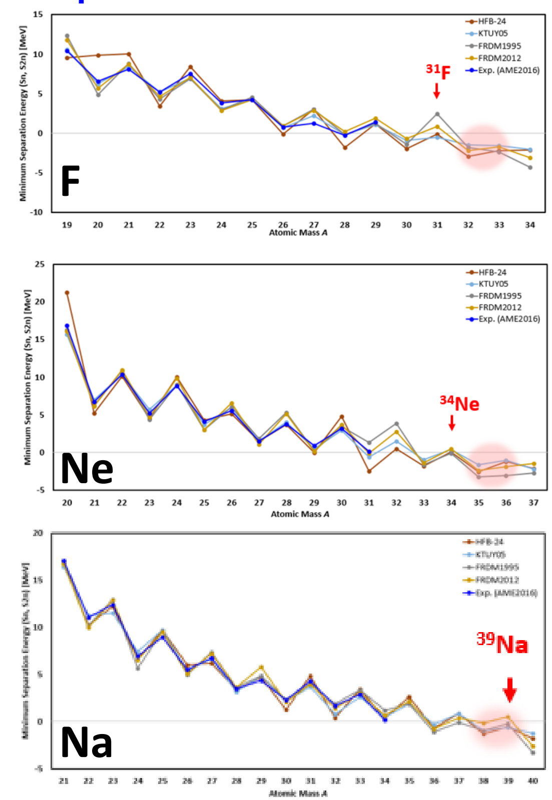
Mass models

- HFB (Hatree-Fock-Bogoliubov)
- FRDM(Finite-Range Droplet Mass Model)
- KTUY(Koura, Tachibana, Uno, Yamada)
- WS4RMF (Weizsäcker–Skyrme relativistic mean-field mass model)
- UNEDF
- ab-initio models

Atomic Mass Evaluation



Systematics of min(Sn,S2n)



The neutron dripline is important

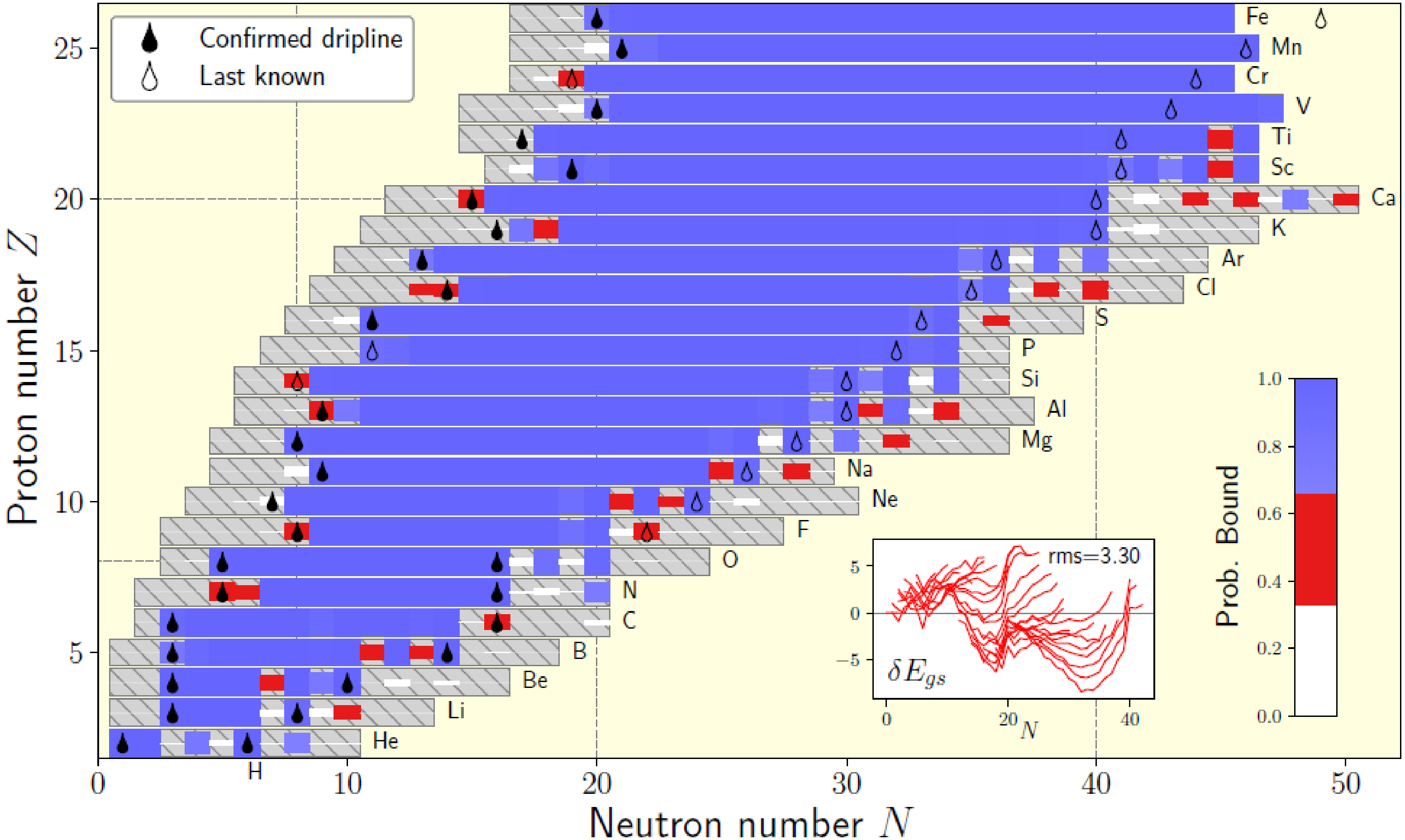
- to verify the mass models
- to understand nuclear structures and astrophysical reactions

→ The various mass models cannot accurately predict the neutron dripline.

Recent ab-initio calculations

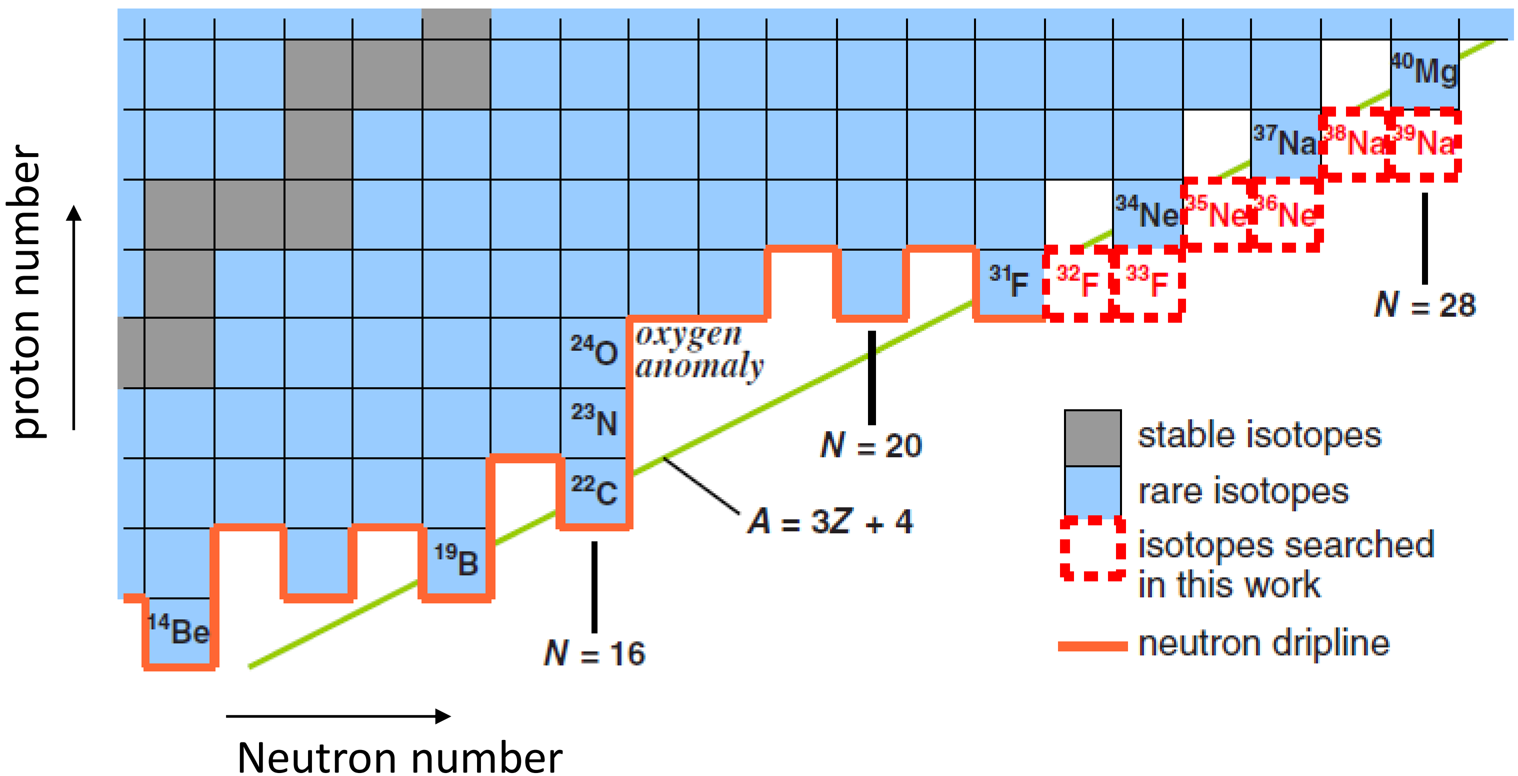
- **Calculated probabilities for low *Z* nuclei**

https://arxiv.org/abs/1905.10475



- Issues with neutron-rich O and N isotopes
- Reproduces well the experimental results (this work & ^{60}Ca experiment)

Search for Fluorine and Neon dripline



Search for Fluorine and Neon dripline

→ A search for the heaviest new isotopes of fluorine, neon and sodium: ^{32,33}F, ^{35,36}Ne and ^{38,39}Na was conducted by fragmentation of an intense ^{48}Ca beam with 20mm-thick beryllium target at 345 MeV/nucleon

F/Ne dripline experiment (2014 experiment)

A search for $^{32,33}F$, $^{35,36}Ne$, $^{38,39}Na$ using a ^{48}Ca beam

Requirements for dripline-search experiment

- High intensity primary beam

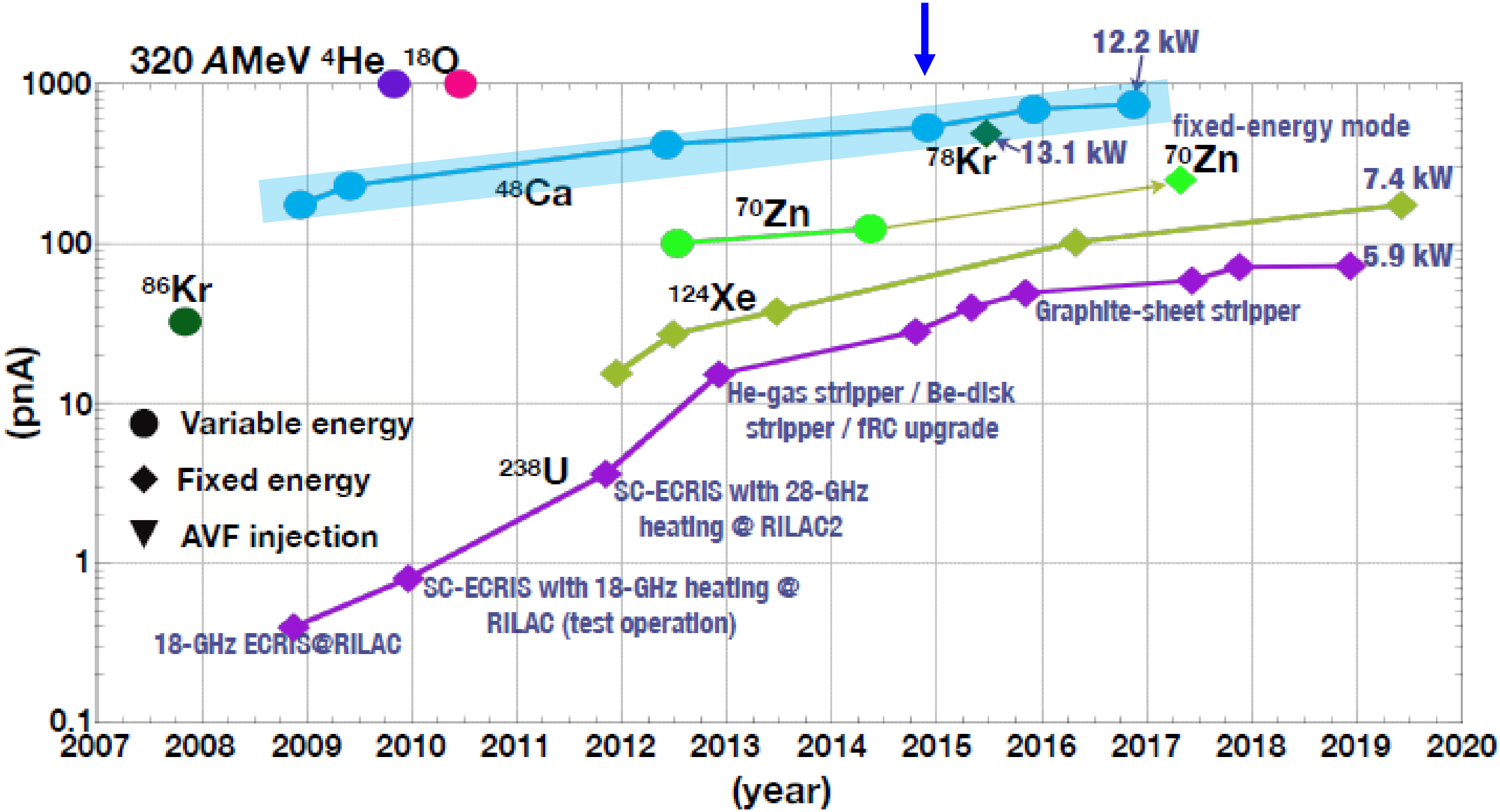
- Good separation and Good transmission
  - Cross sections are too small.
  - Improving the capability of BigRIPS separator
  - High counting rate : collimator to reject the light particles (Tritons)

- Unambiguous PID
  - Excellent particle Identification
  - Removal of background events

Beam intensity of RIBF

345 MeV/u ^{48}Ca beam,
~450 pnA @2014 experiment

From Accelerator Group (Courtesy of N. Fukunishi)



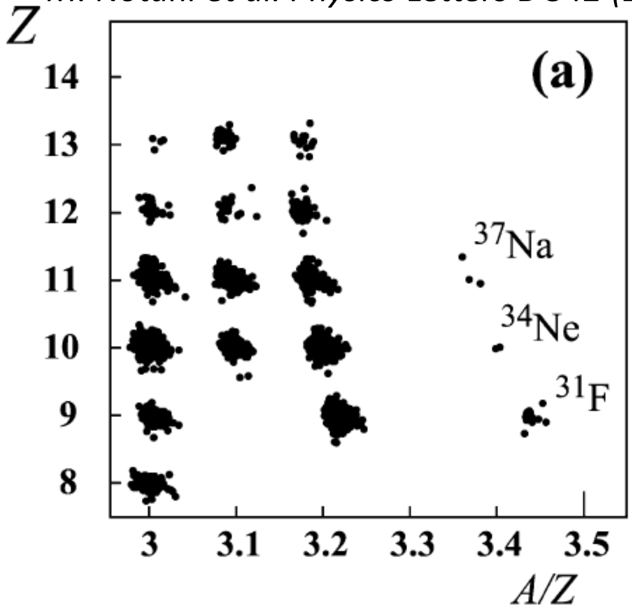
- Maximum energy is 345 MeV/nucleon for heavy ions up to ^{238}U ions
- Beam intensities increase in every year.
- Goal intensity is 1 pμA for all ions.

High-intensity ^{48}Ca beam

RIKEN RIPS

140 pnA @RIPS,
64A MeV ^{48}Ca beam + **Ta** target

M. Notani et al. Physics Letters B 542 (2002) 49–54



~ 100 times up

RIKEN BigRIPS

450 pnA @BigRIPS,
345 MeV/u ^{48}Ca beam + **Be** target

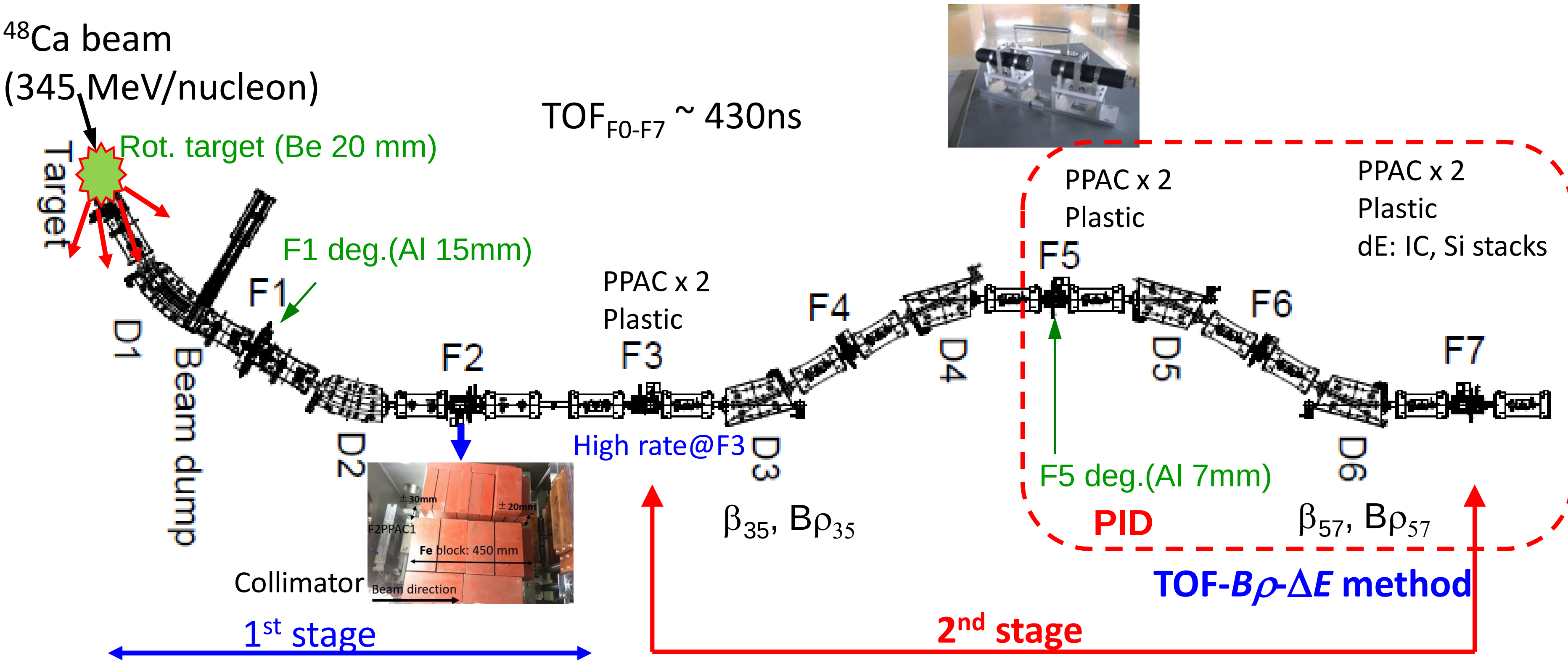
^{34}**Ne** setting
→ **330 counts/h**

High-intensity high-energy ^{48}Ca primary beams now available!

Experimental setup and particle identification

BigRIPS in-flight separator :

- large acceptances
- Two-staged separator scheme



- $B\rho$ determination from X positions at F5 and F7
- TOF(F5,F7 Plastic Scintillators) → A/Q
- ΔE_{si} → Z

$$\frac{A}{Q} = \frac{B\rho c}{\beta\gamma m_u}$$

$f(Z,\beta) = \Delta E_{si}$ → Z

Setting for ^{33}F and $^{36}Ne+^{39}Na$ setting

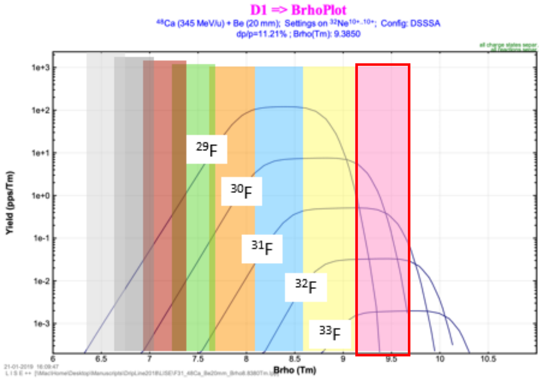
	^{33}F Setting	$^{36}Ne + ^{39}Na$ Setting
Primary beam	^{48}Ca	^{48}Ca
Target	^{9}Be 20 mm	^{9}Be 20 mm
Tuned for	^{33}F	Center for $^{36}Ne + ^{39}Na$
Bρ (at D1)	9.385 Tm	9.385 Tm
F1 degrader	Al 15 mm (d/R=0.17)	Al 15 mm (d/R=0.18)
F5 degrader	Al 7 mm	Al 7 mm
Beam intensity	429 pnA	448 pnA
Data accumulation	14.8 hours	7.77 hours

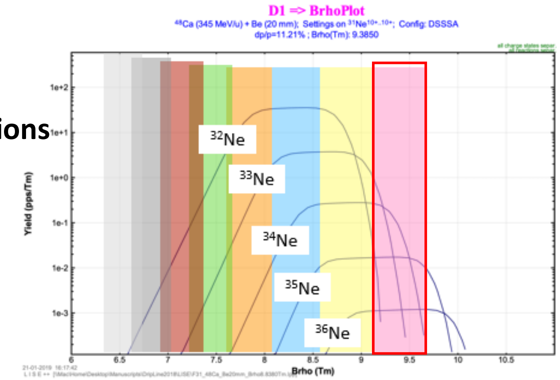
Momentum distributions

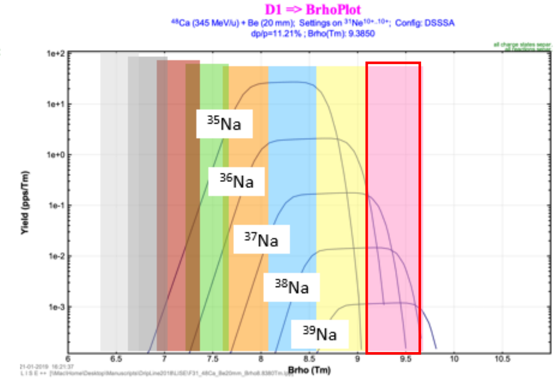
^{33}F setting

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

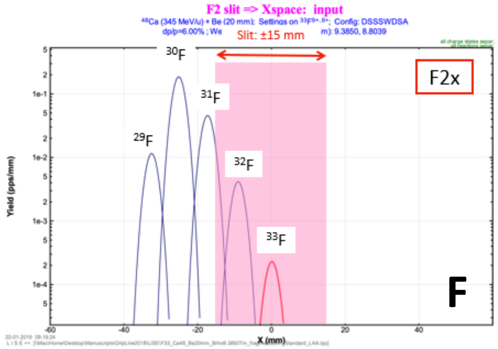
Bρ distributions

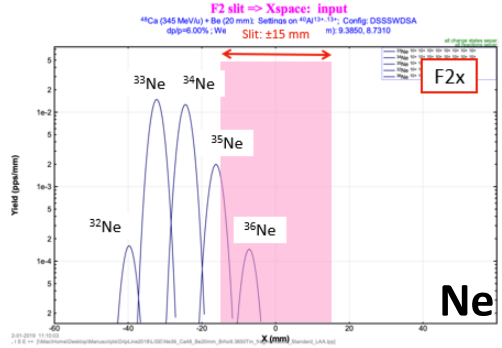


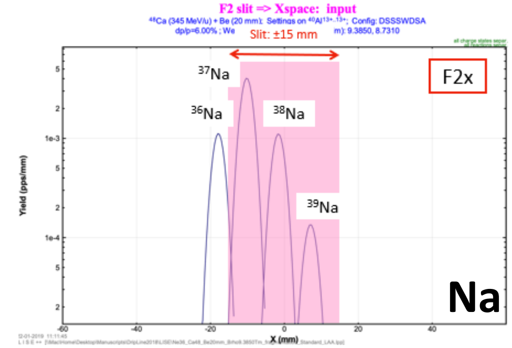


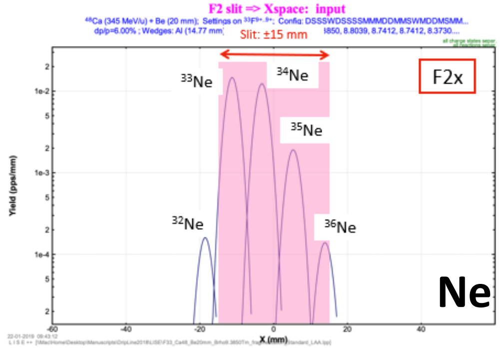


F2 positions



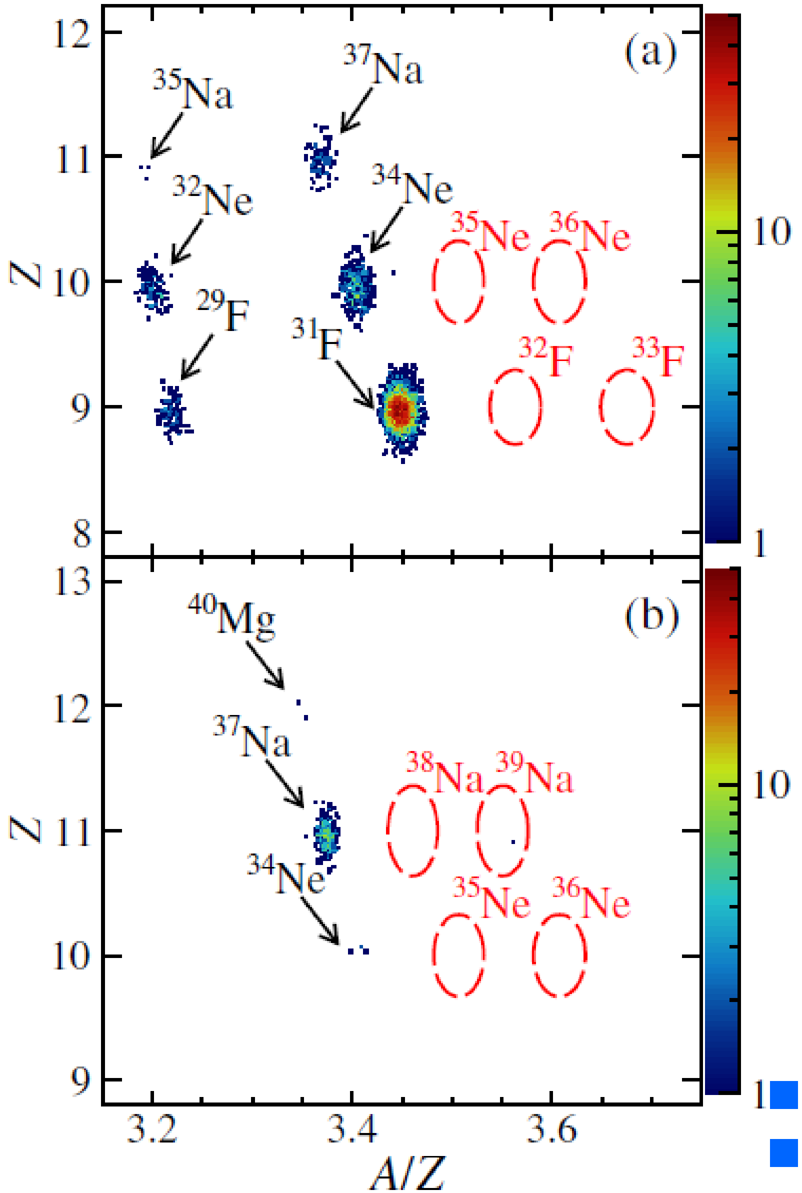






→ The LISE^{++} simulations were confirmed trajectories.
→ The calculated transmission is good.

Particle identification



345 MeV/u ^{48}Ca beam + Be target (20 mm)

^{33}F setting

→ ^{32,33}F, ^{35,36}Ne

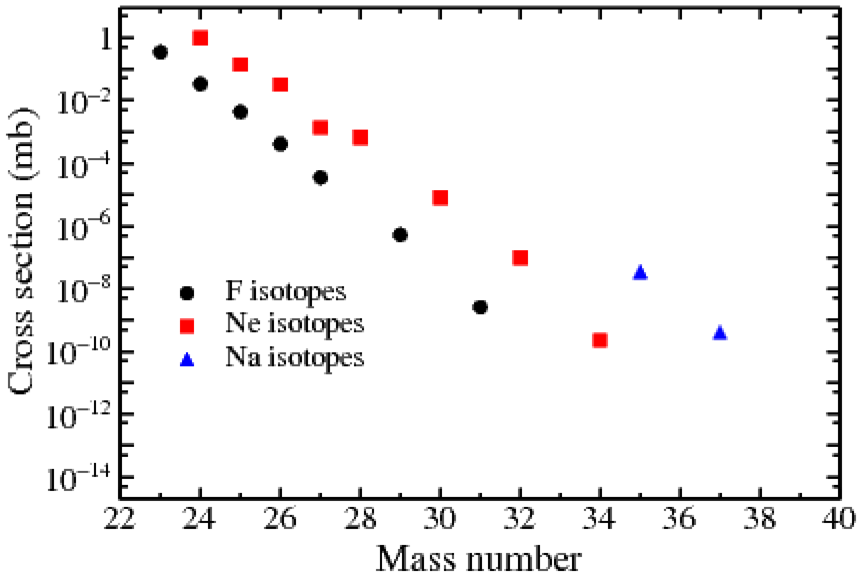
^{36}Ne+^{39}Na setting

→ ^{36}Ne, ^{38,39}Na

- No events were observed for ^{32}F, ^{33}F, ^{35}Ne, ^{36}Ne, ^{38}Na
- One event for ^{39}Na → Follow-up experiment (2017)

Bound or Unbound? $^{32,33}F$, $^{35,36}Ne$, ^{38}Na

Systematic measurement of production cross sections



- Cross sections evaluation with EPAX2.15 and Q_g systematics
- Expectation yields

$$\boldsymbol{N_f} = \boldsymbol{\sigma} \times (N_{beam} \times N_{target} \times \epsilon_{tran.} \times \epsilon_{BG} \times \epsilon_{live})$$

σ : Cross section
N_f : Number of fragments
N_{beam} : Beam Dose
N_{target} : Number of target atoms
$\epsilon_{tran.}$: Transmission
ϵ_{BG} : Efficiency for lost events
ϵ_{live} : Efficiency of DAQ live time

- Probability (Zero-event probability)

$$P(k|\lambda) = \lambda^k e^{-\lambda}/k! \xrightarrow{k=0} P(0|\lambda) = e^{-\lambda}$$

(Poisson distribution) λ : expected yield

Q_g systematics

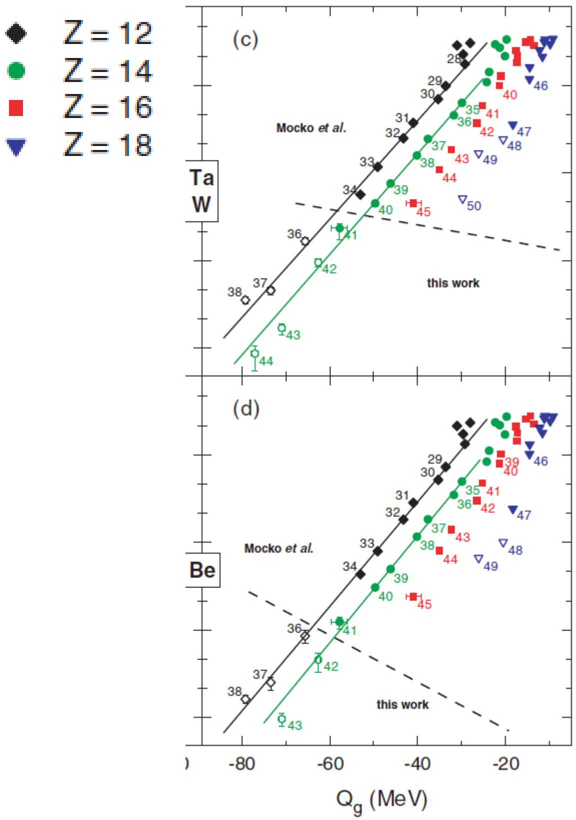
Q_g : Difference in mass excess of the beam particle and observed fragments

$= \Delta M_P - \Delta M_F$

= Mass Excess(20,48) – Mass Excess(Z,A)

$\sigma(Z,A) = \mathbf{f(Z)}\ \exp(Q_g/T)$

T: effective temperature
f(Z): normalization



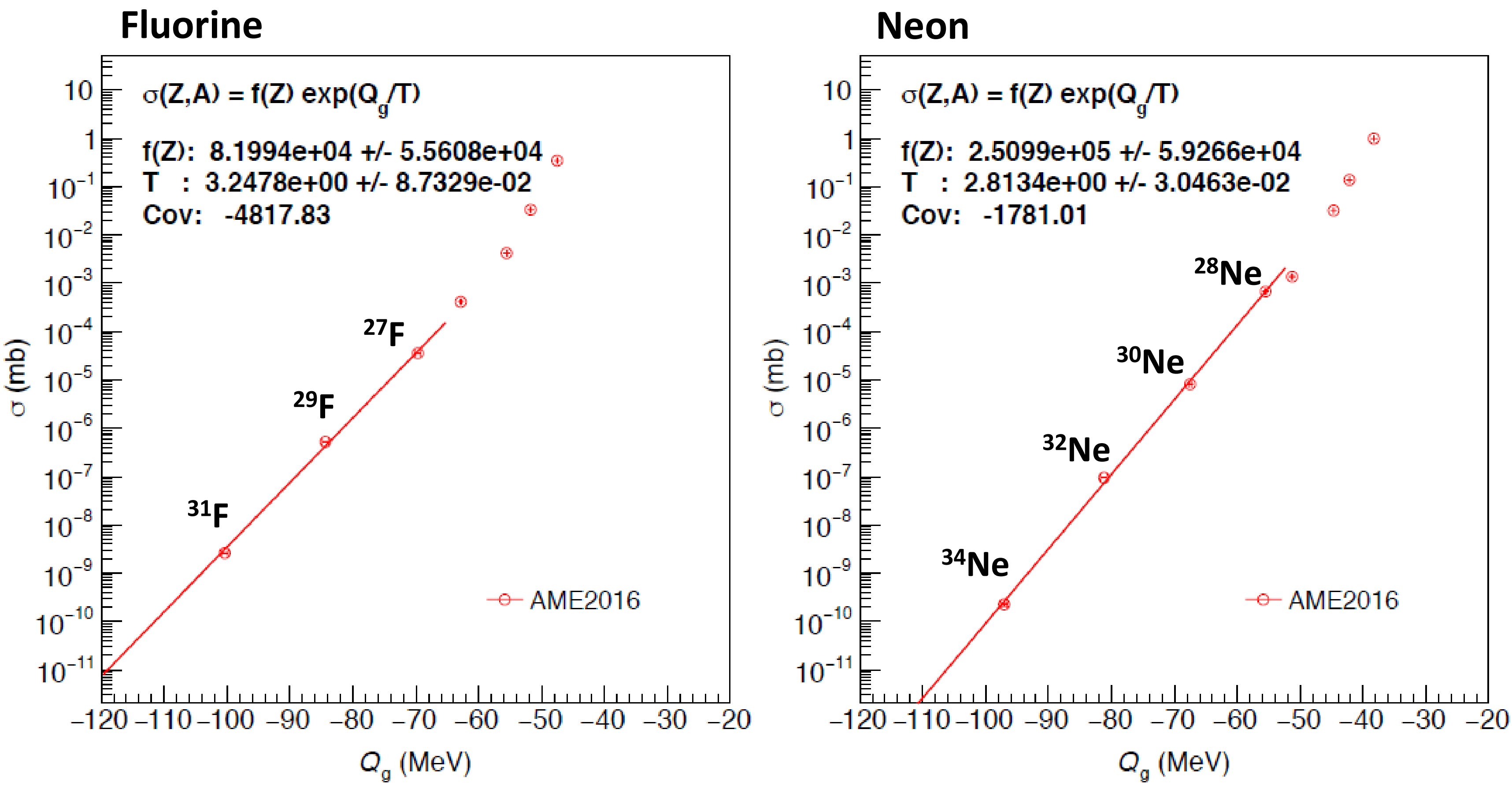
O. Tarasov et al., PRL102, 142501 (2009)
O. Tarasov et al., PRC75, 064613 (2007)

→ **Estimation of expected production cross sections and yields for unobserved isotopes**

→ **Q_g systematics is useful to estimate yields of drip-line nuclei.**

Q_g systematics

Qg systematics fitting

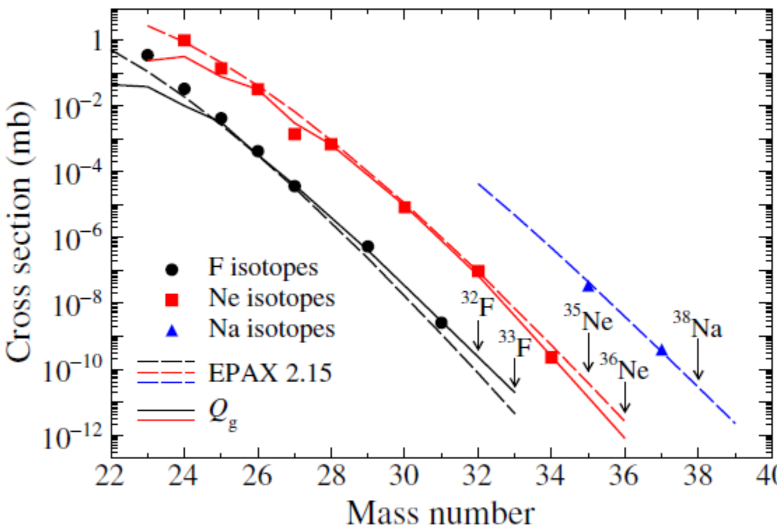


* AME2016 evalution

* Assume the S_{1n}=0 for ^{32}F and ^{35}Ne

* Assume the S_{2n}=0 for ^{33}F and ^{36}Ne

Probability of instability



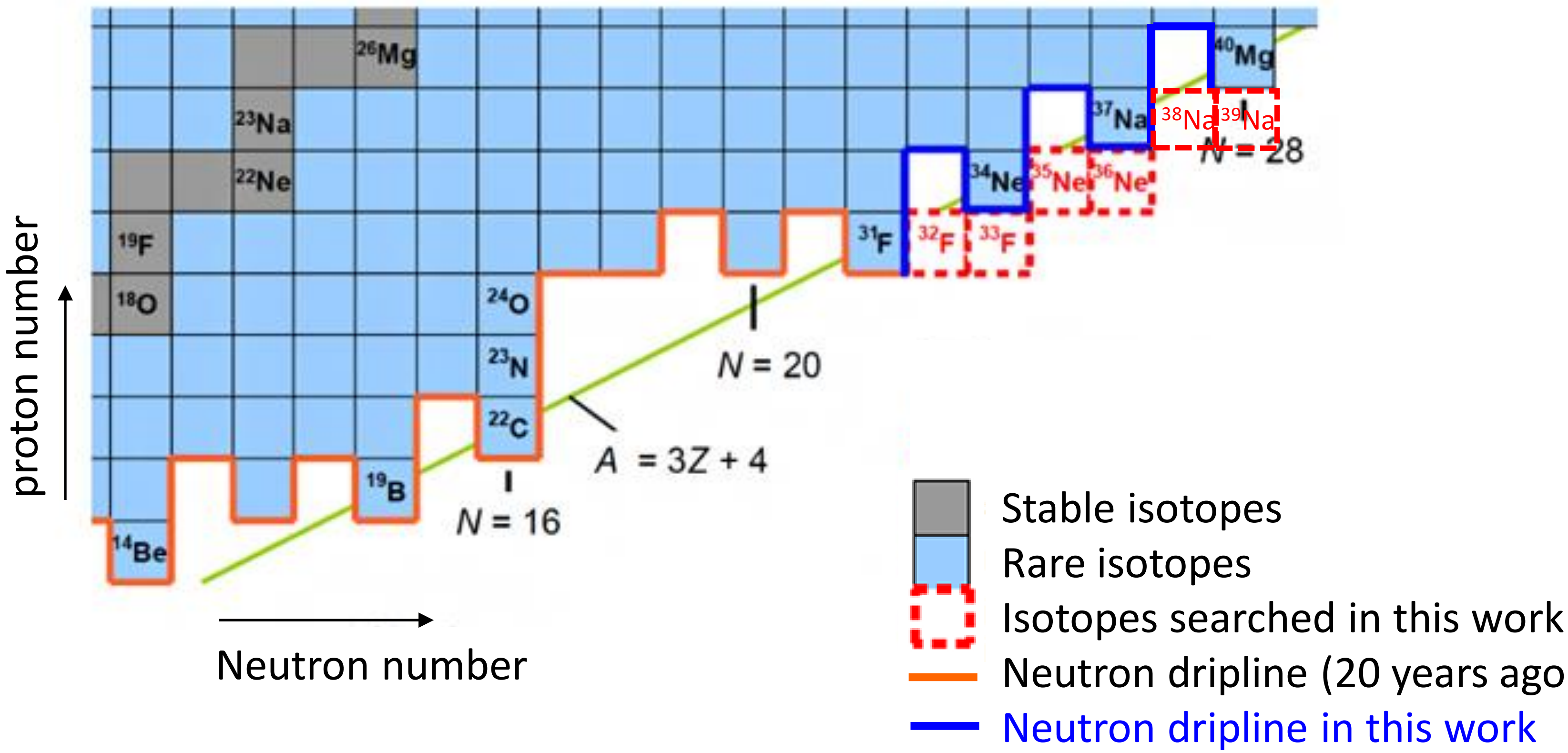
*(a): ^{39}Na+^{36}Ne setting
*(b): ^{33}F setting

Isotope	method	Cross Section [fb]	Expected yields [counts]	Probability being unbound [CL]
^{32}F	**EPAX**	**73.5**	**323 ± 97**	**1- 5 x 10^{-141}**
	Qg	258 ± 76	(1.14 ± 0.33) x 10^{3}	1- 2 x 10^{-494}
^{33}F	**EPAX**	**4.39**	**21.5 ± 6.5**	**1- 3 x 10^{-10}**
	Qg	21.6 ± 7.5	106 ± 37	1- 1 x 10^{-46}
^{35}Ne	EPAX	37.8	177 ± 53	1- 1 x 10^{-77}
	Qg	**14.8 ± 3.6**	**69.1 ± 16.7**	**1- 9 x 10^{-31}**
^{36}Ne	EPAX	2.58	15.5 ± 4.7	1- 2 x 10^{-7}
	Qg (a)	0.839 ± 0.222	2.30 ± 0.63	$90.0\ \%\ ^{+4.6\%}_{-8.4\%}$
	Qg (b)	0.839 ± 0.222	2.73 ± 0.72	$93.5\ \%\ ^{+3.5\%}_{-7.3\%}$
	Qg (a)+(b)	**0.839 ± 0.222**	**5.03 ± 0.96**	$\mathbf{99.3\ \%\ ^{+0.4\%}_{-1.0\%}}$
^{38}Na	**EPAX**	**27.4**	**61.9 ± 18.6**	**1- 1 x 10^{-27}**

- **Zero-event probability(P) obtained from the expected yield and poisson distribution.**
- **Comparison with predicted yields excludes the existence of these unobserved isotopes with high confidence levels**

CL_{32F}= 1-P(0, 323)=~100%, CL_{33F}= 1-P(0, 21.5)=~100% [EPAX2.15]
CL_{35Ne}= 1-P(0, 69.1)=~100%, CL_{36Ne}= 1-P(0, 5.03)= 99.3% [Q_g]
CL_{38Na}= 1-P(0, 27.4)=~100% [EPAX2.15]

Location of neutron dripline



- The neutron dripline has been confirmed up to neon for the first time since ^{24}O was confirmed to be the dripline nucleus nearly 20 years ago.
- The observation of one event for ^{39}Na seems to suggest the existence of bound ^{39}Na.

Upper limits of half-lives

Observation limit of 1 count

Isotope	Setting	Method	Expected counts	TOF (ns)	$T_{1/2}$_upper (ns)
^{32}F	^{33}F	EPAX 2.15	323.0	421.5	50.6
		Qg	1140.0	421.5	41.5
^{33}F	^{33}F	EPAX 2.15	22.0	429.6	96.3
		Qg	106.0	429.6	63.9
^{35}Ne	^{33}F	EPAX 2.15	177.0	417.4	55.9
		Qg	69.1	417.4	68.3
^{36}Ne	^{33}F	EPAX 2.15	8.4	424.6	138.3
		Qg	2.7	424.6	293.0
^{36}Ne	^{36}Ne+^{39}Na	EPAX 2.15	7.1	427.3	151.1
		Qg	2.3	427.3	355.6
^{38}Na	^{36}Ne+^{39}Na	EPAX 2.15	61.9	416.6	70.0

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

Editors' Suggestion   Featured in Physics

Location of the Neutron Dripline at Fluorine and Neon

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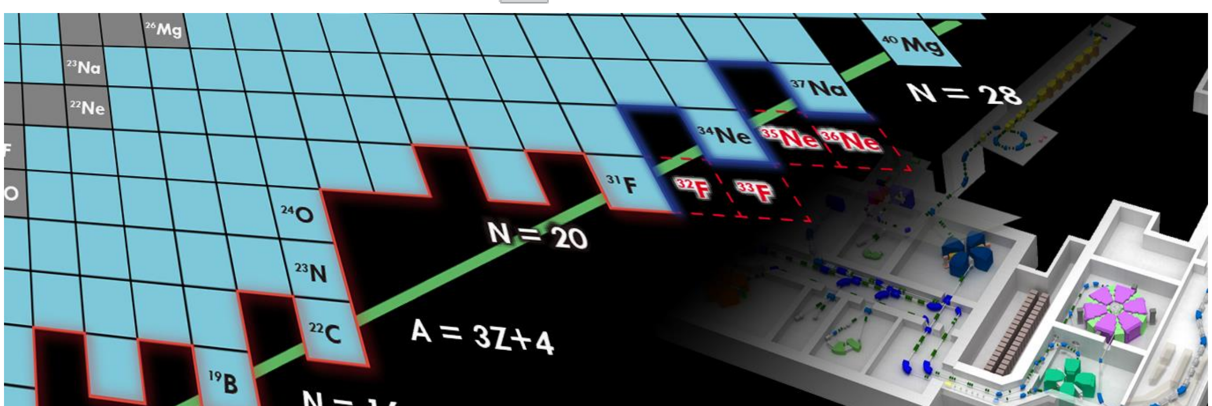


- Editor’s suggestion
- Featured in Physics (Viewpoint)

News & Media

https://physics.aps.org/articles/v12/126
https://physicsworld.com/a/neutron-dripline-extended-to-fluorine-and-neon-isotopes/
https://www.wired.com/story/what-makes-an-element-the-frankenstein-of-sodium-holds-clues/
科学新聞(2019.12.13)

Viewpoint: Reaching the Limits of Nuclear Existence

Artemis Spyrou, Department of Physics and Astronomy, Michigan State University, East Lansing, MI 48824, USA

November 18, 2019 • *Physics* 12, 126

Researchers have identified the largest possible isotopes of fluorine and neon, extending the neutron "dripline" for the first time in 20 years.

APS/ Joan Tycko

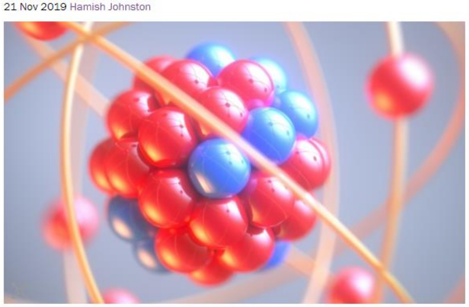
Figure 1: Researchers have mapped the boundary (green line) that charts the heaviest possible isotopes of fluorine (F) and neon (Ne). Previously this so-called neutron dripline was known only for the first eight elements of the periodic table (pink line).

nuclear physics

NUCLEAR PHYSICS | RESEARCH UPDATE

Neutron dripline extended to fluorine and neon isotopes

21 Nov 2019 Hamish Johnston



Dripline: how many neutrons can you pack into a nucleus? (Courtesy: iStock/Altayb)

SOPHIA CHEN SCIENCE 11.22.2019 08:00 AM

What Makes an Element? The Frankenstein of Sodium Holds Clues

By crafting massive versions of sodium, neon, and other elements, physicists are testing what's possible—and impossible—in nature.

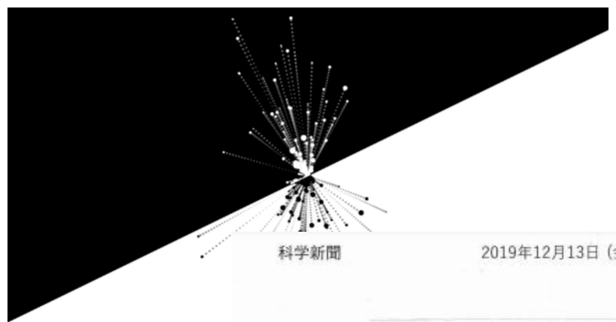


ILLUSTRATION: CASEY CHIN

科学新聞　2019年12月13日（金）朝刊　1面

RIビームファクトリー利用

フッ素とネオンの同位元素 理研が初めて存在限界決定

理化学研究所仁科加速器科学研究センター実験装置運転・維持管理室の稲辺尚人先任技師、福田直樹技師、久保敏幸協力研究員、東京工業大学理学院物理学系の中村隆司教授らの国際共同研究グループは、理研の重イオン加速器施設「RIビームファクトリー（RIBF）」を用い、フッ素（陽子数9）とネオン（陽子数10）の中性子ドリップライン（各元素で中性子数が最も多い同位元素の存在限界）を初めて決定することに成功した。

中性子ドリップラインの同定は容易ではなく、約20年前に陽子数8の酸素で酸素－24と決定されて以来、それより陽子数が多い元素については未決定のままであった。

研究グループは、大強度重イオンビームや高効率のRIビーム分離生成装置BigRIPSの使用、徹底したバックグラウンド除去など、卓越した実験条件の実現により、フッ素（陽子数9）とネオン（陽子数10）のドリップラインが、フッ素－31、ネオン－34であることを初めて同定し、存在限界の境界線を更新した。

久保協力研究員の話「今回の成果は、中性子数が過剰な極限付近にある原子核の構造解明に寄与し、宇宙の元素合成過程において重要な原子核の質量モデルの試金石になります。今後の挑戦は、ナトリウム（陽子数11）など、さらに陽子数の多い元素のドリップラインの決定です」

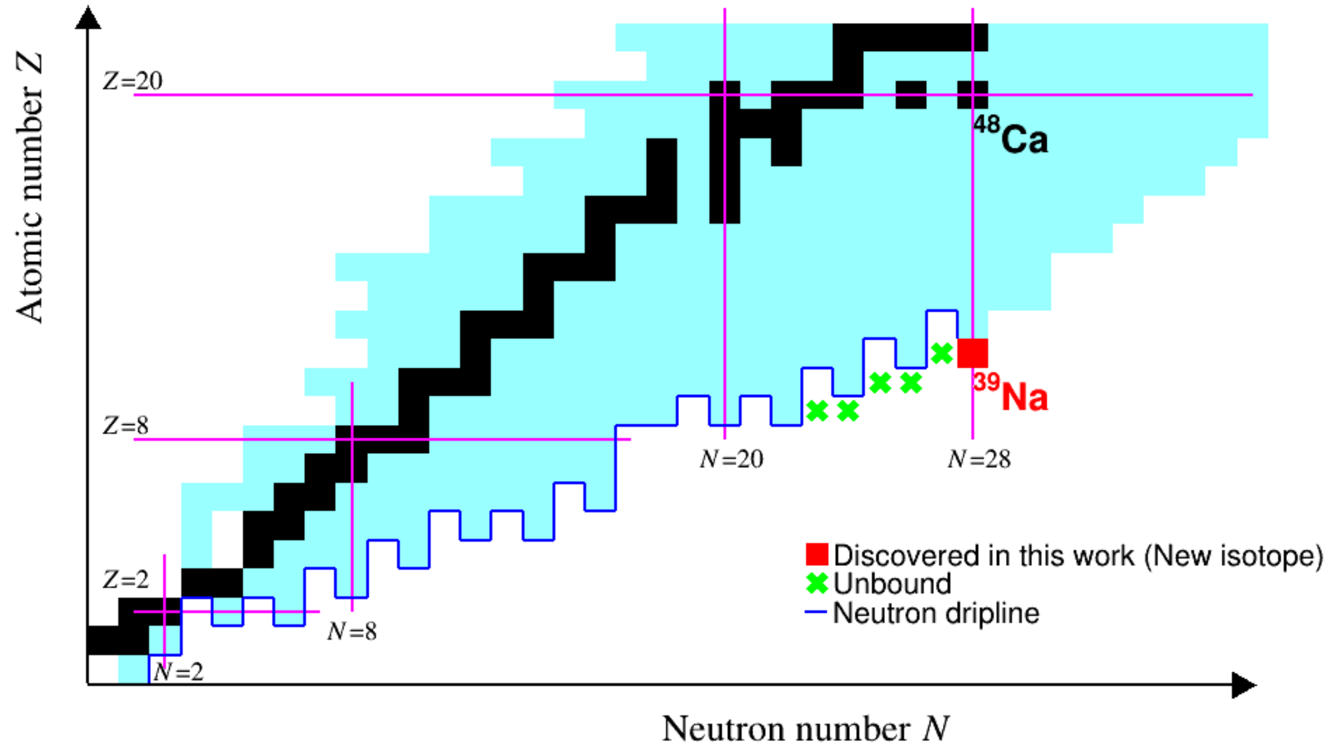
■中性子ドリップライン　同じ元素（同一の陽子数）に中性子数を増やしていくと、束縛エネルギーが減少していき、やがて非束縛状態になり原子核として存在できなくなる。この存在限界を中性子ドリップラインと呼び、同じ元素において、中性子数の最も多い放射性同位元素（原子核）に対応する。

実験に使用したBigRIPSの全景

^{39}Na experiment (2017 follow-up experiment)

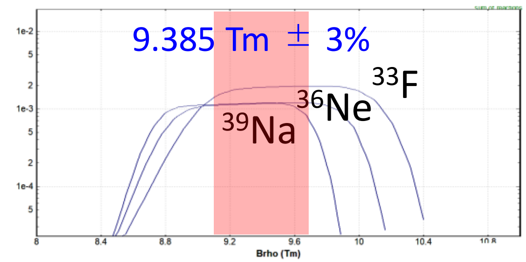
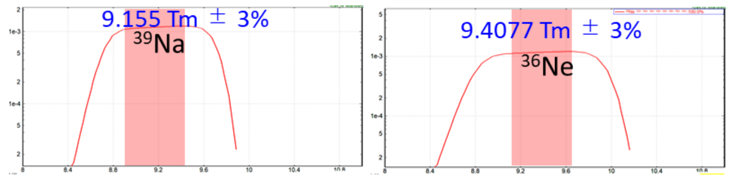
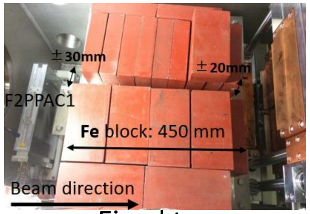
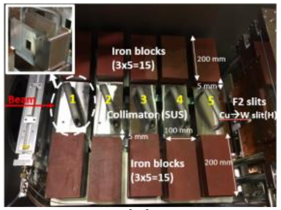
2017 follow-up experiment

- The neutron dripline has been experimentally established up to neon.
- The heaviest bound nuclei for Na isotopes confirmed so far ^{37}Na. One event for ^{39}Na.



- Follow-up experiment, which was conducted to confirm the ^{39}Na event
  - Search the existence of ^{39}Na: Nuclear binding of ^{39}Na (2days experiment)
  - High statistics data of ^{36}Ne to confirm the dripline of Ne (1day experiment)

Comparison of 2014 and 2017 experiment

	isotope	2014 experiment	2017 experiment
$B\rho_{01}$ [Tm]	^{39}Na	9.3850 Tm (+/- 3%), high momentum side	9.1550 Tm (+/- 3%), momentum peak
Distribution	^{36}Ne	9.3850 Tm (+/- 3%), momentum peak 	9.4077 Tm (+/- 3%), momentum peak 
F2 slit		+/- 15 mm (H)	+/- 8.3 mm (H), +/-20 mm(V)
F2 collimator		 Fixed type	F3 total counting rate: ~10^6→~10^4 pps  Removable type Taper-shaped type
		Fe blocks	SUS + Fe blocks + W slits
	x	+/-30(up), +/-20(down)	Hori : +/-23.8 (up), +/-13.8(down)
	Y		Vert: +/-33.2(up), +/-18.2(down)
F7 (dE)		IC, Si	Si
Irr. Time (h) Dose, Intensity	^{39}Na	^{39}Na+^{36}Ne setting: 7.77 h 7.80E+16, 448 pnA	
	^{36}Ne	^{39}Na+^{36}Ne setting: 7.77 h 7.80E+16, 448 pnA ^{33}F setting: 14.18 h 1.37E+17, 429 pnA	

Particle Identification for Na isotopes

Production cross sections for Na isotopes

Particle Identification for Ne isotopes

Estimation of expected cross sections

Collaboration

For 2017 follow-up experiment

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Tokyo Tech: T. Nakamura

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Tohoku University: N. Iwasa, S. Ishikawa, T. Sakakibara

Rikkyo University: J. Amano

GSI: H. Geissel

Summary & Future prospect

Summary & Discussion

- A search for the heaviest new isotopes of fluorine, neon and sodium ($^{32,33}F$, $^{35,36}Ne$, $^{38,39}Na$) was conducted by fragmentation of an intense ^{48}Ca beam at 345 MeV/nucleon.

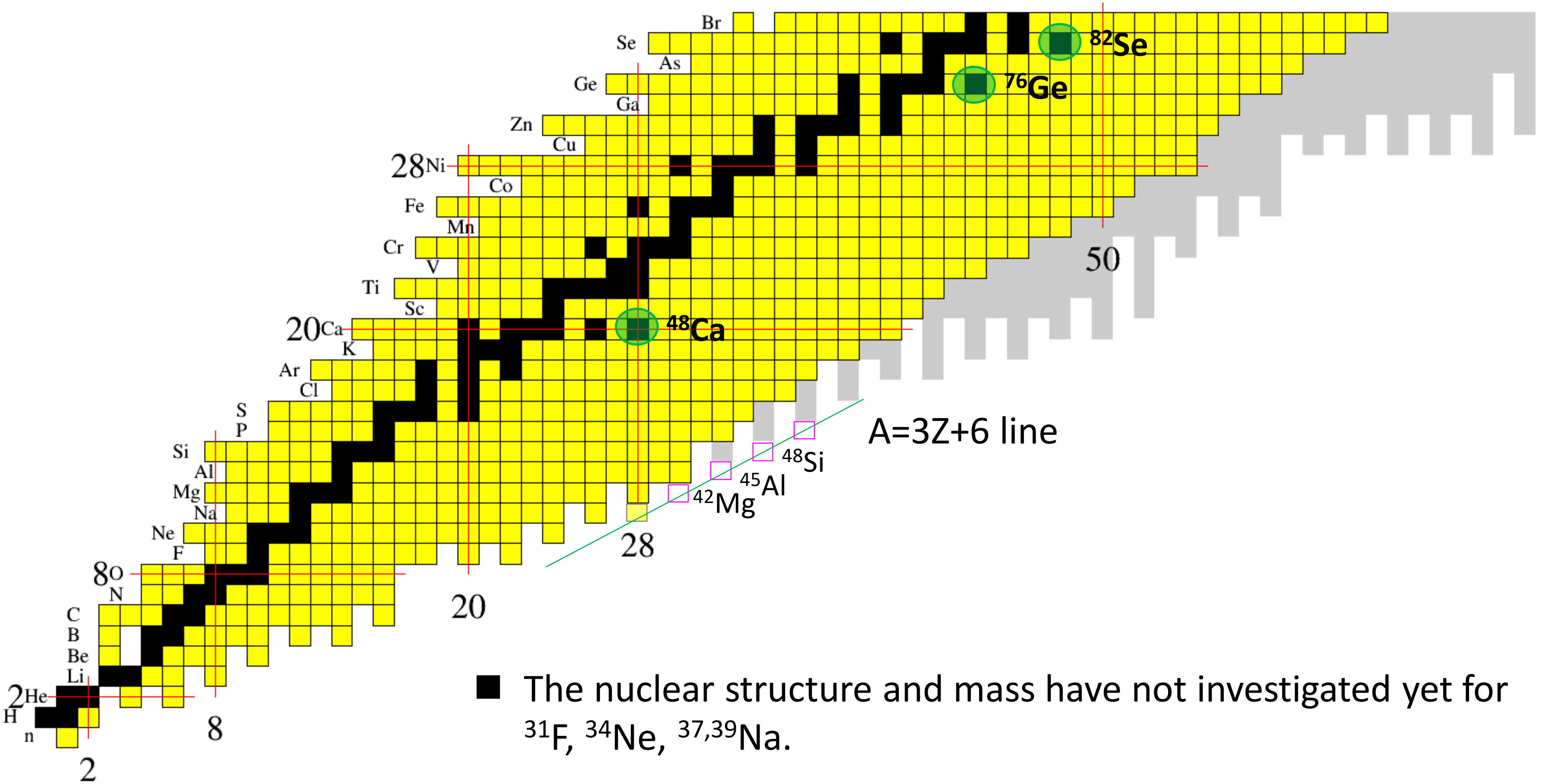
- No events were observed for $^{32,33}F$, $^{35,36}Ne$, ^{38}Na and only one event for ^{39}Na after extensive running. → The neutron dripline has been confirmed up to neon for the first time since ^{24}O was confirmed to be the dripline nucleus nearly 20 years ago.

- No observation of ^{36}Ne nuclei in the high-statistics measurement confirming the 2014 experiment. → Confirmation of ^{36}Ne is unbound with higher confidence level

- The observation of ^{39}Na
  - 2014 experiment (1 event) → It seems to suggest the existence of bound ^{39}Na.

- The various mass models cannot accurately predict the neutron dripline.

- These results provide new keys to understanding the nuclear stability at extremely neutron-rich conditions.



- The nuclear structure and mass have not investigated yet for ^{31}F, ^{34}Ne, ^{37,39}Na.

- Locating the neutron dripline continues to be an important challenge for new-generation facilities and the neutron-dripline search will continue to play an important role in the nuclear structure at extremely neutron-rich conditions.
- These results provide a key benchmark for nuclear mass and structure models.
- Development of much more primary beam species are necessary to expand the nuclear chart.