RIKEN NiSHiNA CENTER

Morphometric studies of the“Island of Inversion” (Status and Results of NP0702-RIBF32)

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Outline

- “Island of Inversion”
  - Time-line
- Our Setup
  - RIBF/BRS/ZDS
  - DALI2@F8
  - Atomic background
- Results
  - First RIBF results: $E(2_1^+)$ in ^{32}Ne
  - $E(2_1^+)$ and $E(4_1^+)/E(2_1^+)$ ratio in ^{36,38}Mg
  - First excited state in ^{29}F

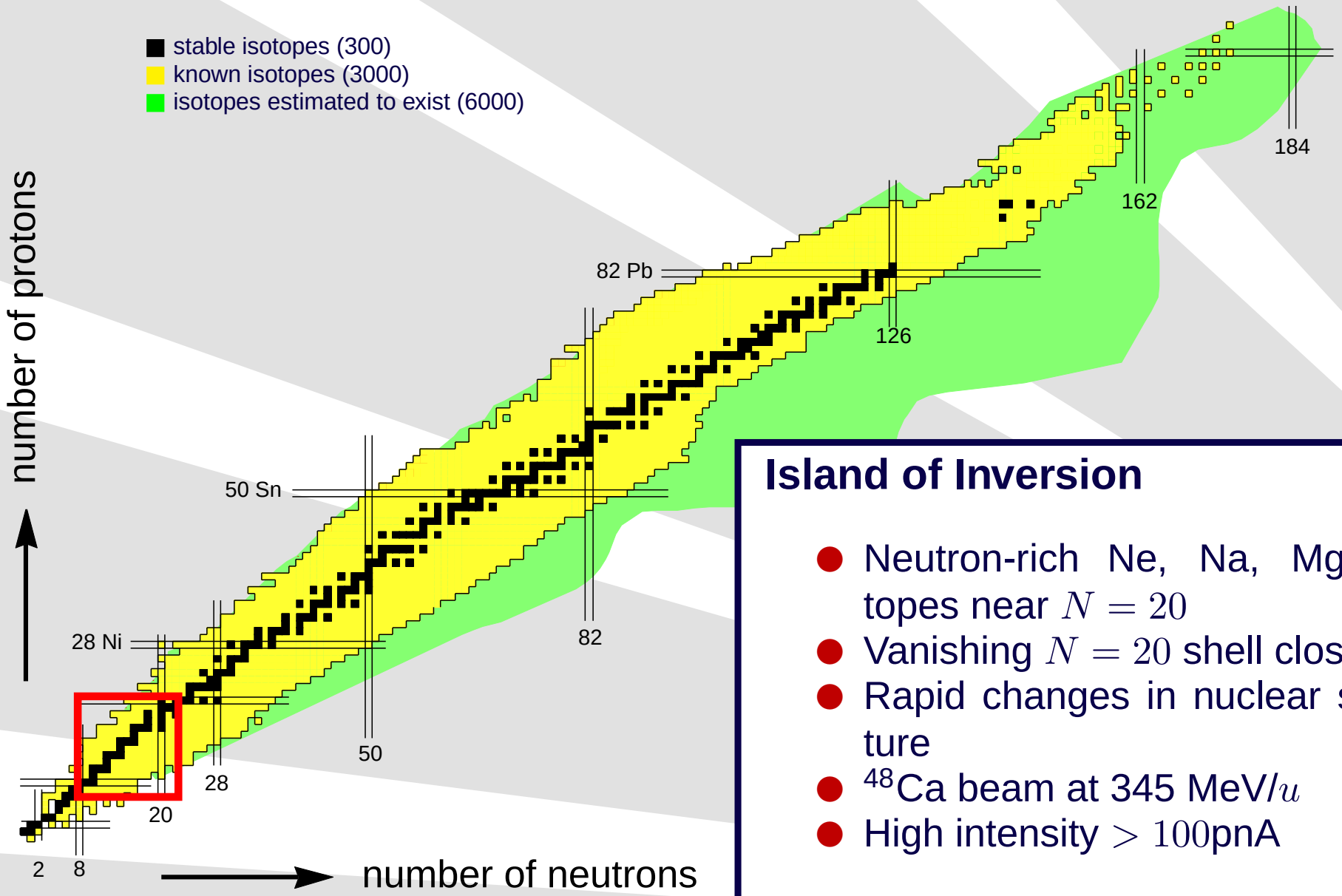
Geomorphometry

From Wikipedia:

Geomorphometry is the science of quantitative land surface analysis. It gathers various mathematical, statistical and image processing techniques that can be used to quantify morphological, hydrological, ecological and other aspects of a land surface. Common synonyms for geomorphometry are geomorphological analysis, terrain morphometry or terrain analysis and land surface analysis. In simple terms, geomorphometry aims at extracting (land) surface parameters (morphometric, hydrological, climatic etc.) and objects (watersheds, stream networks, landforms etc.) using input digital land surface model (also known as digital elevation model) and parameterization software. Extracted surface parameters and objects can then be used, for example, to improve mapping and modelling of soils, vegetation, land use, geomorphological and geological features and similar.

The "Island of Inversion"

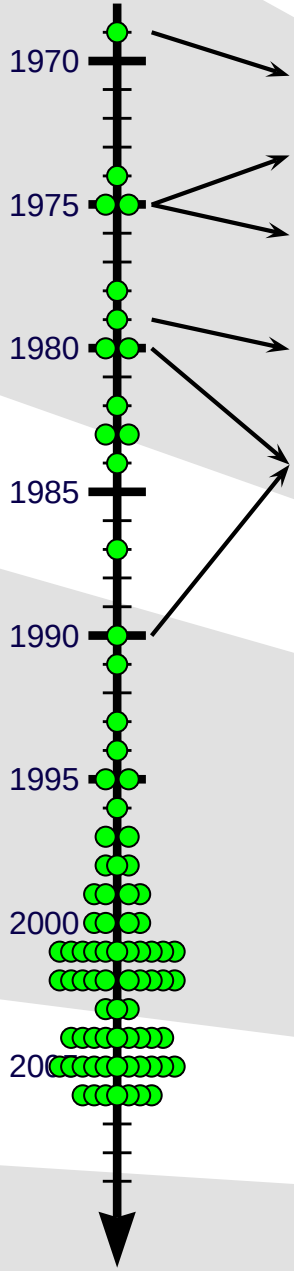
Nuclear Chart



Island of Inversion

- Neutron-rich Ne, Na, Mg isotopes near $N = 20$
- Vanishing $N = 20$ shell closure
- Rapid changes in nuclear structure
- ^{48}Ca beam at 345 MeV/u
- High intensity > 100pnA

Time Line – 1 (1969-1990)

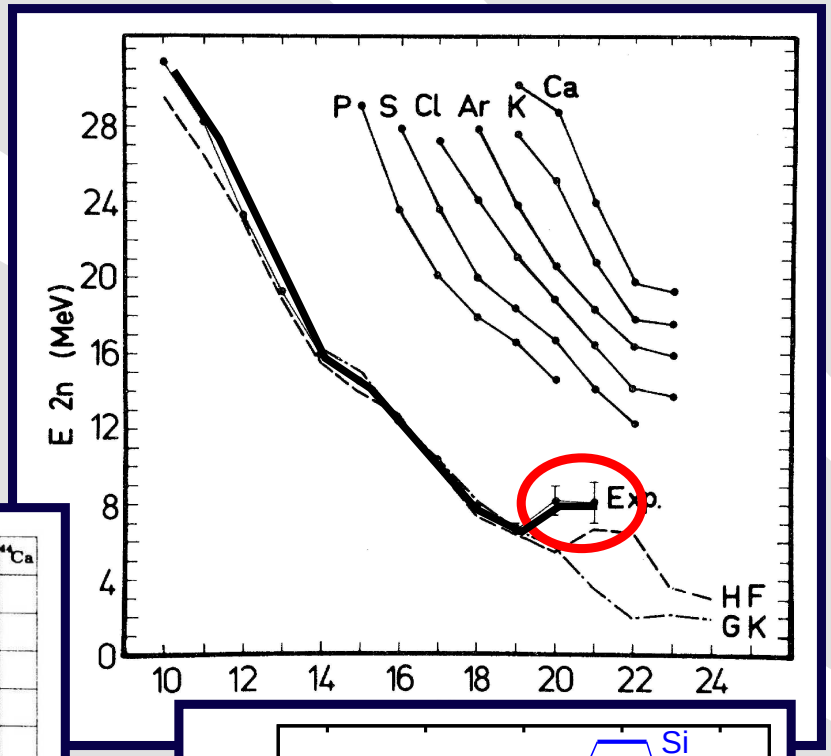


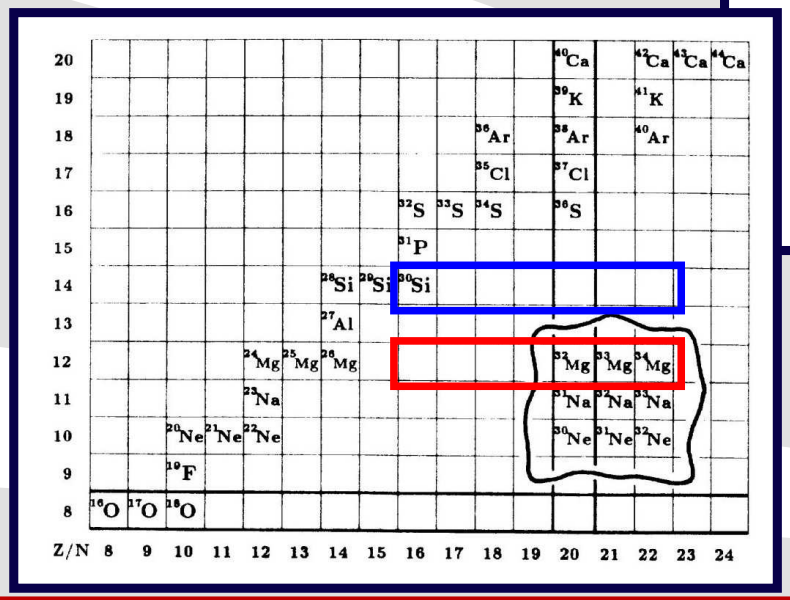
- First observation of $^{27\text{-}32}$Na isotopes R. Klapisch *et al.*, PRL 23, 652 (1969)
- Mass measurement C. Thibault *et al.*, PRC 12, 644 (1975)
- Explanation of "unusual" masses
  X. Campi *et al.*, NPA 251, 193 (1975)
- Low $E(2^+)$ in ^{32}Mg
  C. Dètraz *et al.*, PRC 19, 164 (1979)
- "Island of inversion"

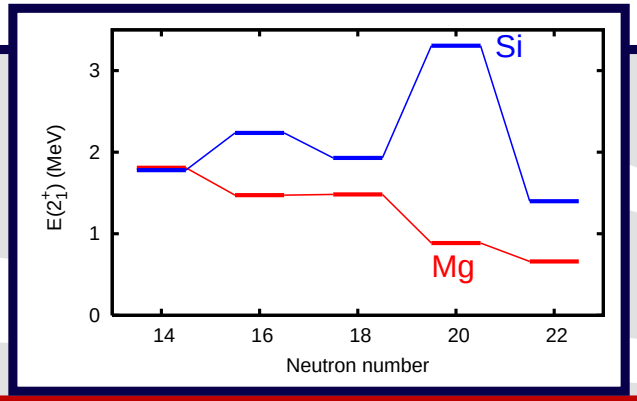
  B.H. Wildenthal, W. Chung, PRC 22, 2260 (1980)

  E.K. Warburton, J.A. Becker, B.A. Brown,

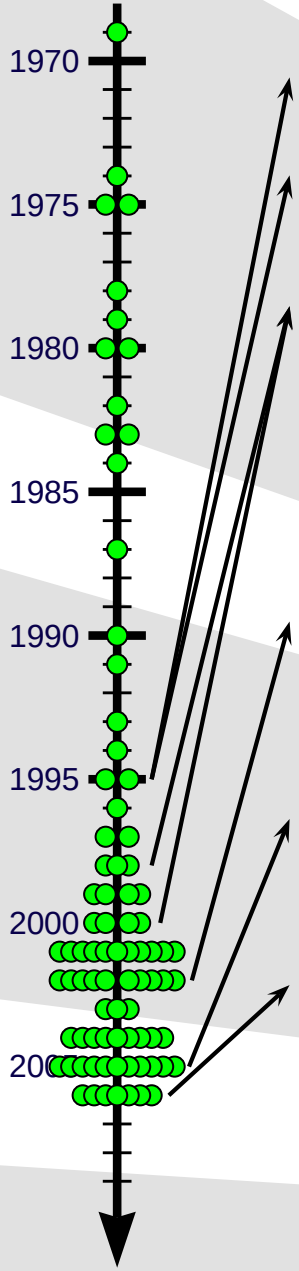
  PRC 41, 1147 (1990)



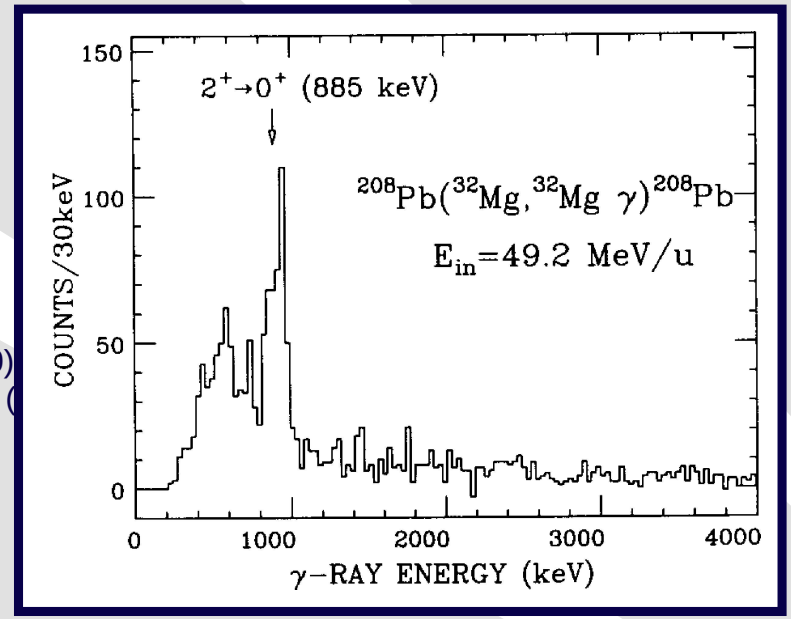




Time Line – 2 (1990-2006)

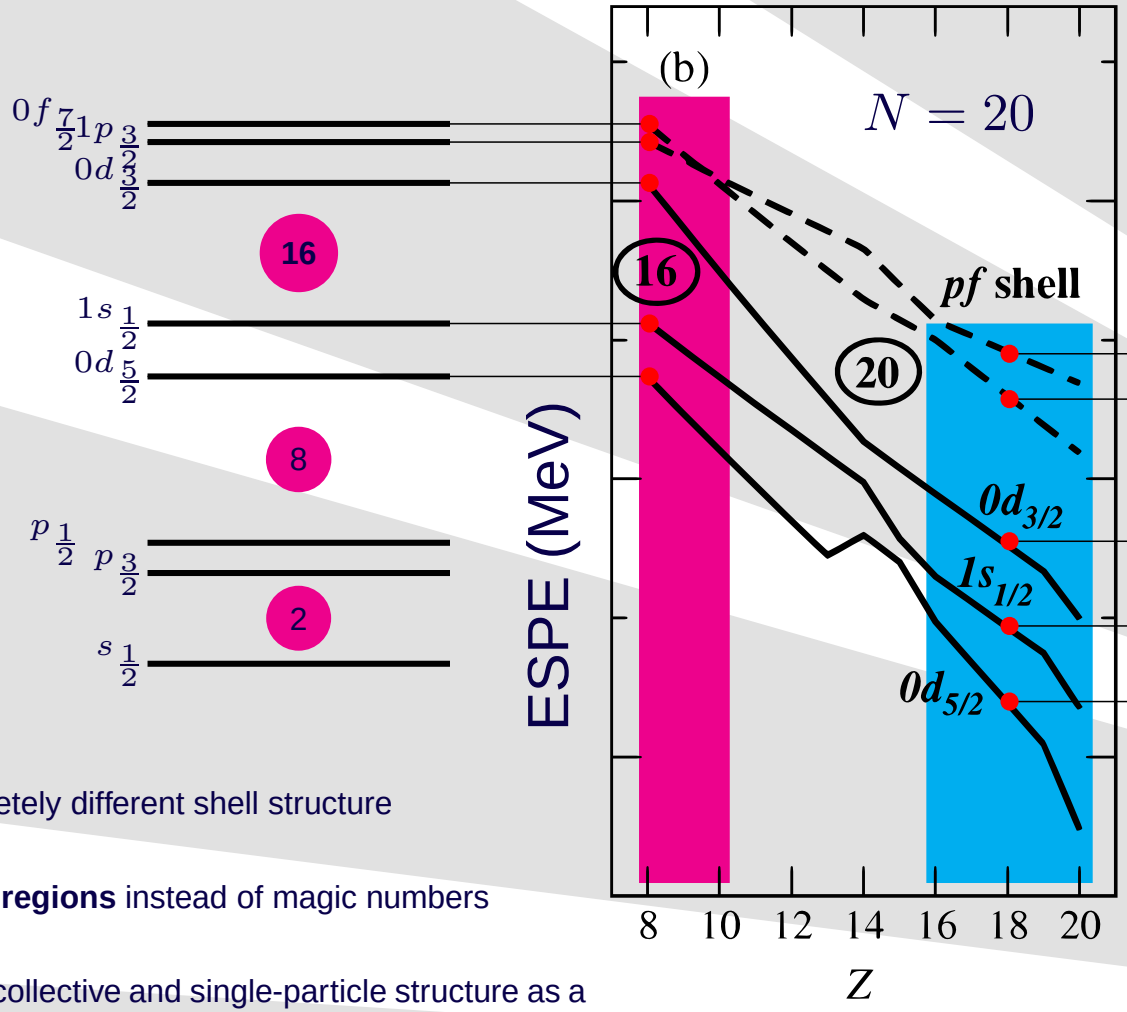


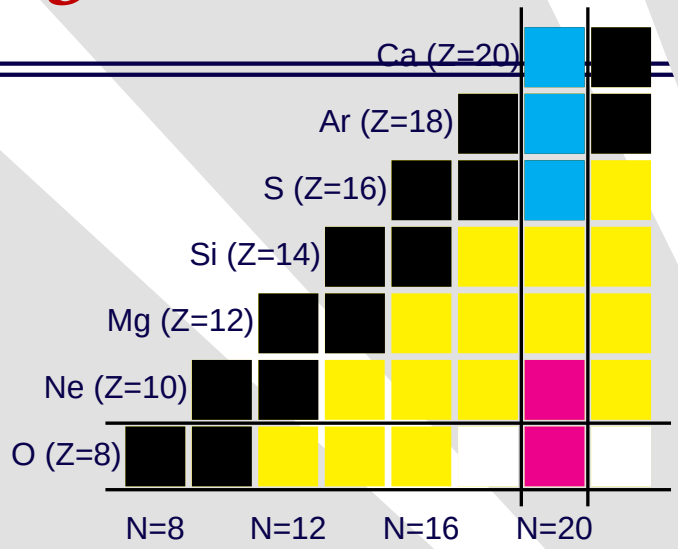
- $B(E2;\ 0^+_{\mathrm{g.s.}} \rightarrow 2^+_1)$ of ^{32}Mg T. Motobayashi *et al.*, PLB 346, 9 (1995)
- Radii of neutr.-rich Na isotopes
  T. Suzuki *et al.*, PRL 75, 3241 (1995)
- New predictions
  SDPF-M:Y. Utsuno *et al.*, PRC 60, 054315 (1999)
  MCSM: T. Otsuka *et al.*, PRL 87, 082502 (2001)
  AMD: M. Kimura, H. Horiuchi, PTP 107, 33 (2002)
  SM: E. Caurier *et al.*, NPA 693, 374 (2001)
  AMPGCM: R. Rodríguez-G. *et al.*, PLB 474, 15 (2000)
  HFB+QRPA: M. Yamagami, N. Giai, PRC 69, 034301 (
- REX-ISOLDE, MINIBALL
  Coulomb excitation, transfer reactions
  with re-accelerated ISOL beams
- ^{31}Mg gs: $J^\pi = \frac{1}{2}^+$
  G. Neyens *et al.*, PRL 94, 022501 (2005)
- New sd-shell interactions (USDA, USDB)
  B. Alex Brown and W. A. Richter, PRC 74, 034315 (2006)



Effective Single Particle Energies

Frontiers and challenges of nuclear shell model
T. Otsuka *et al.*, Phys. Rev. Lett. **87**, 082502 (2001), EPJ A **15**, 151 (2002)

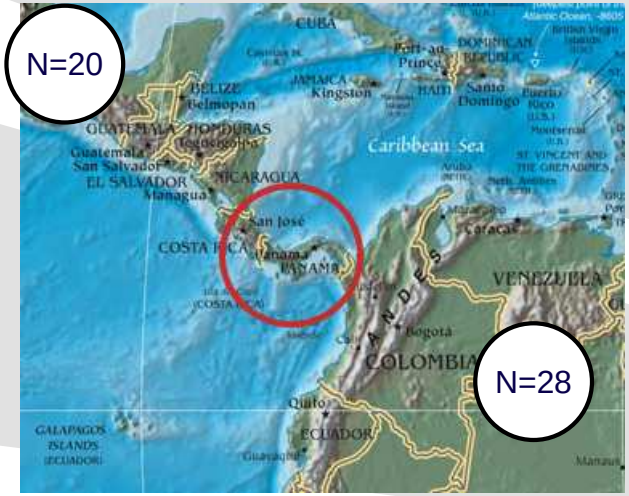




- Completely different shell structure
- **Magic regions** instead of magic numbers
- Study collective and single-particle structure as a function of **isospin**

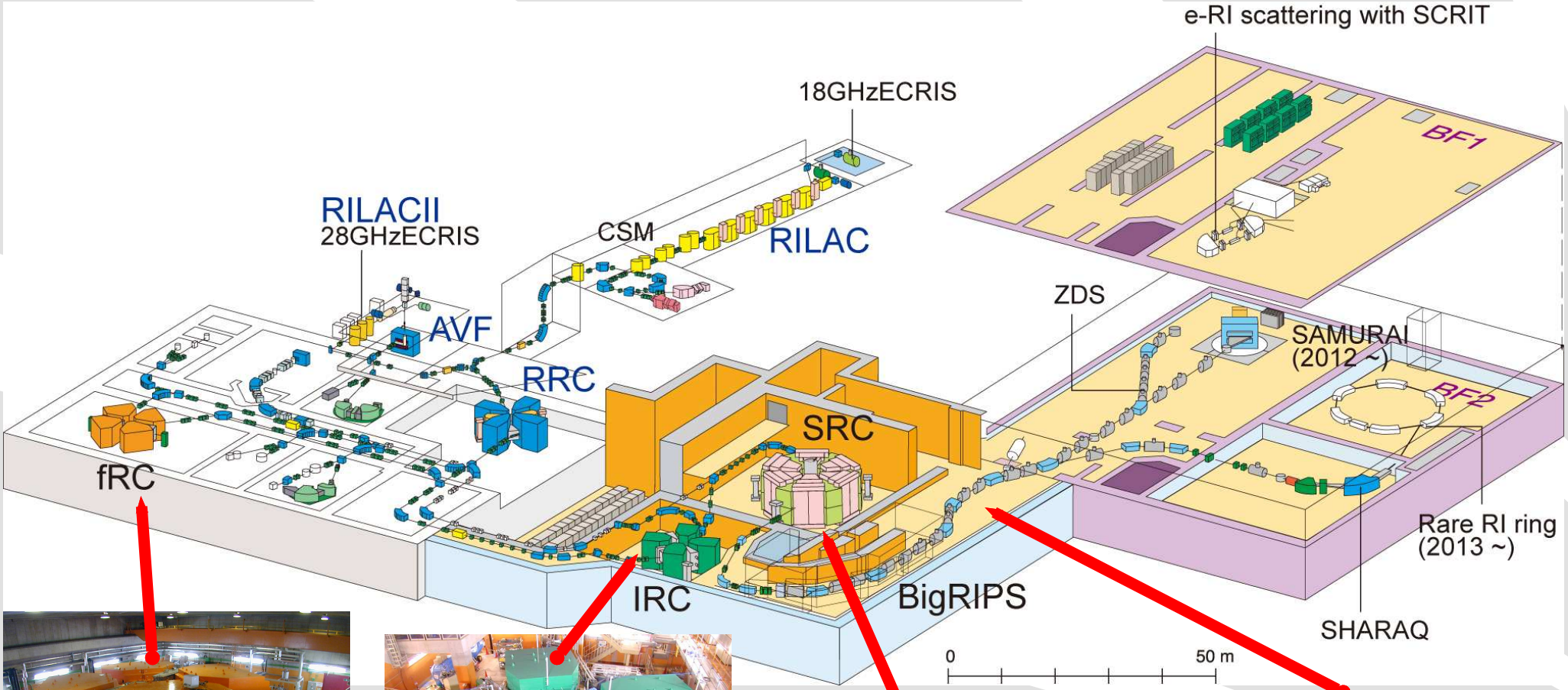
(Nuclear-)morphometric Studies on the "Island of Inversion"

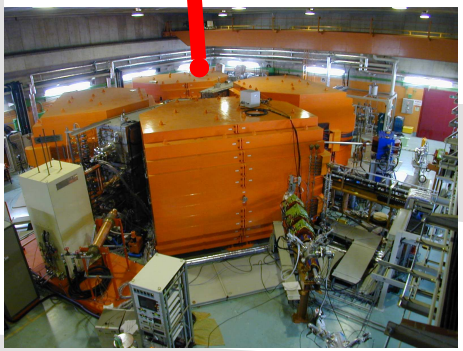
- What are the exact borderlines of the "Island of Inversion"?
  - ❖ Can they be sharply defined?
- Is it an isolated island?
  - ❖ Is there an isthmus to the $N = 28$ shell closure erosion?
- What is the topography of the "Island of Inversion"?

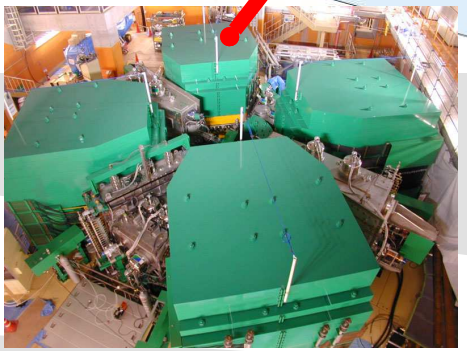


In-Beam γ-Ray Spectroscopy at the RIBF

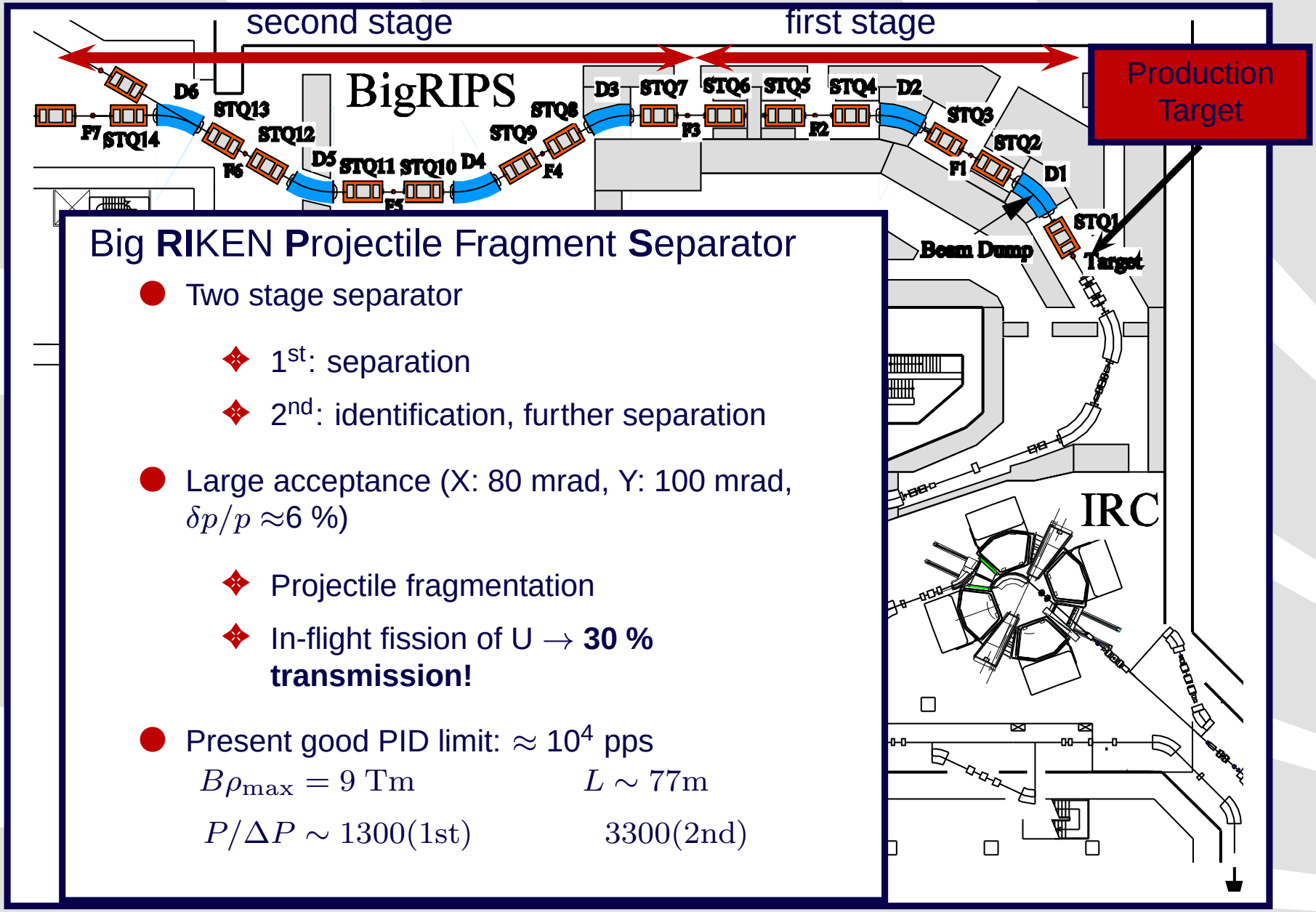
RIBF Overview







BigRIPS Overview



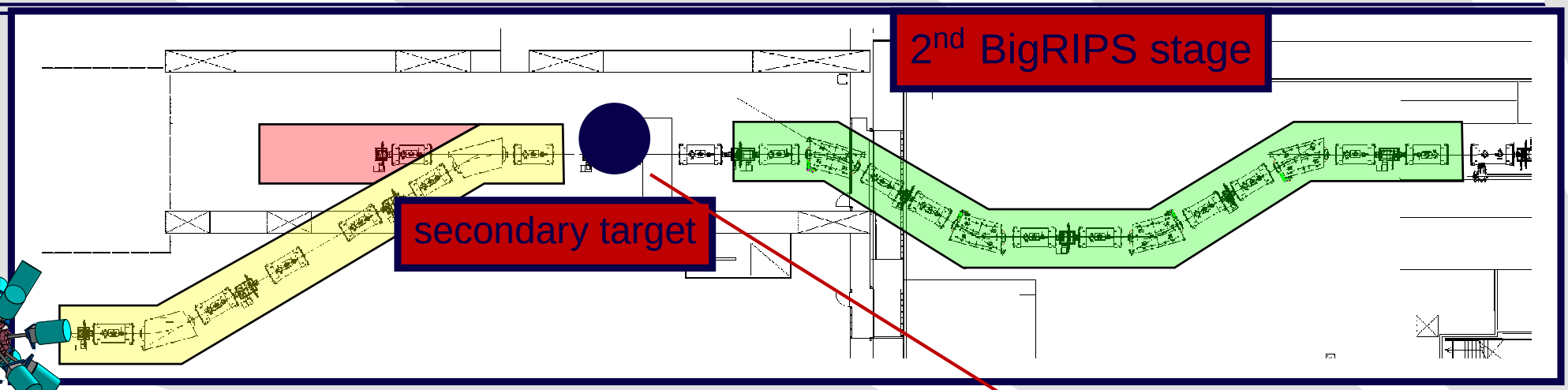
Big **RI**KEN **P**rojectile Fragment **S**eparator

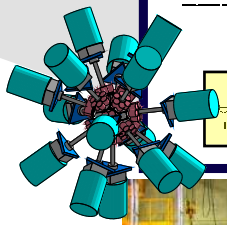
- Two stage separator
  - 1st: separation
  - 2nd: identification, further separation
- Large acceptance (X: 80 mrad, Y: 100 mrad, $\delta p/p \approx$6 %)
  - Projectile fragmentation
  - In-flight fission of U $\rightarrow$ **30 % transmission!**
- Present good PID limit: $\approx 10^4$ pps

$B\rho_{\max} = 9$ Tm $\qquad L \sim 77$m

$P/\Delta P \sim 1300(1\text{st}) \qquad 3300(2\text{nd})$

ZeroDegree Spectrometer





~ 3 m between Q-poles

- DALI2 array, 180 (186) NaI(Tl)
- GRAPE HPGe array
- $E_{\text{beam}} \sim 100 - 250$ MeV/u

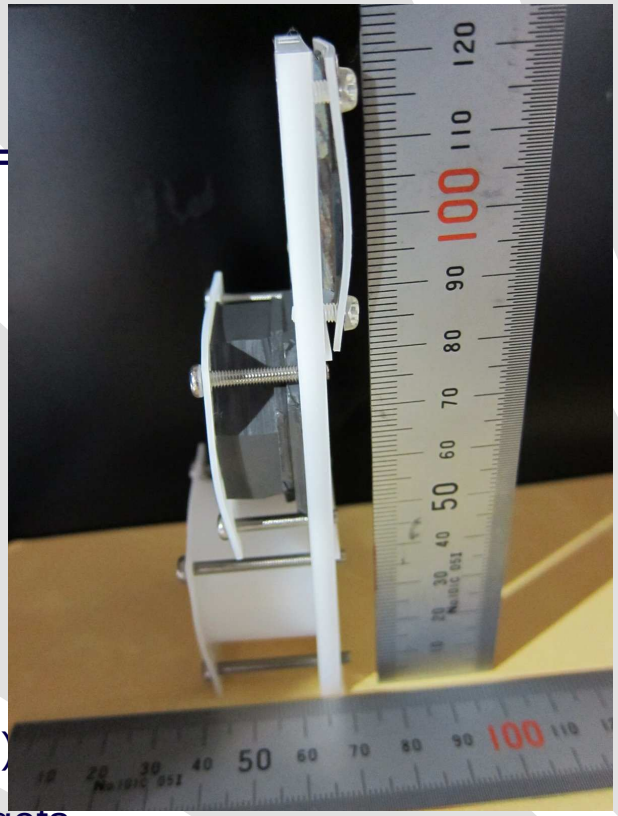
0° Spectrometer ZeroDegree

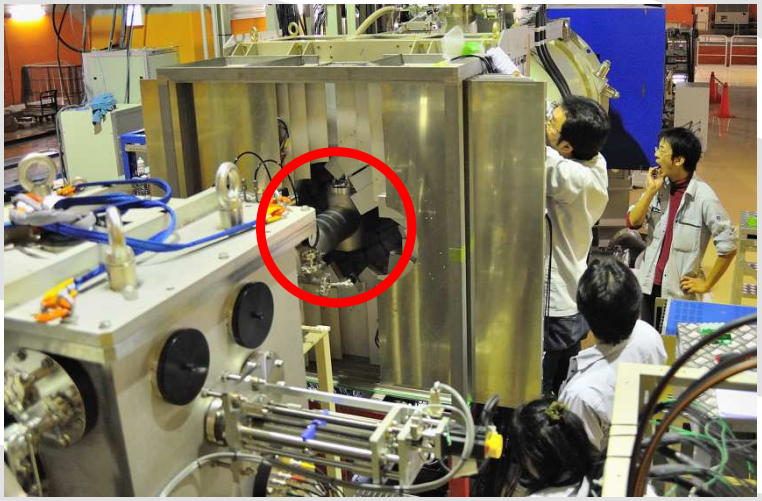
- **Particle ID** after secondary target
- Fragment momentum distribution
- Various modes of operation

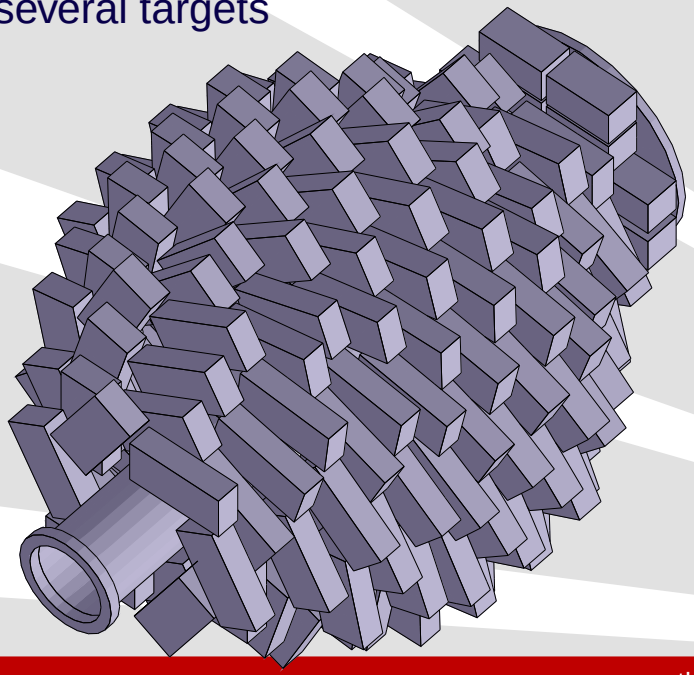
mode	$p/\Delta p$	Δp	Ang. Accep.
Large Accep.	1240	$\pm 3\%$	± 45 mrad(V) ± 30 mrad
High res.(achrom)	2120	$\pm 3\%$	± 20 mrad(V) ± 30 mrad(H)
Dispersive	4130	$\pm 2\%$	± 20 mrad(V) ± 30 mrad(H)

DALI2 (2008)

- 180 NaI(Tl) detectors
- ϑ coverage 11° to 165°
- Crystals of large volumes
  $\rightarrow$ large angular coverage per crystal
- $\Delta E/E \approx$**10(11) % (FWHM) at 100(250) MeV/**u
- $\approx$ **20% FEP efficiency at 1 MeV**
- Thick secondary targets
- S. Takeuchi *et al.*, RIKEN Pr. Rep. 36, 148 (2003)
- “Sophisticated” beam pipe containing several targets







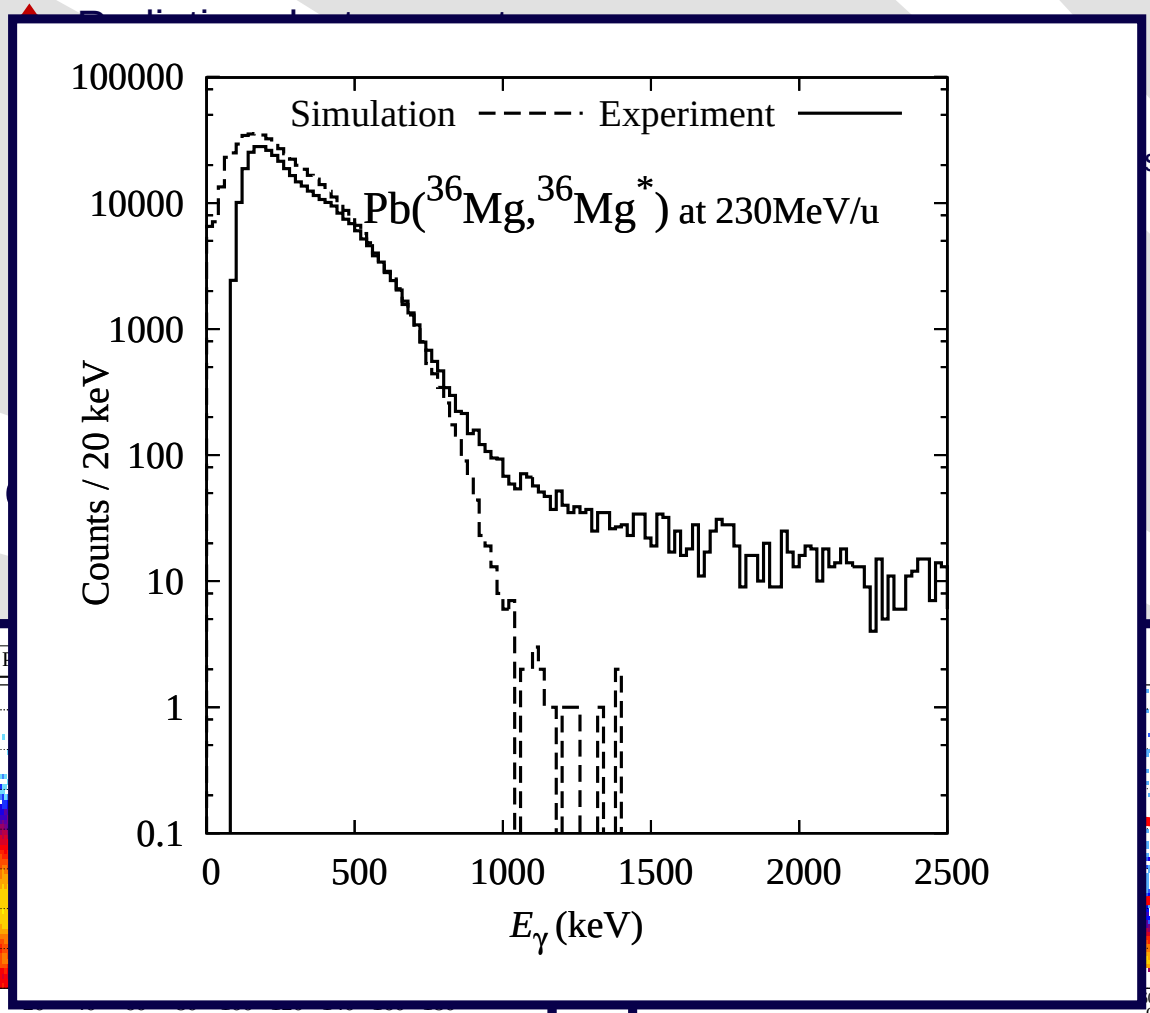
Atomic Background

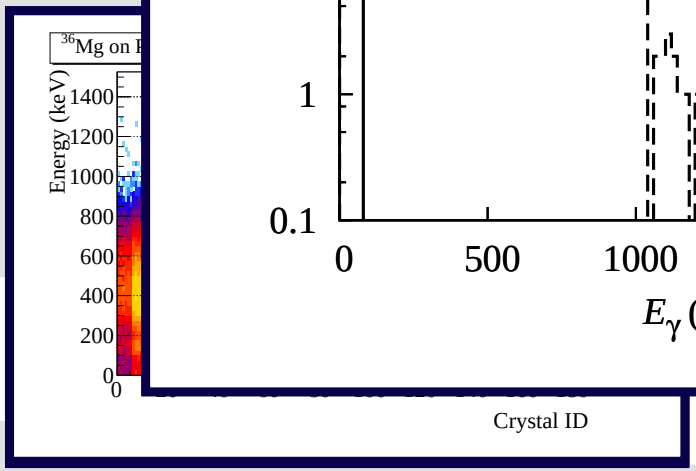
- Components of radiation

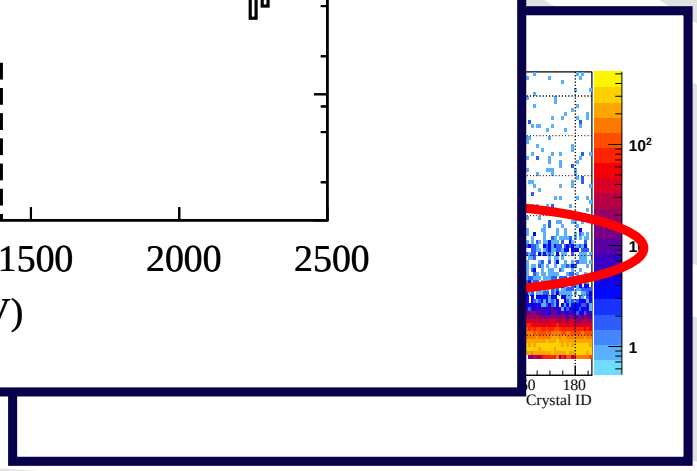
of the projectile)

s of the projectile)

- M







Experimental Results

DayOne Campaign (Dec. 2008)

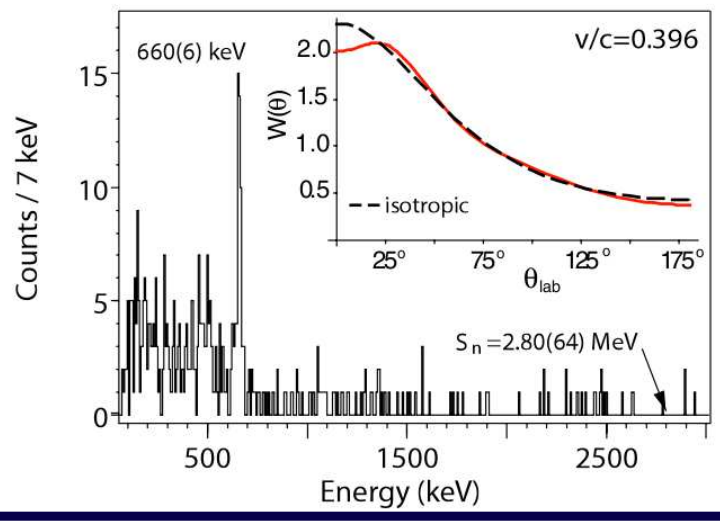
- High intensity ^{48}Ca primary beam $\approx$ 100 pnA
- several independent experimental setups
- Reaction Cross Sections (Ohtsubo *et al.*)
  - $^{29\text{-}32}$Ne, $^{30\text{-}34}$Na — 3 days
- Coulomb Breakup (Nakamura *et al.*)
  - ^{31}Ne, ^{19,20,22}C — 2.5 days
- γ-ray Spectroscopy (Scheit *et al.*)
  - ^{32}Ne — 12 hours
- γ-ray Spectroscopy (Takeuchi *et al.*)
  - ^{42}Si — cancelled

A Closer Look at the "Island of Inversion"

$Z = 14$

$Z = 12$

$Z = 10$



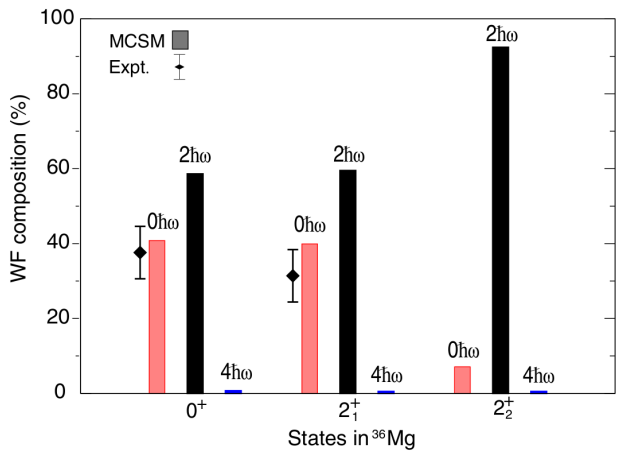
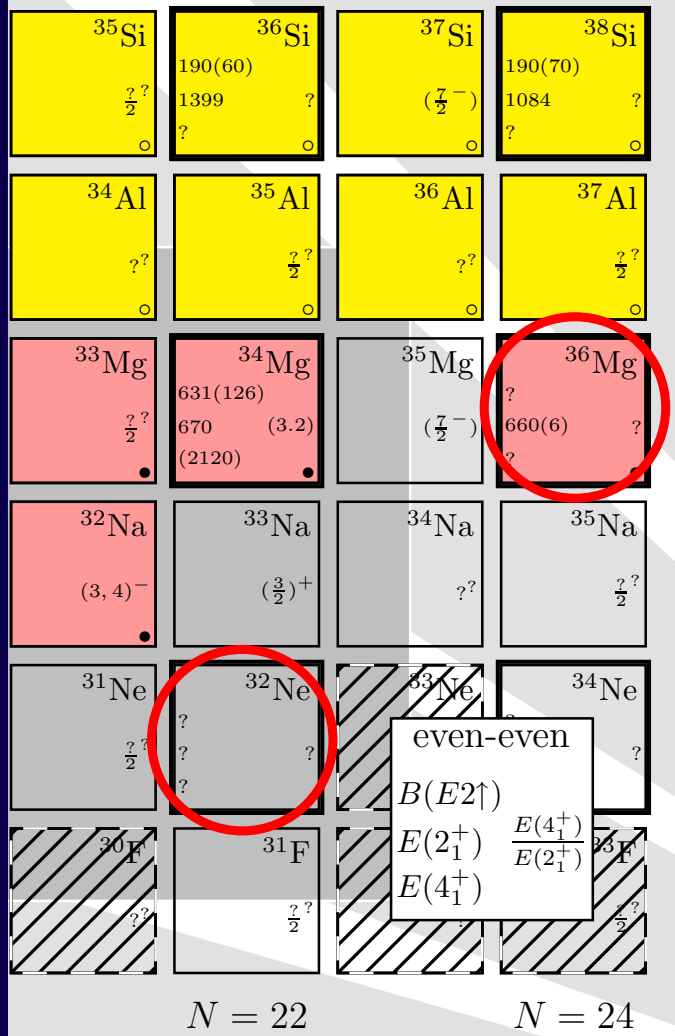
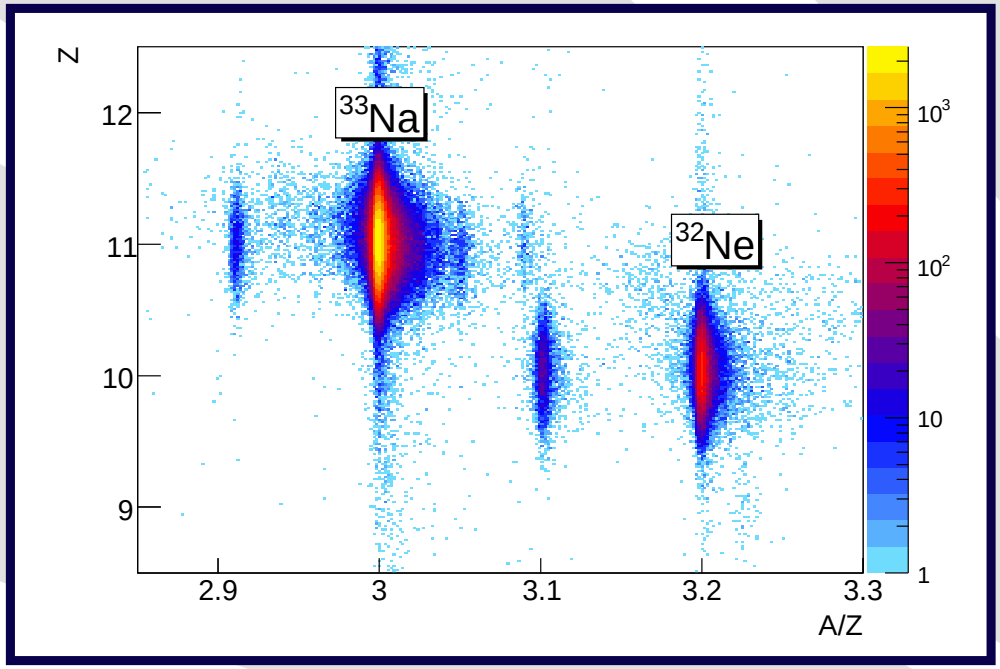


FIG. 3 (color online). Composition of the wave functions (WF) of the lowest-lying states of ^{36}Mg with respect to $n\hbar\omega$ components according to the MCSM calculation.



Prediction by E. K. Warburton *et al.*, Phys. Rev. C **41**, 1147 (1990)
A. Gade *et al.*, PRL **99**, 072502 (2007)

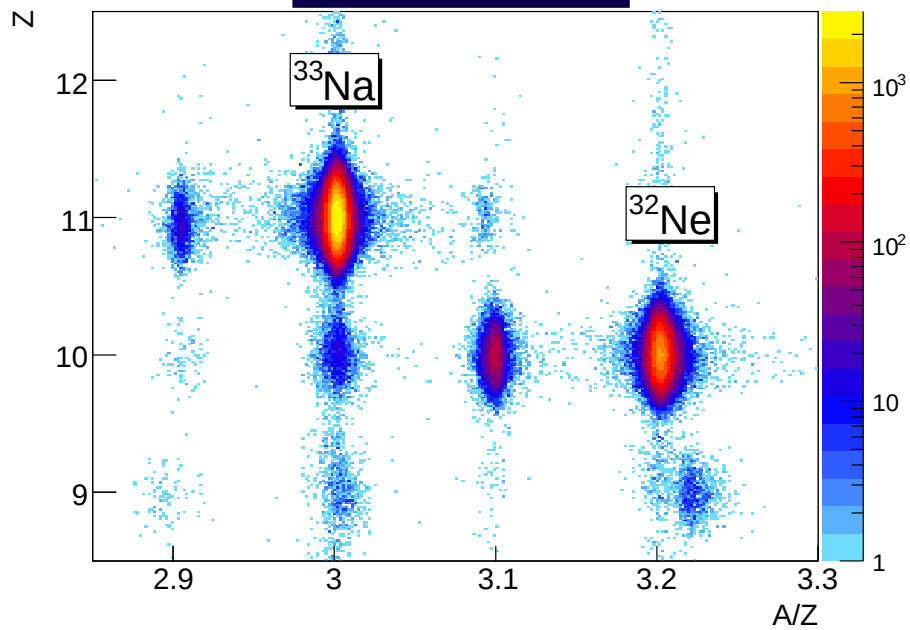
DayOne (Dec. 2008)
PID in Front of Secondary Target



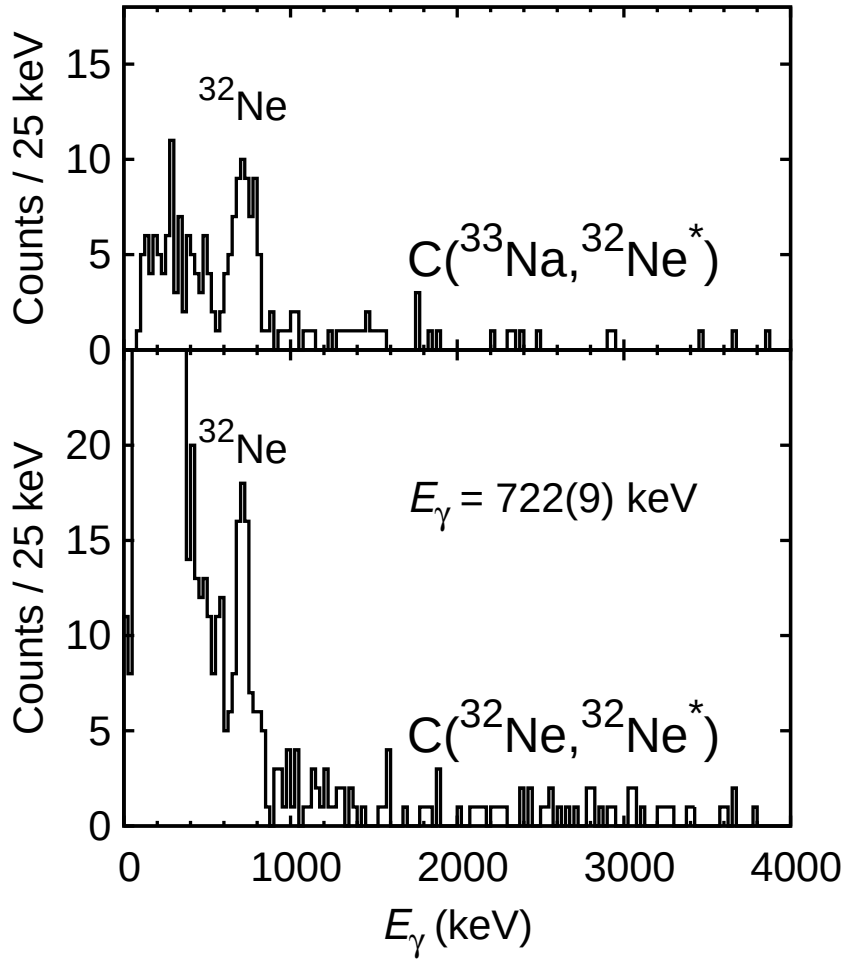
- $\Delta E - B\rho -$TOF method
  - ❖ $Z \propto \Delta E$ $\Delta Z = 0.5$ (FWHM)
  - ❖ $A/Q \propto$ TOF $\Delta A = 0.06$ (FWHM)
- ^{32}Ne: 6/s $E \approx 230$ MeV$/u$
- ^{33}Na: 30/s

PID Behind Target and γ-ray Spectra

PID after F8



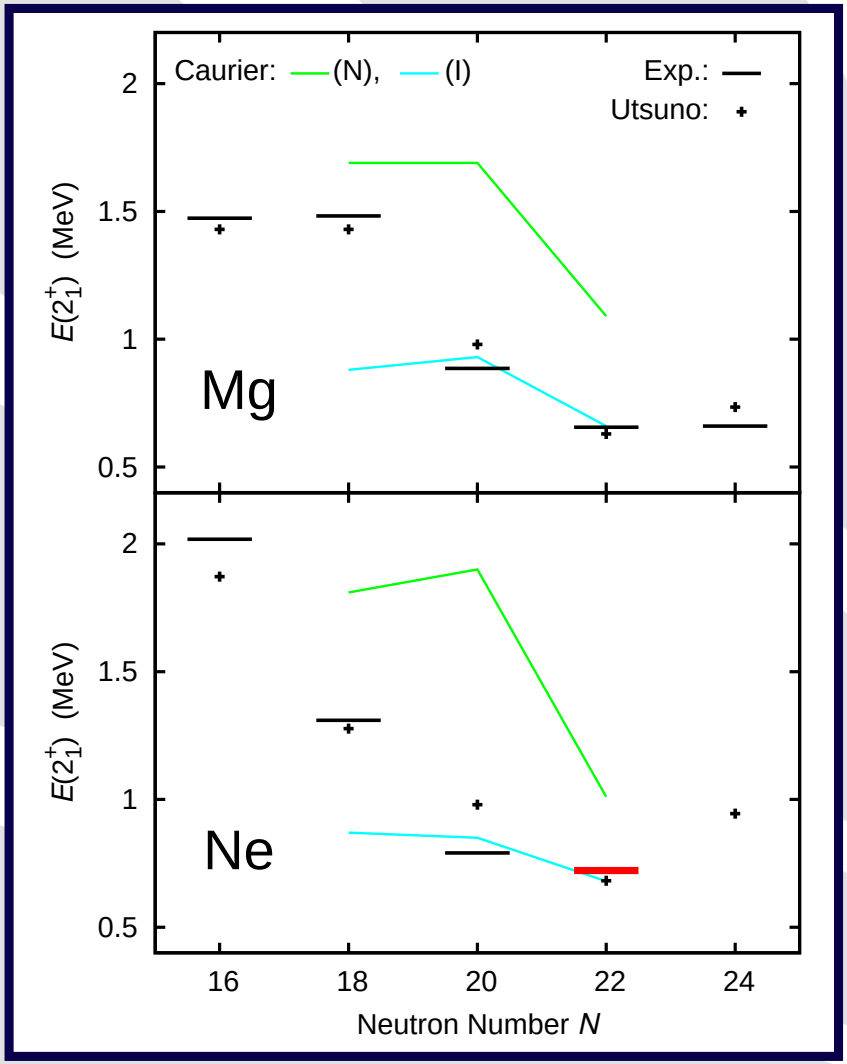
Doppler corrected γ-ray energy



- C(^{32}Ne,^{32}Ne*), C(^{33}Na,^{32}Ne*)
- ^{32}Ne: 6 pps, 230 MeV/u
- F8 target: $^{nat.}$C (2.54 g/cm^2) for Day-One
- DALI2 array: 180 NaI(Tl) detectors
- total data taking: **8 hours**

$E(2^+)$ as Function of N

- lowest $E(2^+)$ of Ne isotopes
- very good agreement with Utsuno *et al.*, PRC 60, 054315 (1999)
- very good agreement with Intruder calculation of Caurier *et al.*, NPA 693, 374 (2001)
- ^{32}Ne belongs to the "Island of Inversion"



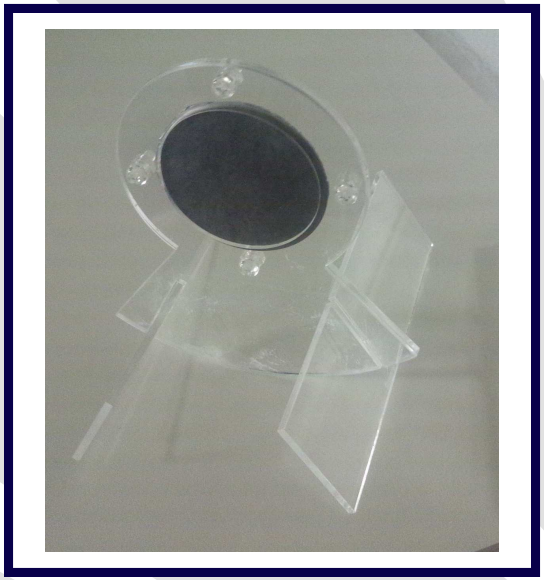
P. Doornenbal, H. Scheit *et al.*
Phys. Rev. Lett. 103, 032501 (2009)
arXiv:0906.3775

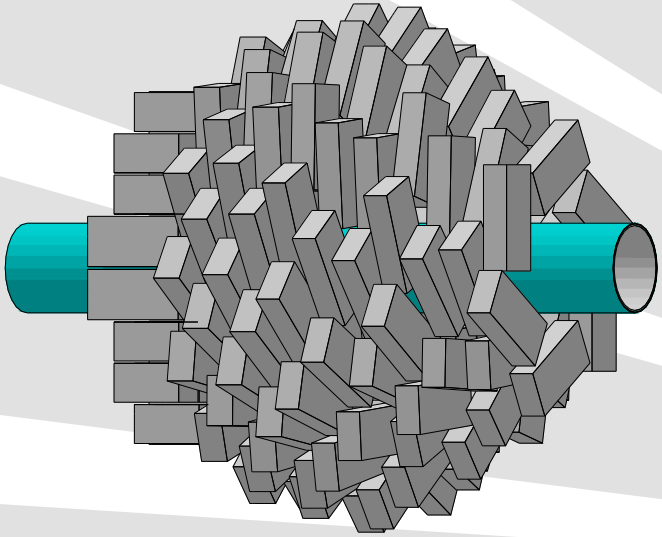
Sunday ^{48}Ca (Nov./Dec. 2010)

- **H. Scheit *et al.*, 9.5 days → 3 days**
  - $B(E2)\uparrow$: $^{(26,28),30(,32)}$Ne, $^{(34),36(,38)}$Mg
  - $E(2_1^+)$: ^{38}Mg
  - $E(4_1^+)$: $^{(32)}$Ne, ^{36,38}Mg
  - M_n/M_p: $^{30(,32)}$Ne, $^{(34,)36}$Mg
  - 1n knockout of $^{(26,28),30(,32)}$Ne, $^{(34),36}$Mg
- P. Fallon *et al.*, 3(+3) days → 1 day
  - $E(2_1^+)$: ^{40}Mg
- S. Takeuchi *et al.*, 6 days → 3.5 days
  - $E(4_1^+)$: ^{38,40,42}Si
- D. Bazin *et al.*, 4 days
  - Single nucleon knockout towards ^{33}Mg
- T. Nakamura *et al.*, 4.5 days
  - Search for halo nuclei
- M. Takechi *et al.*, 6 days → 4 days
  - Total interaction cross-sections of neutron rich Mg isotopes

DALI2 (2010–to Present)

- Changed configuration of forward angle detectors
- Included DALI1 crystals
- 186 NaI(Tl) detectors
- ϑ coverage 11° to 165°
- $\Delta E/E \approx$**10(11) % (FWHM) at 100(250) MeV/**u
- $\approx$ **20% FEP efficiency at 1 MeV**
- Simplified target holder and beam pipe, 1mm Pb (+1mm Sn) shielding



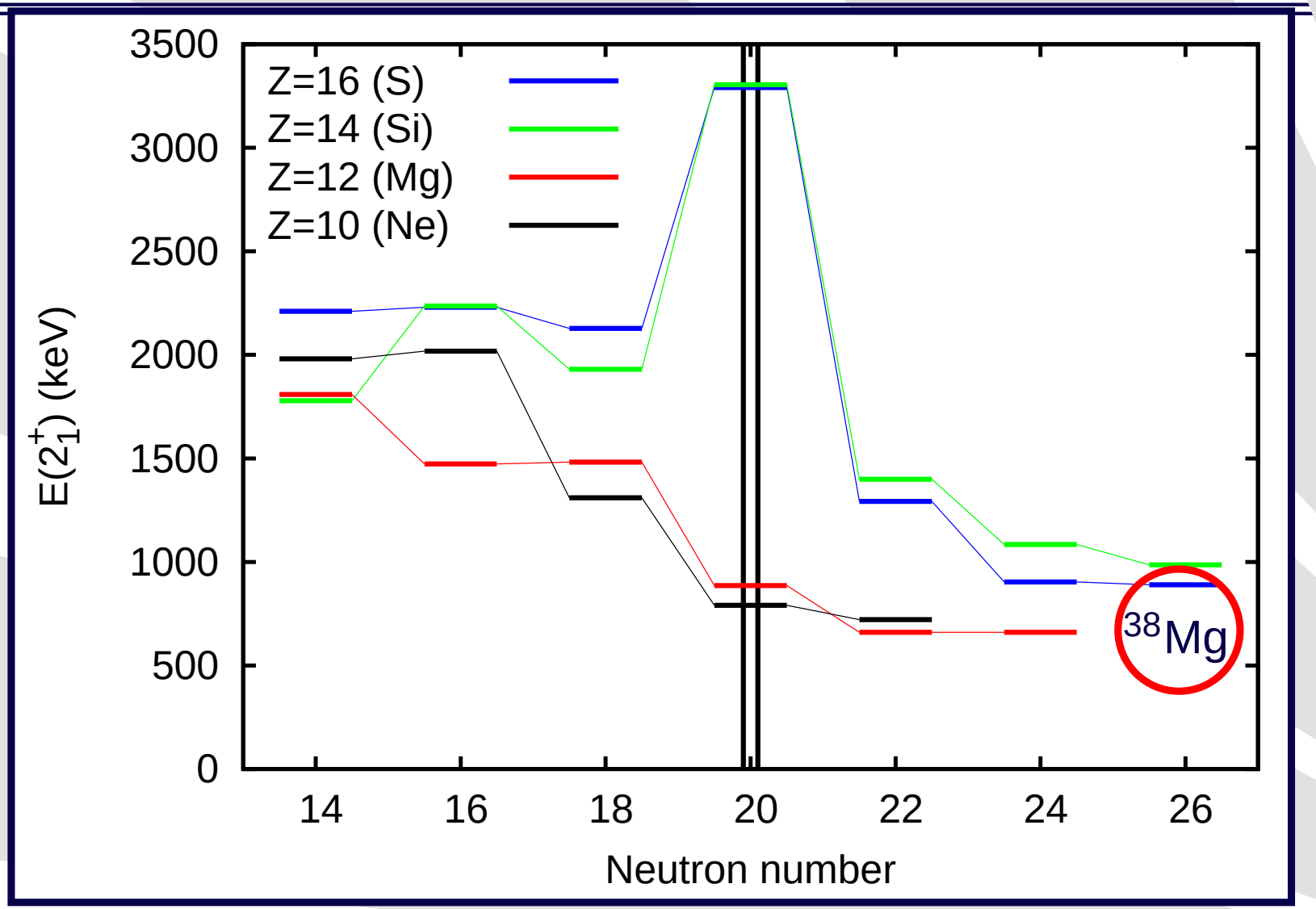


Experimental Settings

- 2.54 g/cm^2 C, 2.13 g/cm^2 CH_2, and 3.37 g/cm^2 Pb targets
- About one hour to change target + stationary source calibration

Setting	Measuring Time/h
C(^{40}Si,^{38}Mg)	15
C(^{36}Mg,^{36}Mg)	6
C(^{36}Mg,^{35}Mg)	9
CH_2(^{36}Mg,^{36}Mg)	5
Pb(^{36}Mg,^{36}Mg)	15
Pb(^{30}Ne,^{30}Ne)	5
C(^{30}Ne,^{30}Ne)	3
C(^{30}Ne,^{29}Ne)	3
C(^{30}Ne,^{29}F)	3
CH_2(^{30}Ne,^{30}Ne)	2
total	66

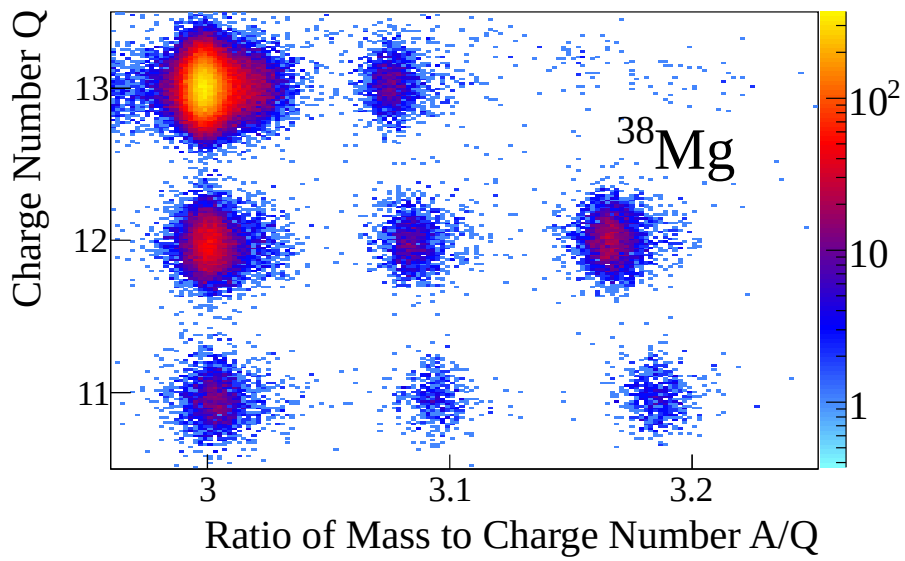
$E(2_1^+)$-Systematics



- $E(2^+)$ is a qualitative indicator of "magicity"
- a more quantitative indicator is the $B(E2)\uparrow$ value

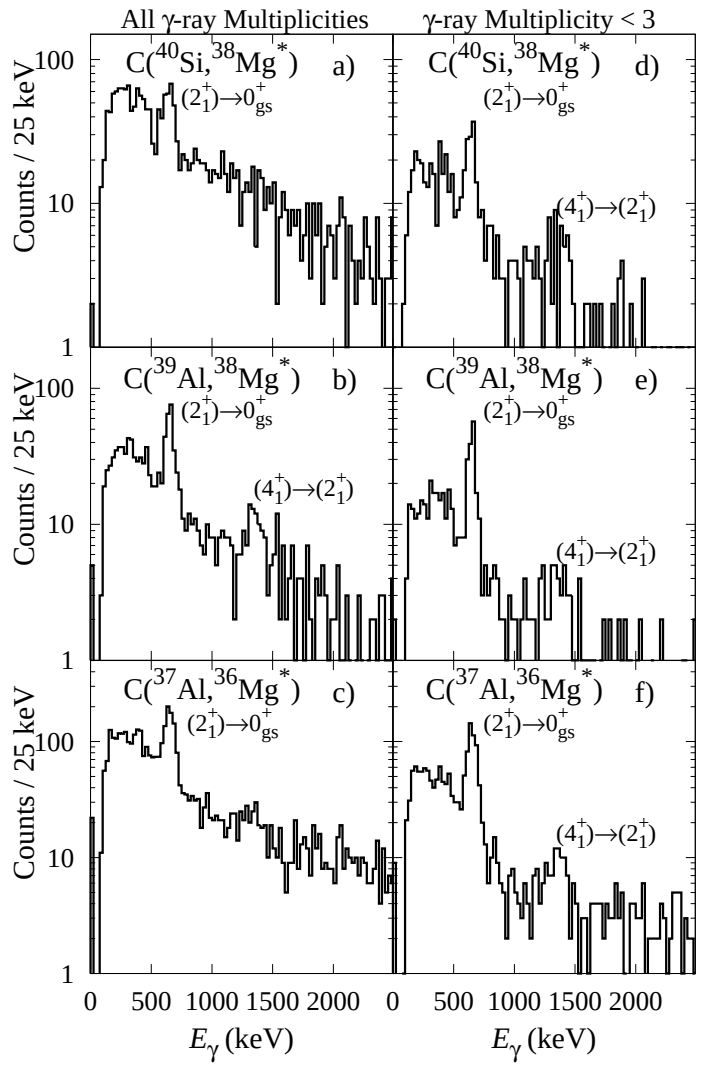
In-Beam γ-ray Spectroscopy of ^{36,38}Mg

Particle identification behind target

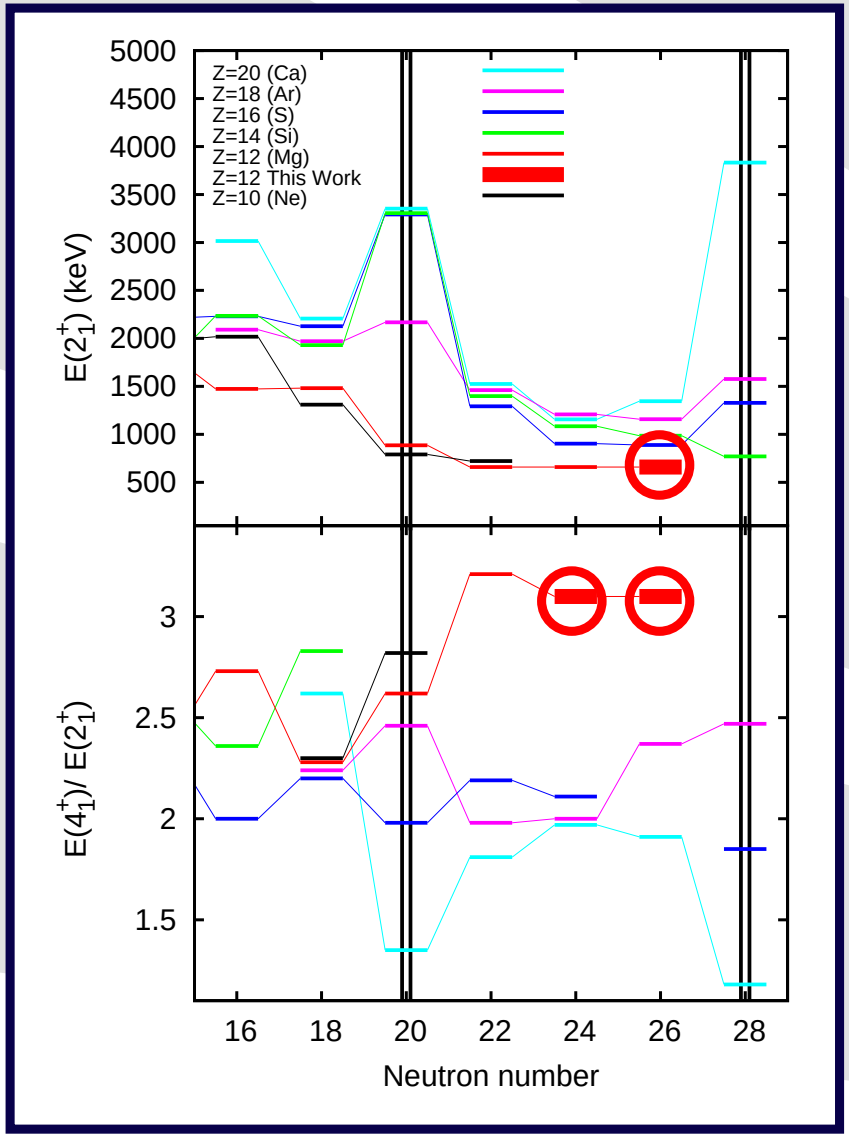


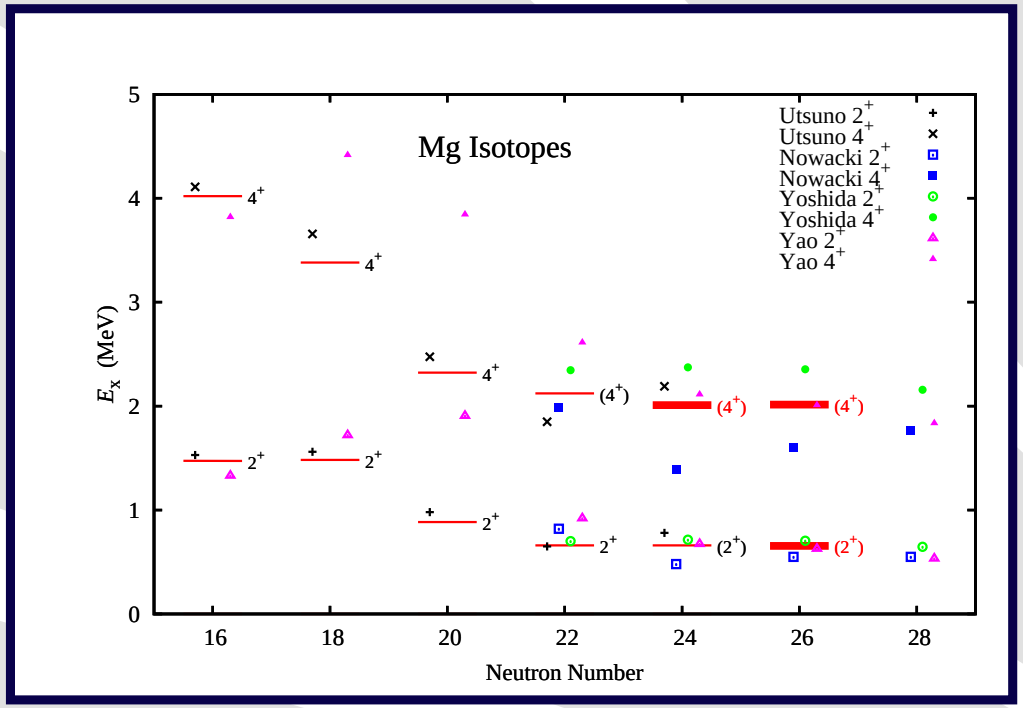
- ^{48}Ca, 70 pnA primary beam
- C(^{40}Si,^{38}Mg*), C(^{39}Al,^{38}Mg*)
- F8 target: $^{nat.}$C, 2.54 g/cm^2
- ^{40}Si: 3000 pps, 230 MeV/u
- ^{39}Al: 110 pps, 220 MeV/u
- **15 hours data taking**
- ^{38}Mg $E(2_1^+)$ 655(6) keV
- $E(4_1^+)/E(2_1^+) \approx 3$

Doppler corrected γ-ray energy



2_1^+ Level and $E(4_1^+)/E(2_1^+)$ ratio Systematics in $sd-pf$ shell





^{32}Mg 4$^+$: S. Takeuchi *et al.*, Phys. Rev. C 79, 054319 (2009)
^{34}Mg: K. Yoneda *et al.*, Phys. Lett. B 499, 233 (2001)

SDPF-M: Y. Utsuno *et al.*, Phys. Rev. C 60, 054315 (1999)
SDPF-NR $(0\hbar\omega)$: F. Nowacki and A. Poves, Phys. Rev. C 79, 014310 (2009)
Skyrme-QRPA: K. Yoshida, Eur. Phys. J. 42, 583 (2009)
3DAMP+GCM: J. M. Yao *et al.*, Phys. Rev. C 83, 014308 (2011)

Structure of neutron-rich Fluorine Isotopes

sd-shell Interactions

USD, 1984

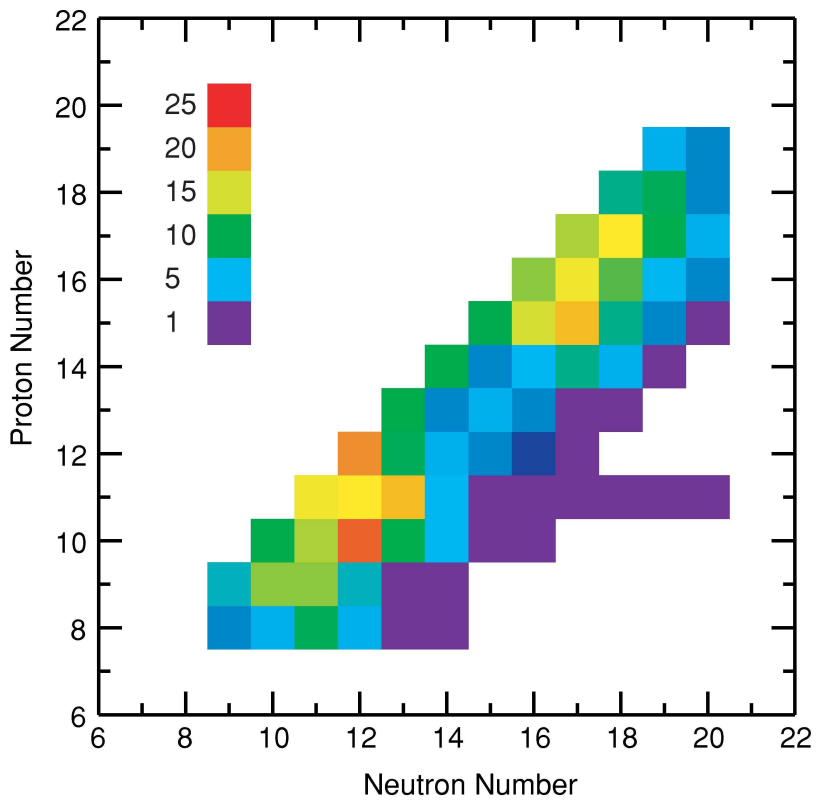


FIG. 1. (Color) Number of states used for the USD Hamiltonian for each nucleus.

USDB, 2006

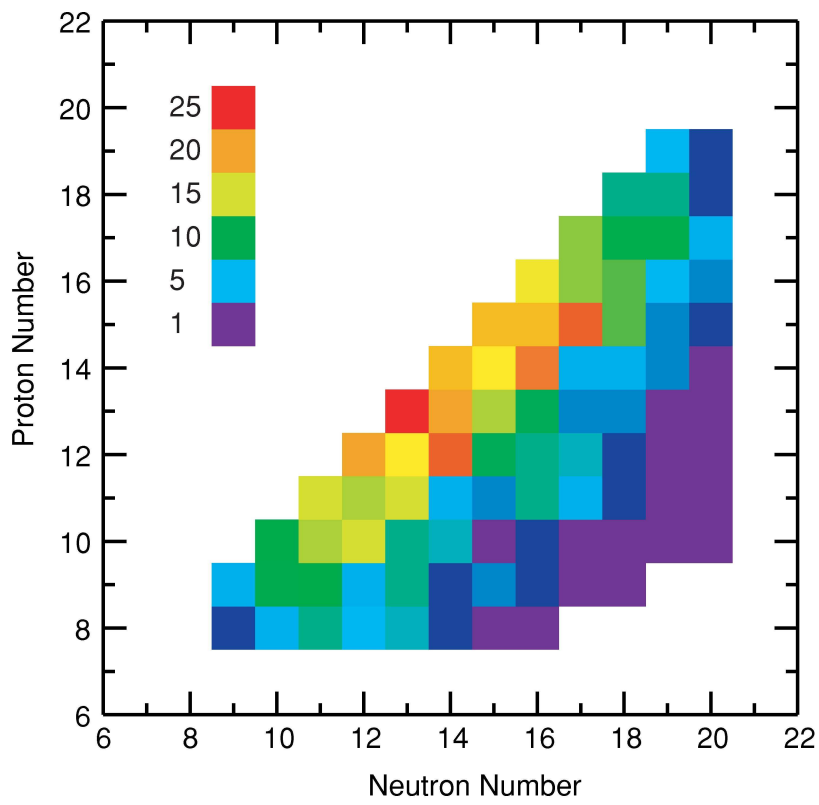


FIG. 2. (Color) Number of states used for the USDA and USDB Hamiltonians for each nucleus.

B. H. Wildenthal, Prog. Part. Nucl. Phys. 11, 5 (1984)
B. Alex Brown and W. A. Richter, Phys. Rev. C 74, 034315 (2006)

sd-shell Interactions II

USD, 1984

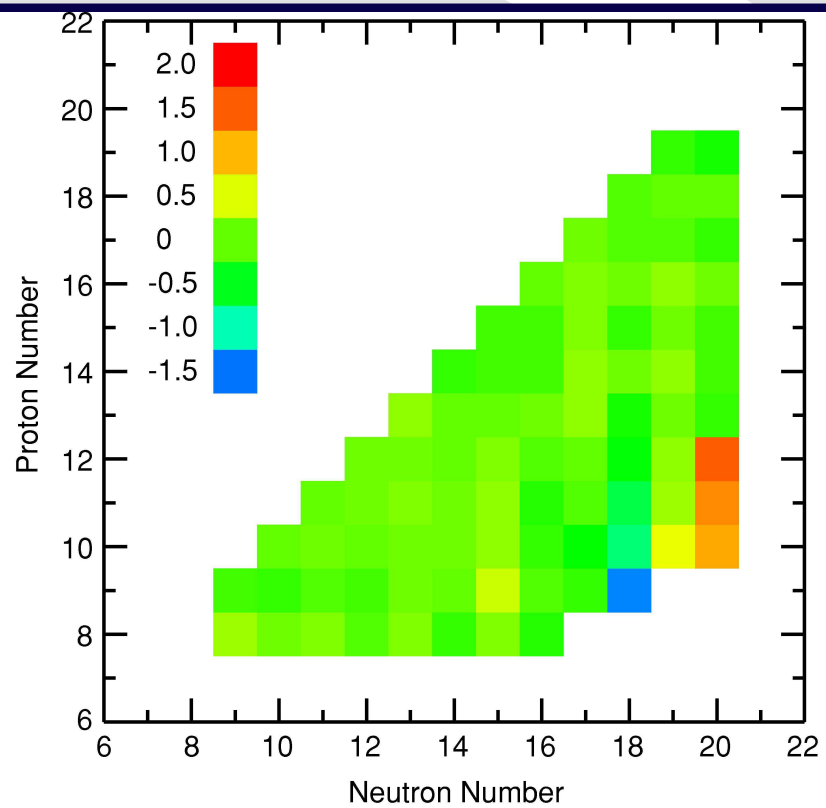
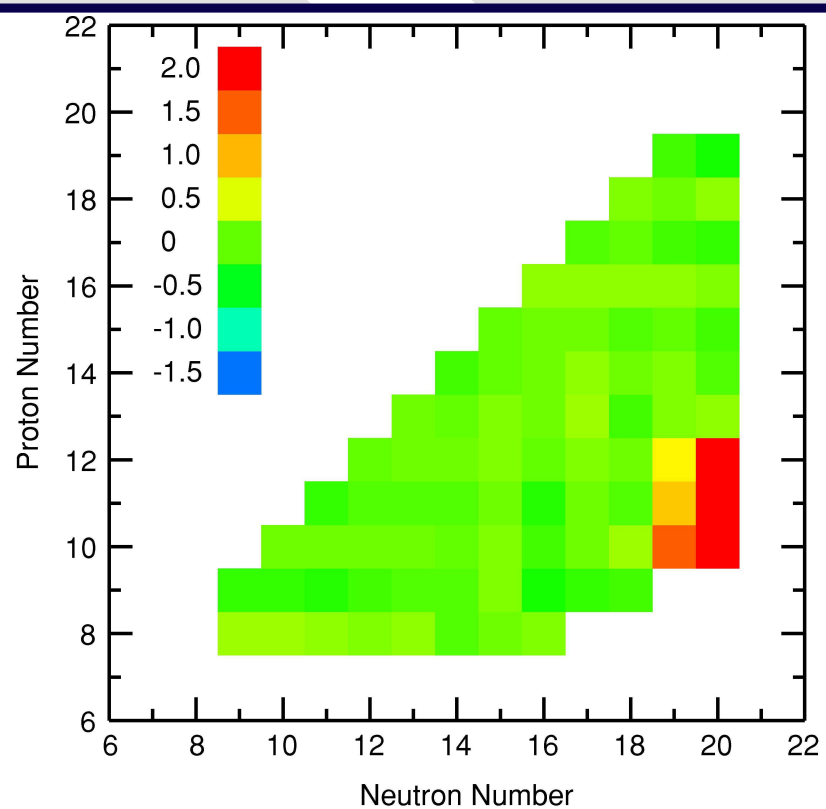


FIG. 9. (Color) Difference between the experimental and theoretical (USD) ground-state binding energies. A positive value indicates that experiment is more bound than theory.

USDB, 2006

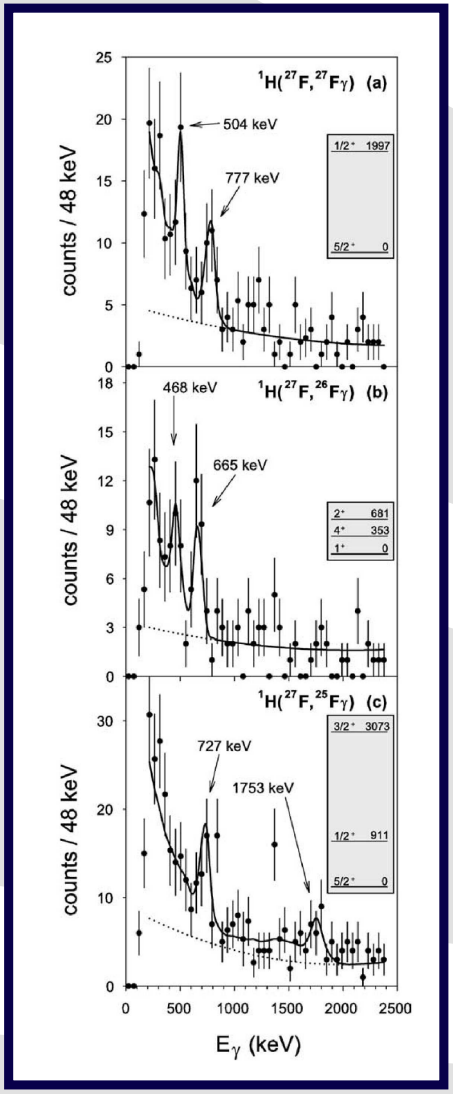


"However, the $Z = 10 - 12$, $N = 20$ difference cannot be corrected, confirming the intruder state (island-of-inversion) interpretation for these nuclei. Although ^{28,29}F appear to lie outside of the island of inversion, they have large experimental errors (0.5–0.6 MeV) and they were thus not included in the fit."

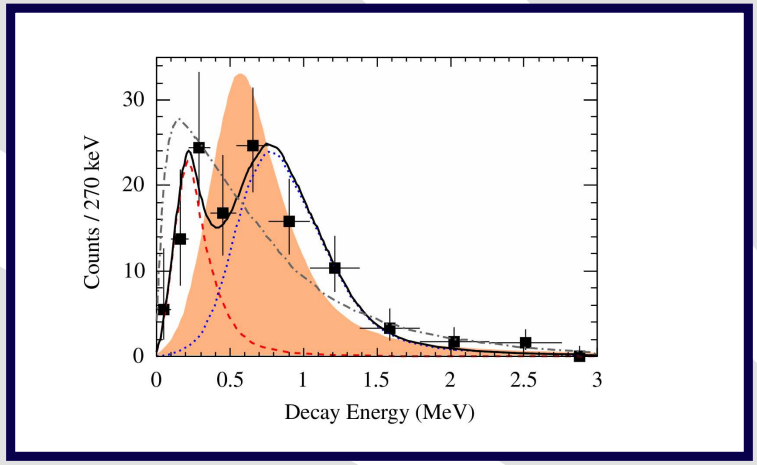
B. H. Wildenthal, Prog. Part. Nucl. Phys. 11, 5 (1984)
B. Alex Brown and W. A. Richter, Phys. Rev. C 74, 034315 (2006)

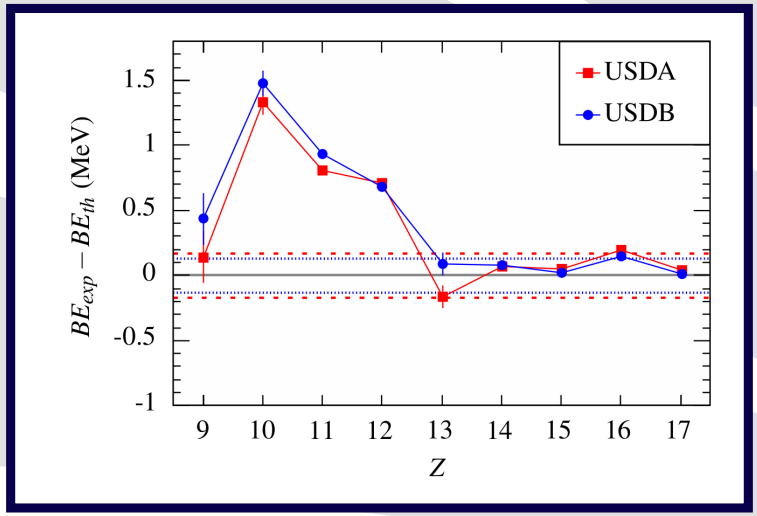
Previous Measurements in Fluorine Isotopes

^{27}F



^{27}F+$1n$

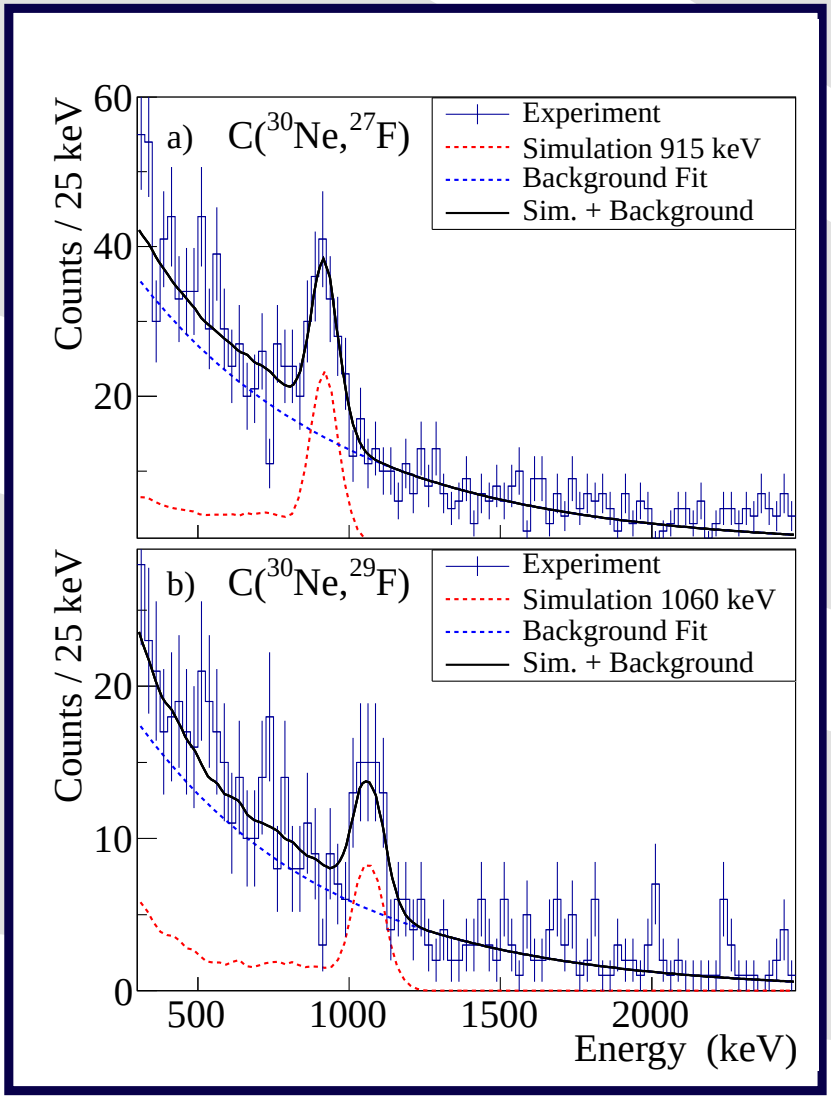


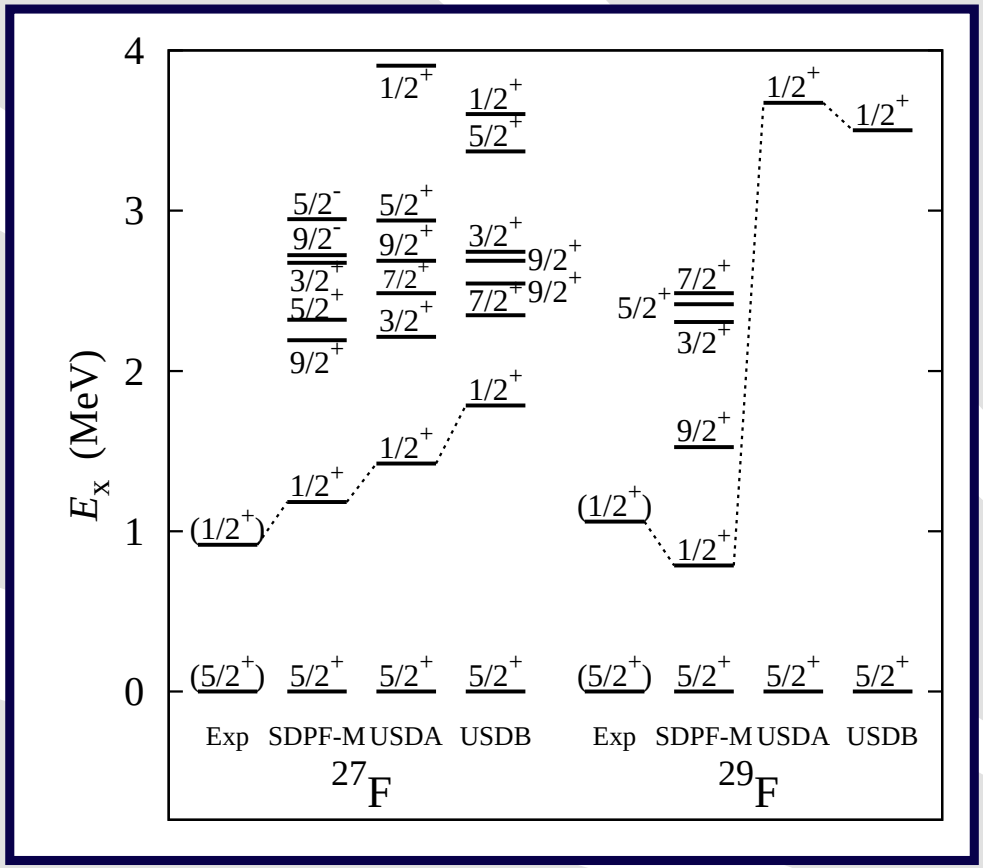


^{27}F: Z. Elekes *et al.*, Phys. Lett. B 599, 17 (2004)

^{28}F: G. Christian *et al.*, Phys. Rev. Lett 108, 032501 (2012)

In-Beam γ-Ray Spectroscopy of $^{27,29}F$

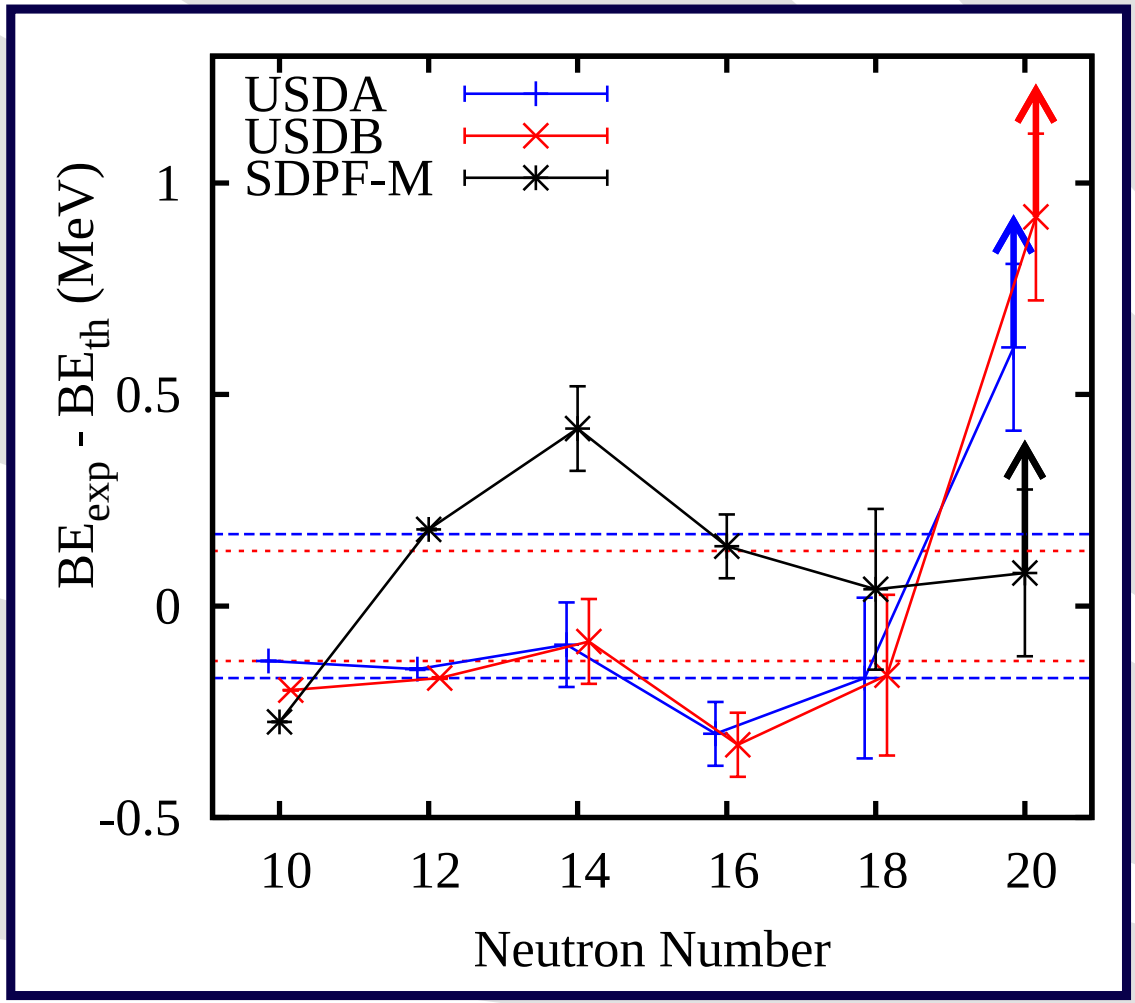




USDA/B: B. Alex Brown and W. A. Richter, Phys. Rev. C 74, 034315 (2006)
SDPF-M: Y. Utsuno *et al.*, Phys. Rev. C 60, 054315 (1999)

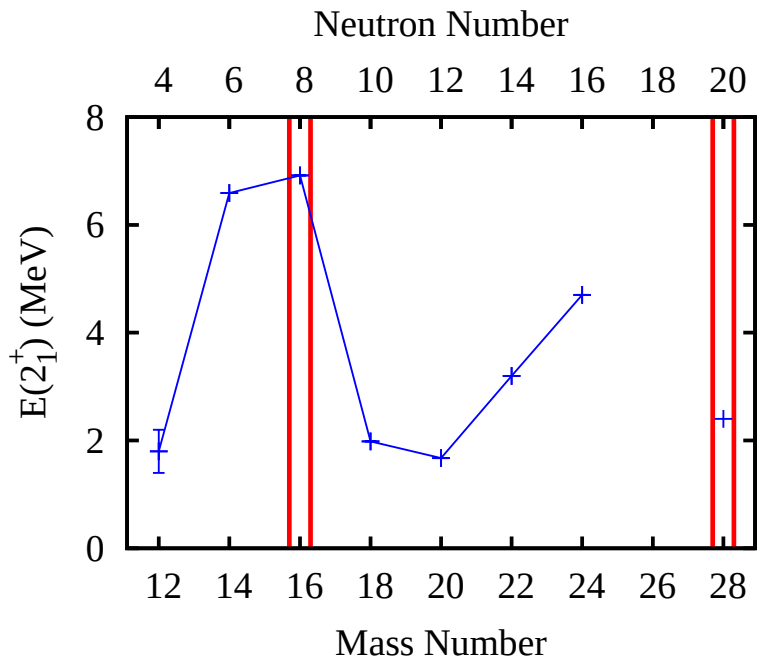
Binding Energies of F isotopes

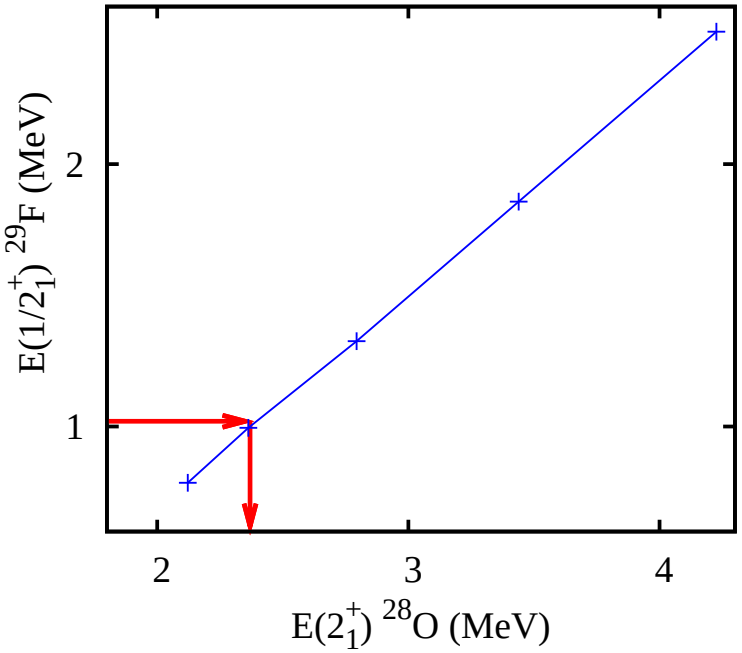
$$S_{2n} = -M(A,Z) + M(A-2,Z) + 2n$$



USDA/B: B. Alex Brown and W. A. Richter, PRC 74, 034315 (2006)
SDPF-M: Y. Utsuno *et al.*, Phys. Rev. C 60, 054315 (1999)
^{27}F mass: B. Jurado *et al.*, Phys. Lett. B 649, 43 (2007)

Breaking of the Doubly-Magic Structure in ^{28}O





Δ_{gap}	^{29}F $E(1/2_1^+)$	S_{2n}	S_n	$0p0h$ $5/2^+_{g.s.}$	$0p0h$ $1/2_1^+$	^{28}O $E(2_1^+)$	$0p0h$ $0^+_{g.s.}$
0.00	**0.786**	**1.028**	**1.614**	**7.9**	**1.0**	**2.122**	**10.9**
0.50	0.995	0.307	1.289	17.9	1.7	2.363	24.7
1.00	1.325	-0.292	1.114	37.8	3.1	2.794	45.4
1.50	1.857	-0.673	0.881	60.3	6.5	3.439	63.6
2.00	2.504	-0.879	0.657	74.4	17.8	4.226	75.0

Effect of enlarging the gap Δ_{gap} between $0_{d3/2}$ and $0f_{7/2}, 1p_{3/2}$ for ^{29}F and ^{28}O. All values in MeV or %. $\Delta_{gap} = 0$ corresponds to original ESPE from SDPF-M interaction.

Summary

RIBF32 Collaboration (Dec. 2010 Campaign)

N. Aoi[1], P. Doornenbal[2], E. Ideguchi[3], N. Kobayashi[4], Y. Kondo[4], G. Lee[4], J. Lee[2], K. Li[2,5], M. Matsushita[2], S. Michimasa[3], T. Motobayashi[2], H. Sakurai[2], **H. Scheit[2,6]**, D. Steppenbeck[2], M. Takechi[2,7], **S. Takeuchi[2]**, Y. Togano[2,7], and H. Wang[2,5]

[1]RCNP, [2]RIKEN, [3]CNS, [4]TITEC, [5]University of Peking, [6]TU Darmstadt, [7]GSI

Summary

- NP0702-RIBF32 received only about 10 % (3.5 days $\times$ 70–110 pnA) of anticipated ^{48}Ca total beam dose (10 days $\times$ 200 pnA)
- $N = 20$ magic number is gone everywhere we looked
- $E(2_1^+)$ of ^{32}Ne at 722(9) keV
- $E(2_1^+)$ of ^{38}Mg at 655(6) keV
- $E(4_1^+)/E(2_1^+) \approx 3$ for $^{34\text{-}38}$Mg
- Neutron-rich Mg isotopes form even-even particle-bound isthmus between $N = 20$ and $N = 28$ shell closure erosions
- ^{29}F belongs to “Island of Inversion”
- **First indication for shell breaking of a “classical” doubly-magic nucleus**
- Many other results not shown today, e.g. $1n$, $2n$, $1p$ knockout

THE END

Backup slides from now

Spectroscopic Factors $^{28}O + 1p$ and ^{30}Ne -$1p$

^{29}F	^{28}O	$d_{5/2}$	$s_{1/2}$	$d_{3/2}$
$1/2_1^+$	0_1^+	—	0.339	—
$1/2_1^+$	2_1^+	0.452	—	0.047
$5/2_1^+$	0_1^+	0.689	—	—
$5/2_1^+$	2_1^+	0.129	0.049	0.007
^{29}F	^{30}Ne	$d_{5/2}$	$s_{1/2}$	$d_{3/2}$
$1/2_1^+$	0_1^+	—	0.257	—
$5/2_1^+$	0_1^+	1.485	—	—

Inclusive cross-section for 1p-knockout: 6.1(4) mbarn, 8(3) % to excited state