Nuclear structure studies with exotic beams

Limits of nuclear existence and modifications to the nuclear shell structure established for stable nuclei

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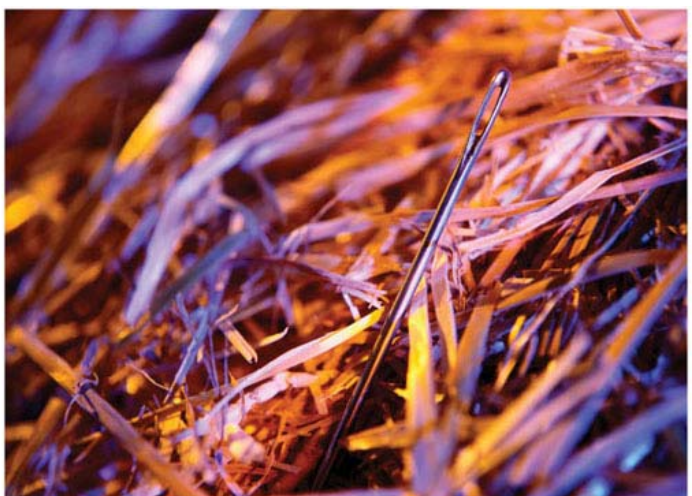
… or how to find a needle in a haystack



Outline

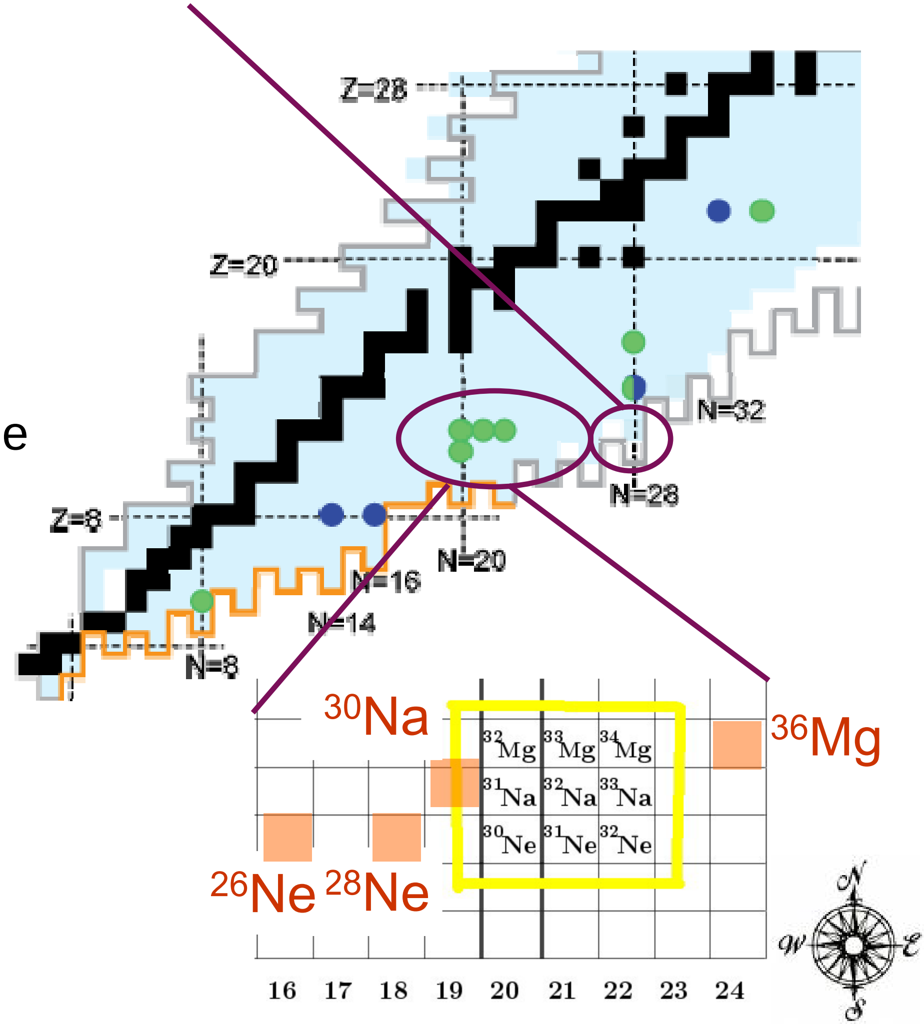
- Motivation and what it takes to do experiments with exotic nuclei
- Nuclear structure from in-beam spectroscopy with fast exotic beams

  I. Limits of Existence … or what combination of protons and neutrons can make up a bound system?

  II. A nuclear physicist's paradise … or the so-called "The Island of Inversion"
     - Introduction
     - Single-particle structure
     - Collectivity

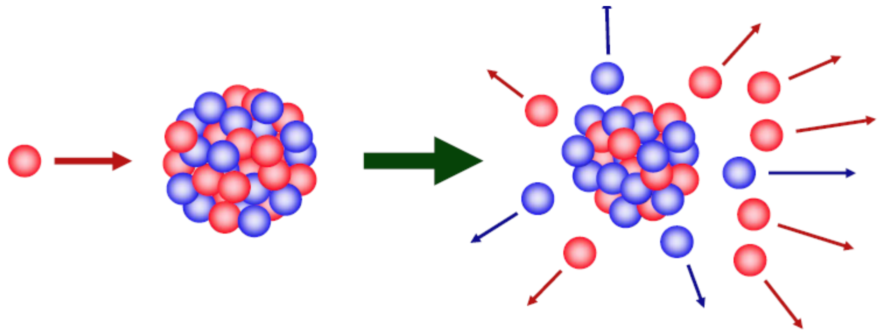
- Summary and outlook

To be or not to be … the limit of nuclear existence for Mg and Al isotopes?



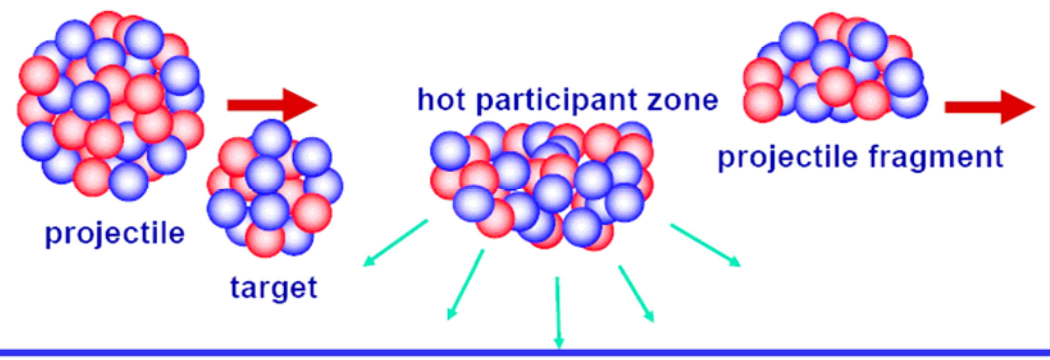
Production of exotic beams

Random removal of protons and neutrons from heavy target nuclei by energetic light projectiles (pre-equilibrium and equilibrium emissions).



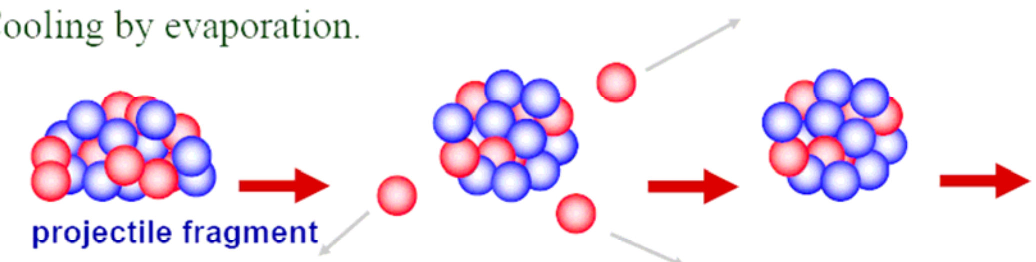
Target fragmentation

Random removal of protons and neutrons from heavy projectile in peripheral collisions



Projectile fragmentation

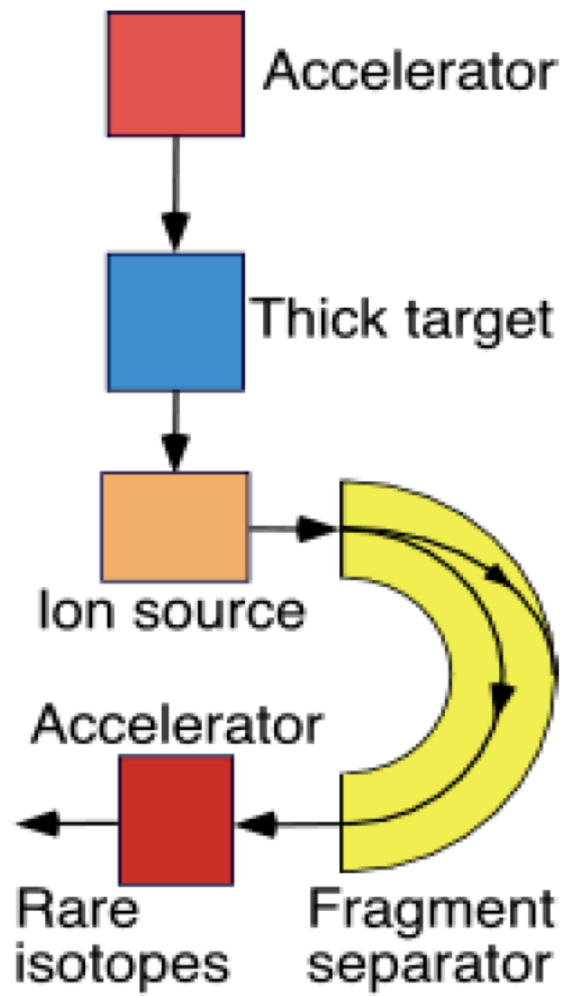
Cooling by evaporation.



Schematic of a target fragmentation facility

Modern example: ISAC facility at TRIUMF, Vancouver, Canada

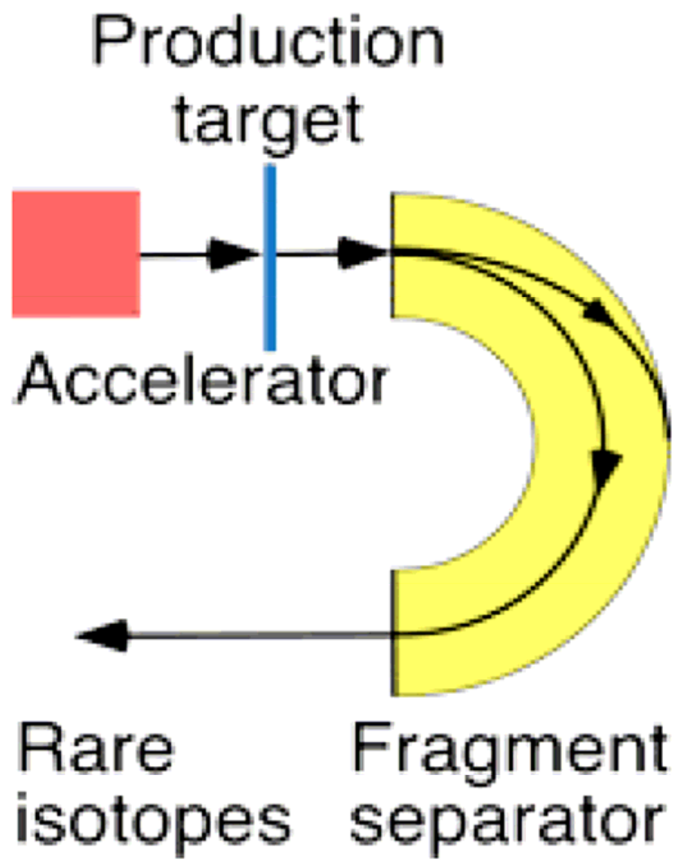
- Excellent beam quality and low beam energies are possible
- Limited to longer lifetimes ($\tau > 1$s)
- Isotope extraction and ionization efficiency depend on chemical properties of element: difficult, element-specific development paths
- The most neutron-rich isotopes will have too low intensities and too short lifetimes to be suitable for re-acceleration



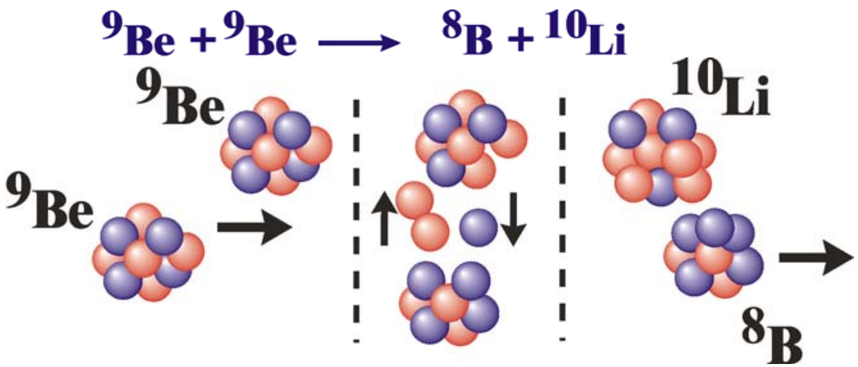
Schematic of a projectile fragmentation facility

Modern example: NSCL Coupled Cyclotron Facility facility

- High-energy beams (E/A > 50 MeV) of modest beam quality
- Physical method of separation, no chemistry
- Suitable for short-lived isotopes ($\tau > 10^{-6}$ s)
- Low-energy beams are difficult
- Beam quality



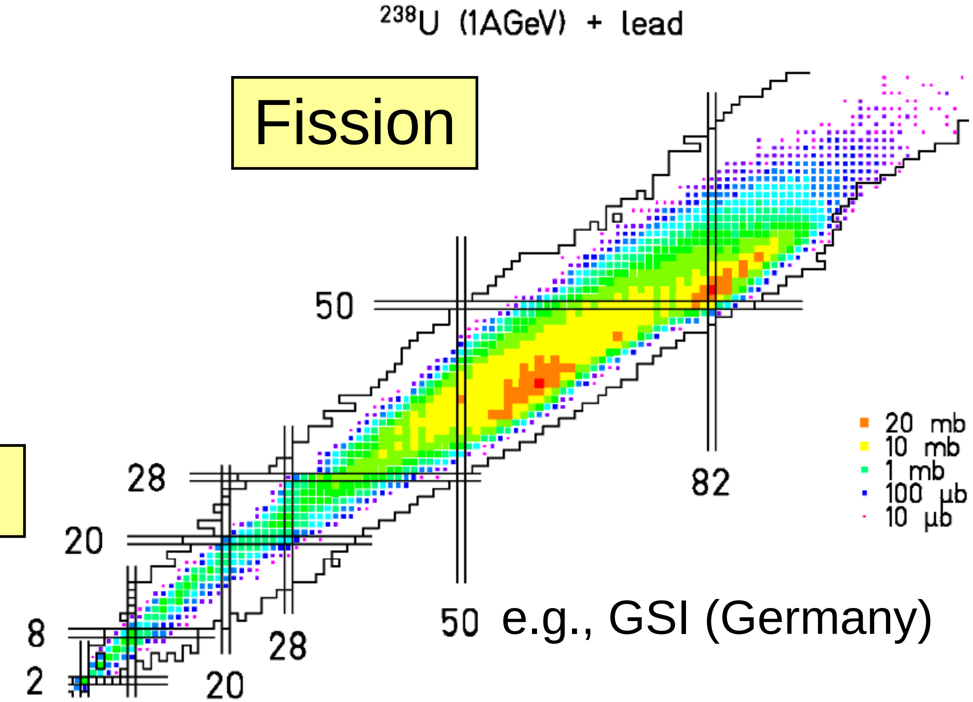
Other approaches



Transfer and in-flight separation

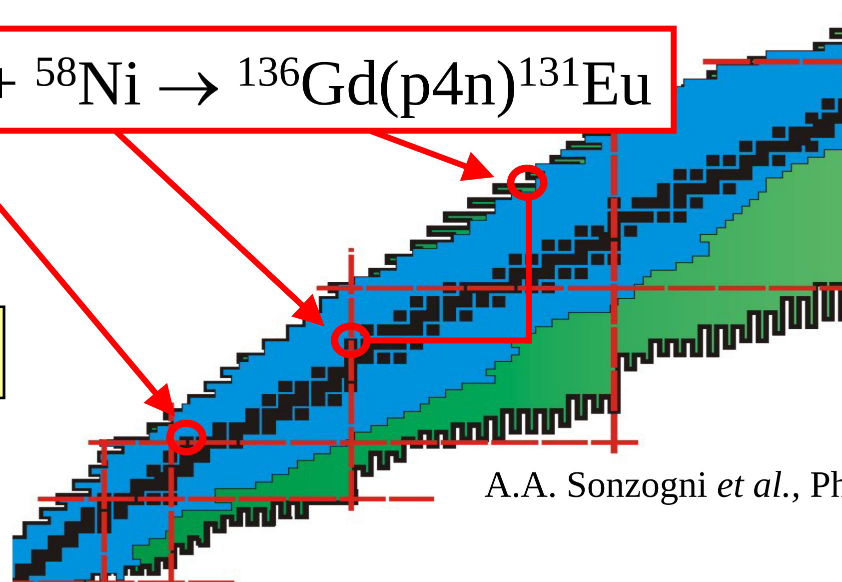
e.g., Notre Dame

Fission



e.g., GSI (Germany)

402 MeV ^{78}Kr + ^{58}Ni → ^{136}Gd(p4n)^{131}Eu

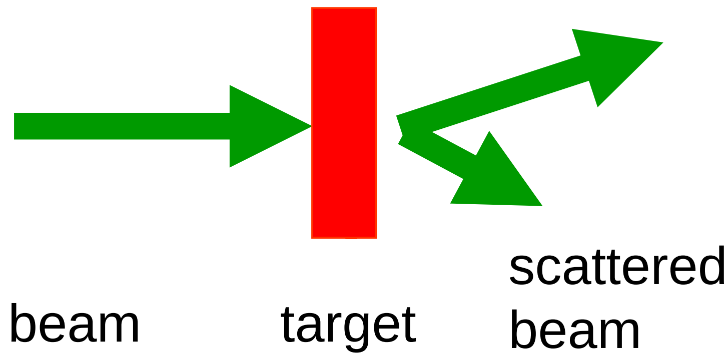


Fusion-evaporation

e.g., Argonne National Lab

A.A. Sonzogni *et al.*, Phys. Rev. Lett. **83** 1116 (1999)

Different experimental probes



- Experimental tasks

  -Particle spectroscopy

  Identification of the reaction residues

  Momentum distributions

  Scattering angle

  - γ-ray spectroscopy

  Identify the final state

  Tag the inelastic process

- Light target for wave-function spectroscopy
  → spectroscopic factors (relate to occupation numbers of orbits)
- *Nucleon knockout reactions*

  P.G. Hansen and J. A. Tostevin, Annu. Rev. Nucl. Sci. 53, 219 (2003)

- High-*Z* target as electromagnetic probe
  → reduced matrix elements
- *Intermediate-energy Coulomb excitation*

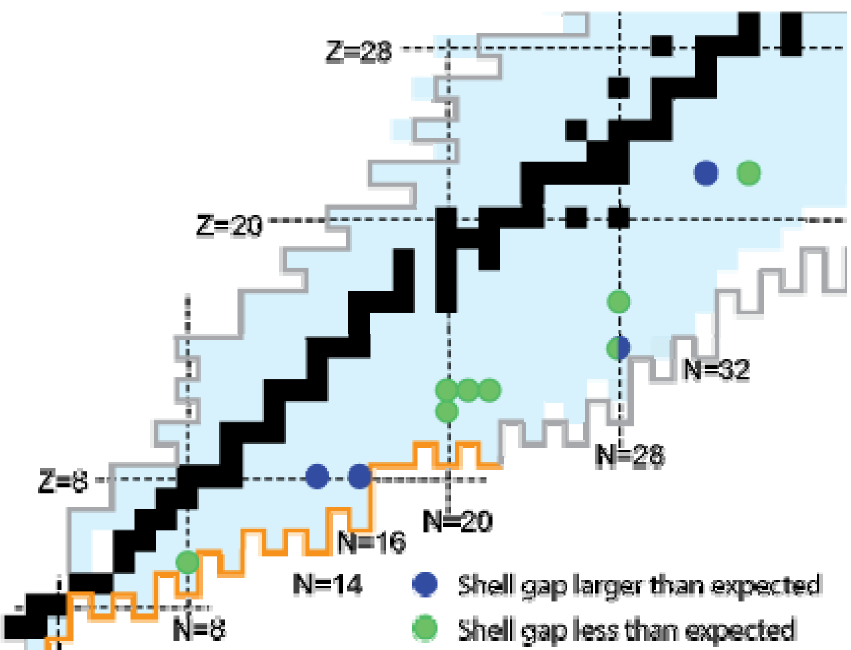
  T. Glasmacher, Annu. Rev. Nucl. Part. Sci. 48, 1 (1998)

Use photons to tag the final state

Light, neutron-rich nuclei have been studied the most

… and reveal a severe loss of predictive power

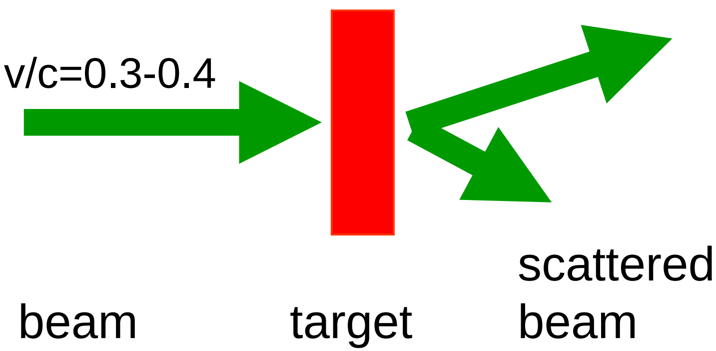
- Nuclear existence
- Masses
- Charge and mass distributions
- Modifications to magic numbers



- Experimental task: Quantify changes encountered in rare isotopes and measure observables that are calculable and can serve to discriminate between theories
- Experiments?! Largely done in inverse kinematics with a beam of exotic nuclei
- Complementary approach: Collectivity + single-particle properties

- The nuclei with the largest *N/Z* ratio accessible are light nuclei and they have low beam rates
- New precision techniques have been developed in past decade to enable spectroscopy of these most exotic nuclei

In-beam spectroscopy with a few atomic nuclei per second

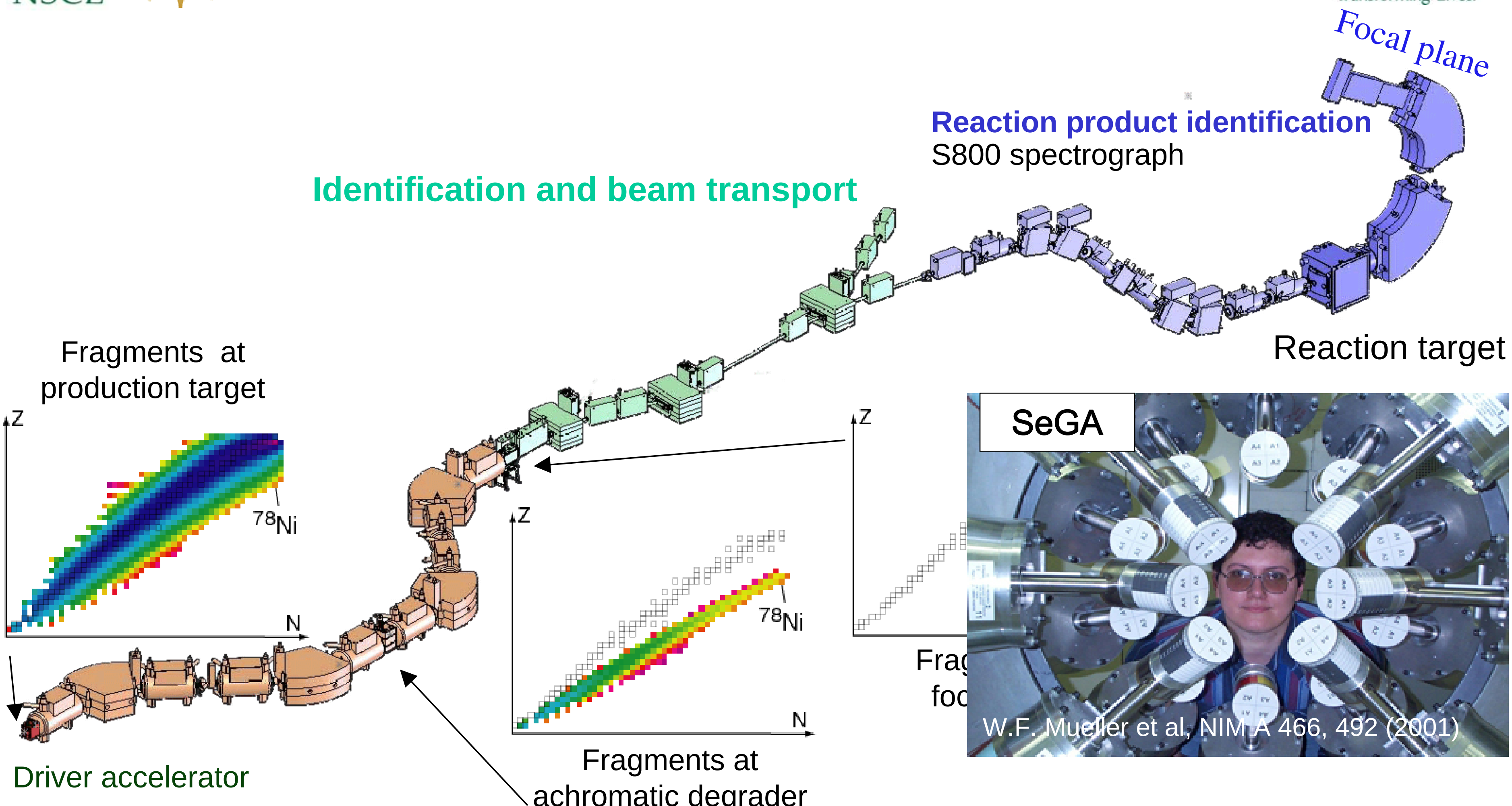


- Fast exotic beams allow for
  - thick secondary targets
  - event-by-event identification
  - Clean trigger

- $N_R = \sigma \times N_T \times N_B$
  - σ Cross section
  - N_T Atoms in target
  - N_B Beam rate
  - N_R Reaction rate

- Example
  - σ = 100 mbarn
  - $N_T = 10^{21}$
  - N_B = 3 Hz
  - N_R =26/day = 3×10^{-4} Hz

In-flight production of rare isotopes
Example: ^{78}Ni from ^{86}Kr at NSCL



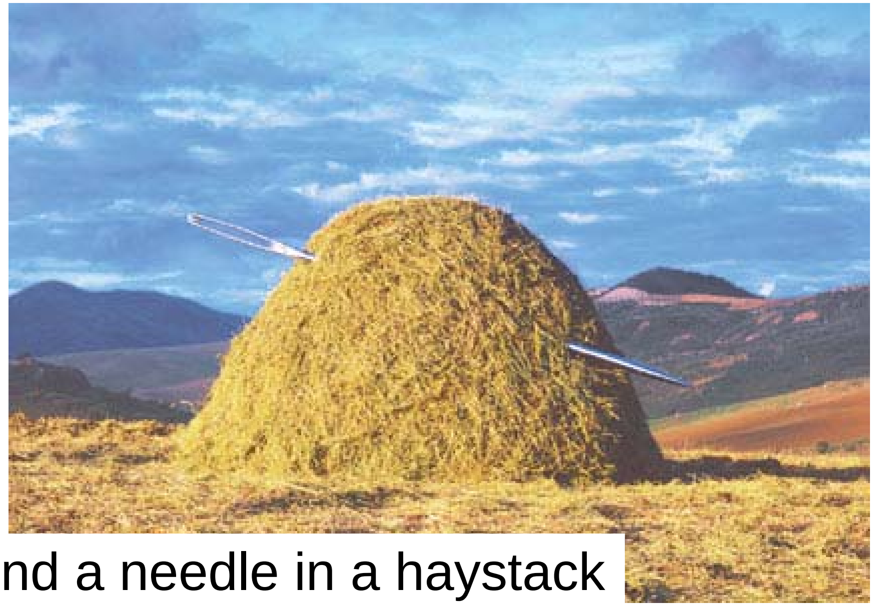
Driver accelerator

- Fragment separator
- Identification and beam transport
  - Stopped beam experiments
  - Fast beam experiments
    - Secondary reaction
    - Reaction product identification

How many neutrons can a proton bind?

The limit of nuclear existence is characterized by the nucleon driplines

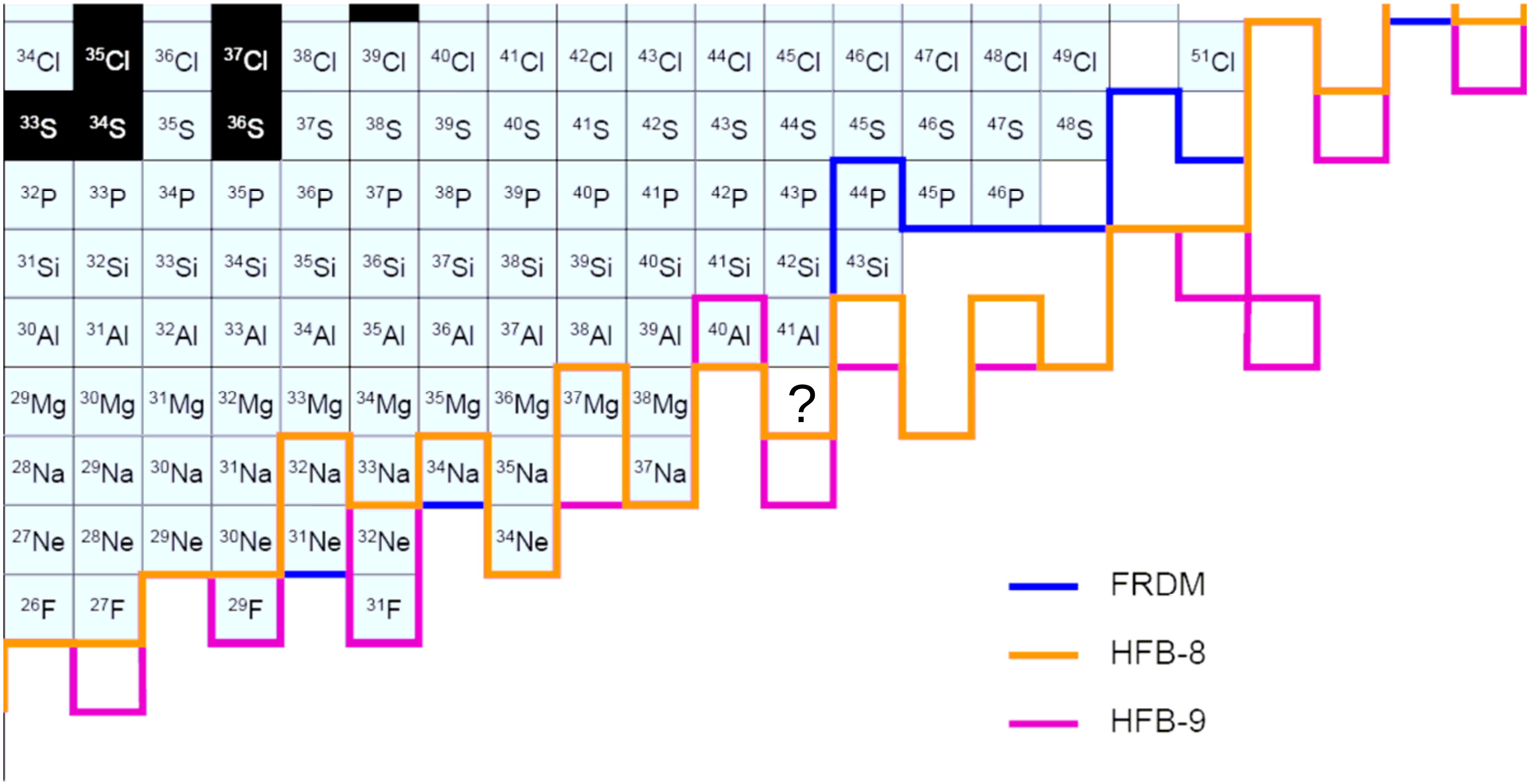
- B. Jonson: "The driplines are the limits of the nuclear landscape where additional protons or neutrons can no longer be kept in the nucleus - they literally drip out.“
- P. G. Hansen & J. A. Tostevin: "(the dripline is) where the nucleon separation energy goes to zero."



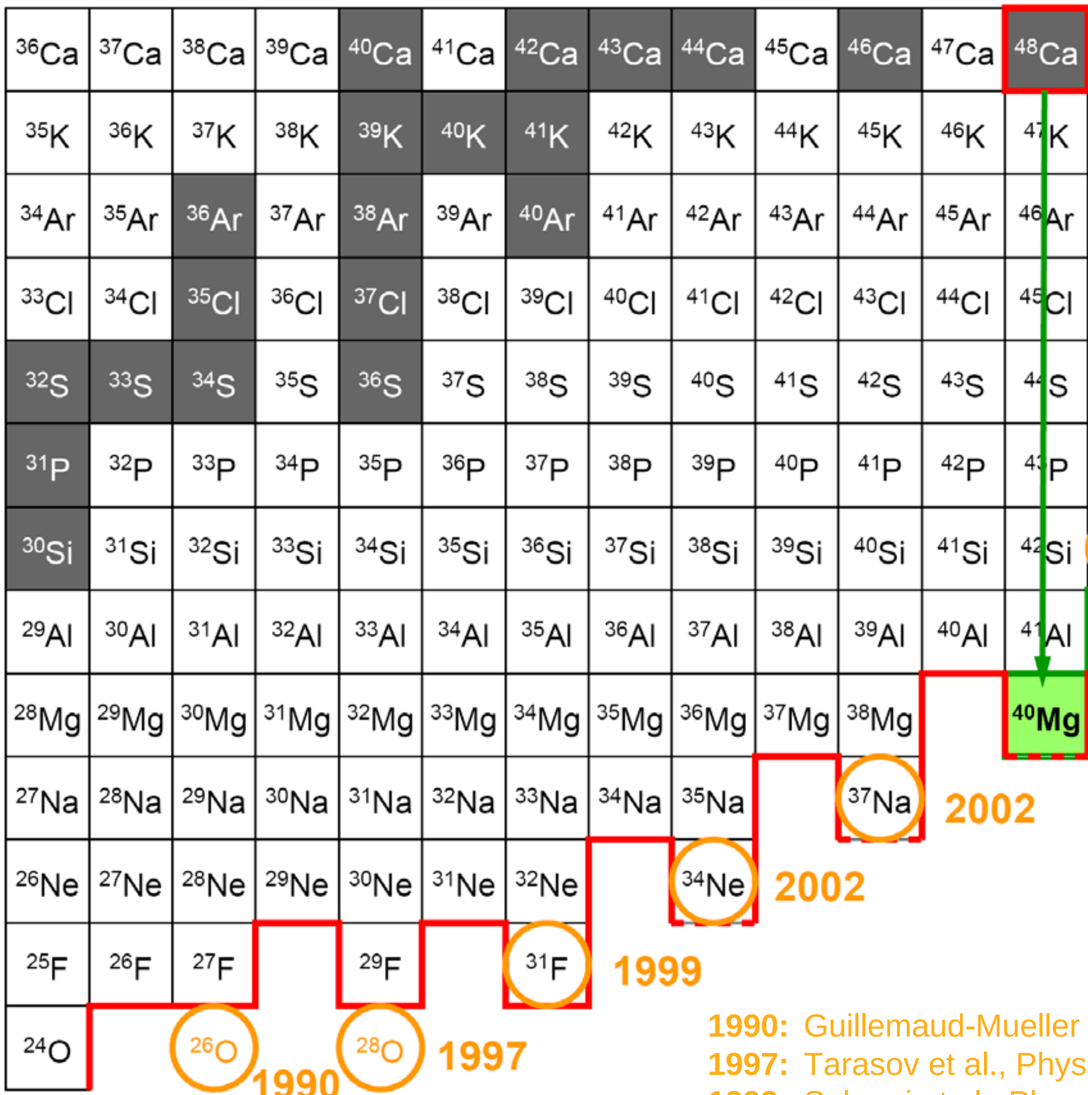
Experimental task: How to find a needle in a haystack

Where is the neutron dripline?

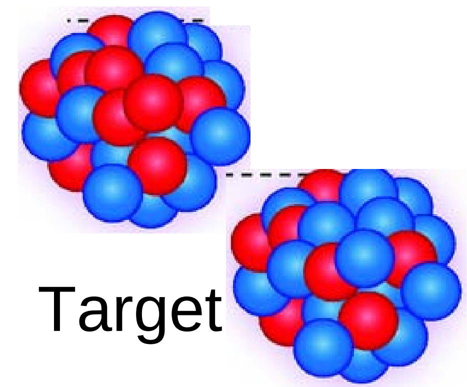
Predictive power, anybody?



Dripline history and a plan …



^{48}Ca (Z=20, N=28)



Production of ^{40}Mg from ^{48}Ca:
Net loss of 8 protons with no neutrons removed!

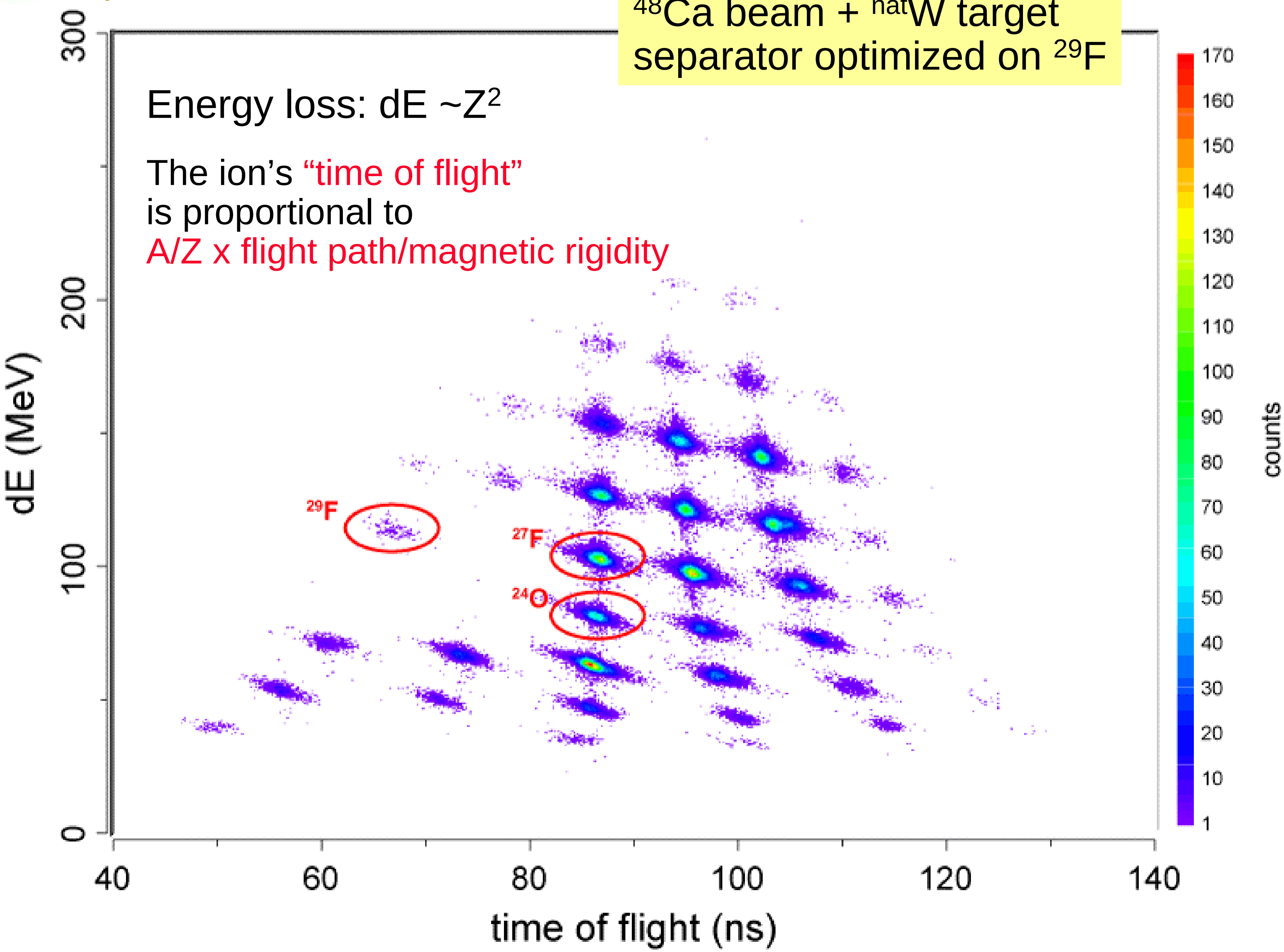
1990: Guillemaud-Mueller et al., Z. Phys. A 332, 189
1997: Tarasov et al., Phys. Lett. B 409, 64
1999: Sakurai et al., Phys. Lett. B 448, 180
2002: Notani et al., Phys. Lett. B 542, 49
Lukyanov et al., J. Phys. G 28, L41

Proof of existence? Detect and identify it!

^{48}Ca beam + ^{nat}W target
separator optimized on ^{29}F

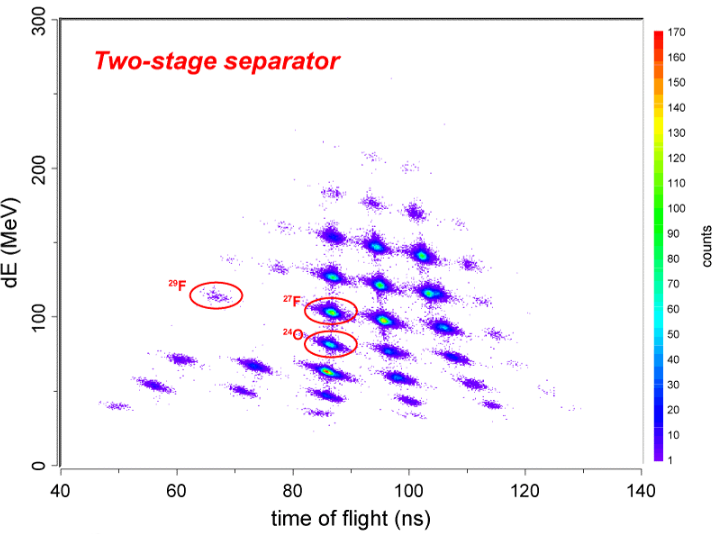
Energy loss: dE ~Z^2

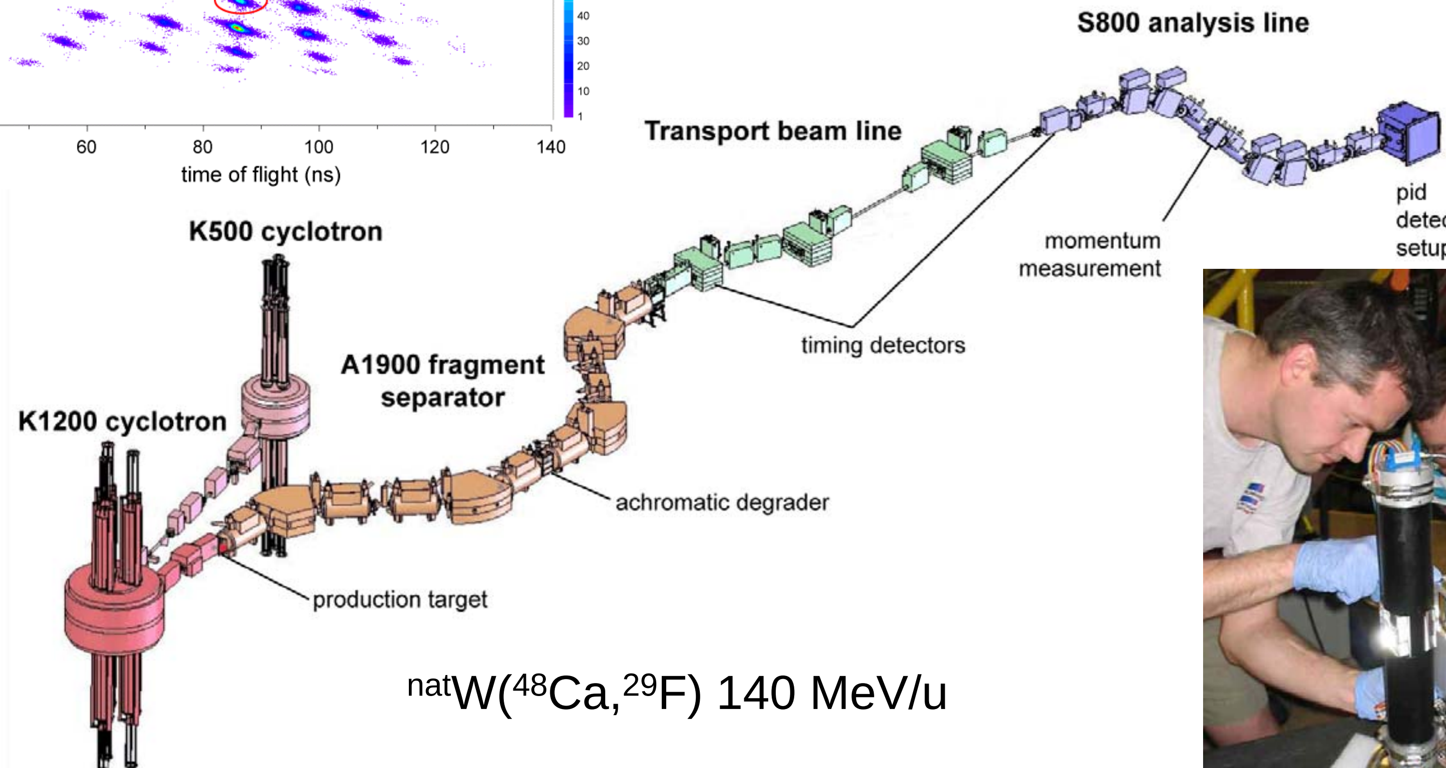
The ion's "time of flight"
is proportional to
A/Z x flight path/magnetic rigidity



A long way …

- Two test experiments at the end of the fragment separator
- During the tests: Production cross sections of neutron-rich isotopes and discovered ^{44}Si along the way
- Implemented the concept of a two-stage separator to discriminate against low-Z events
- … and finally ran the search for ^{40}Mg in April 2007

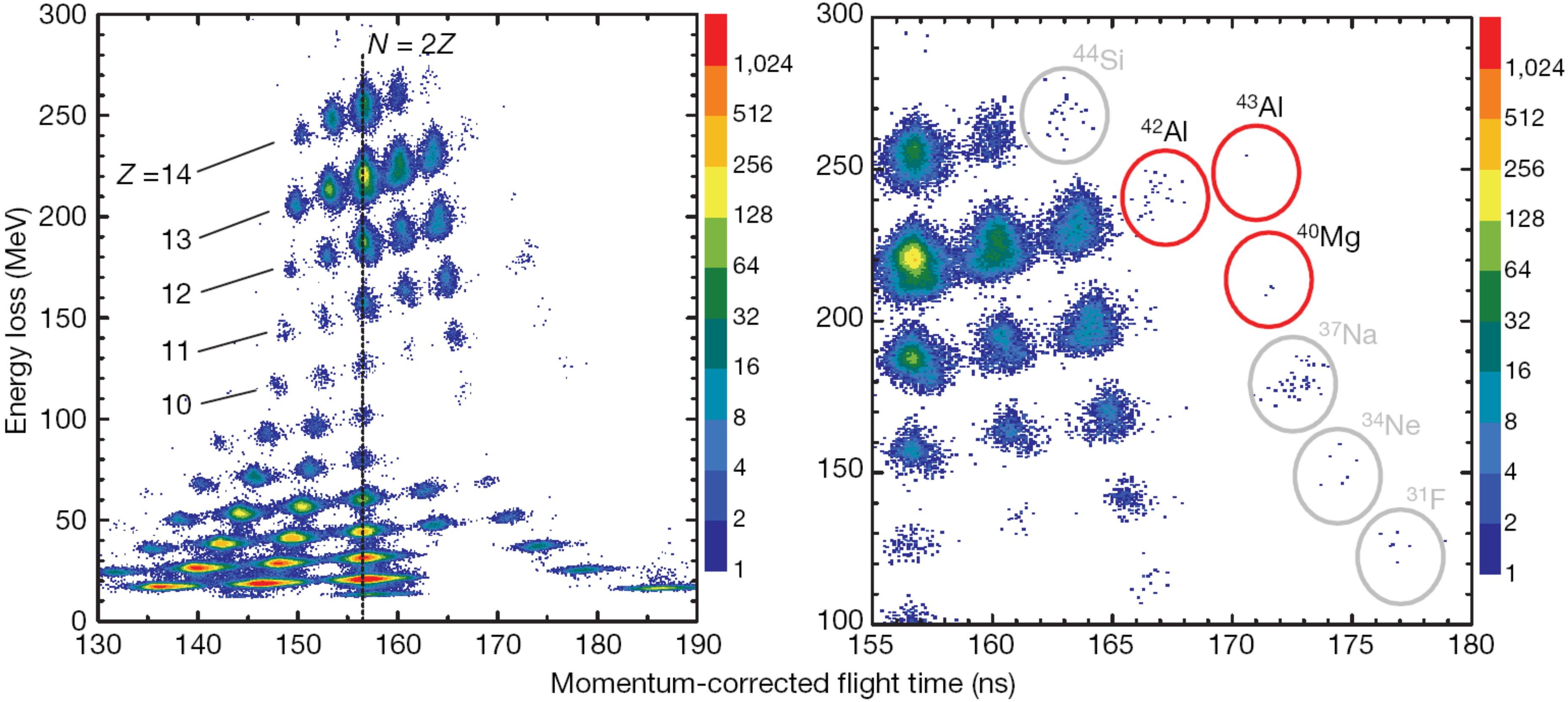




$^{nat}W(^{48}Ca,^{29}F)$ 140 MeV/u

^{40}Mg and more!

nature T. Baumann *et al*., Nature 449, 1022 (2007)



Data taking: 7.6 days at 5 x10^{11} particles/second
3 events of ^{40}Mg
23 events of ^{42}Al
1 event ^{43}Al

The existence of ^{42,43}Al …

nature T. Baumann *et al.*, Nature 449, 1022 (2007)

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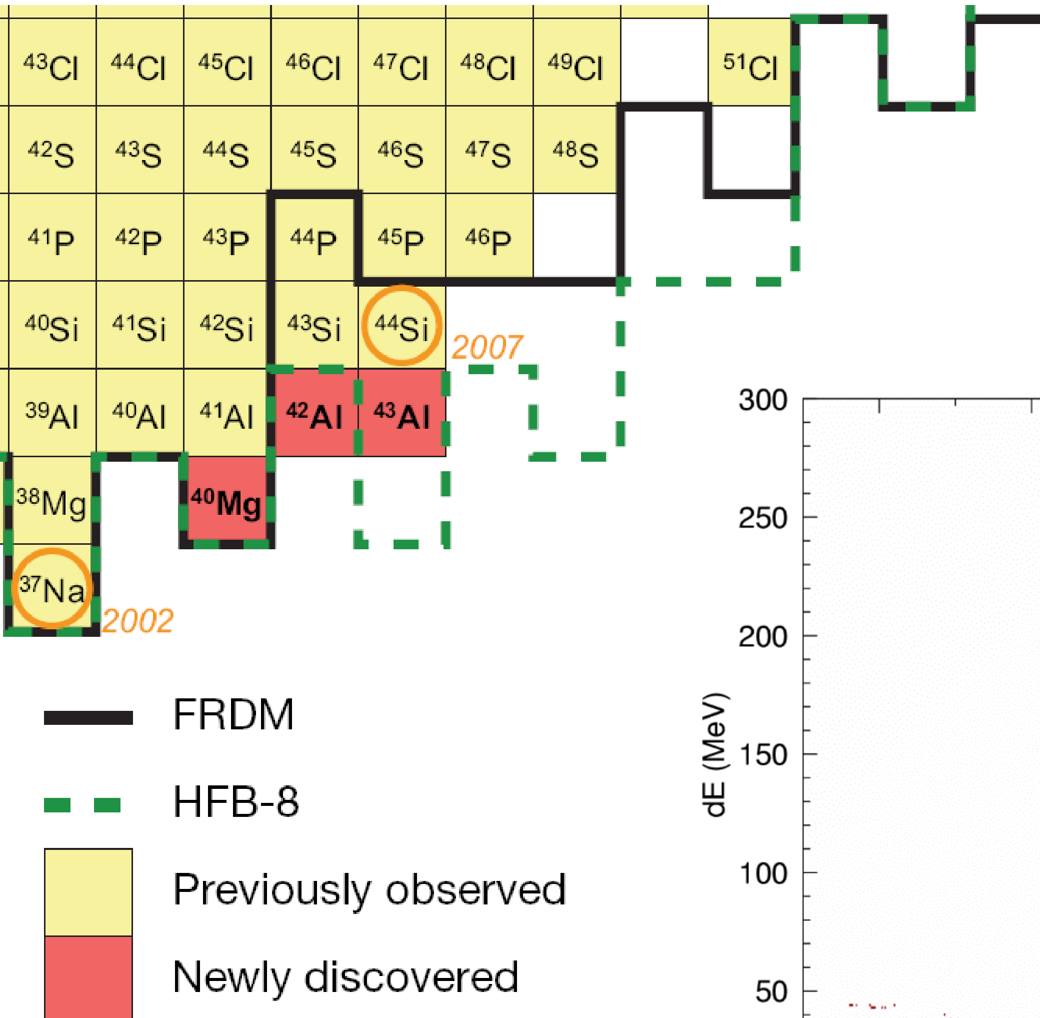
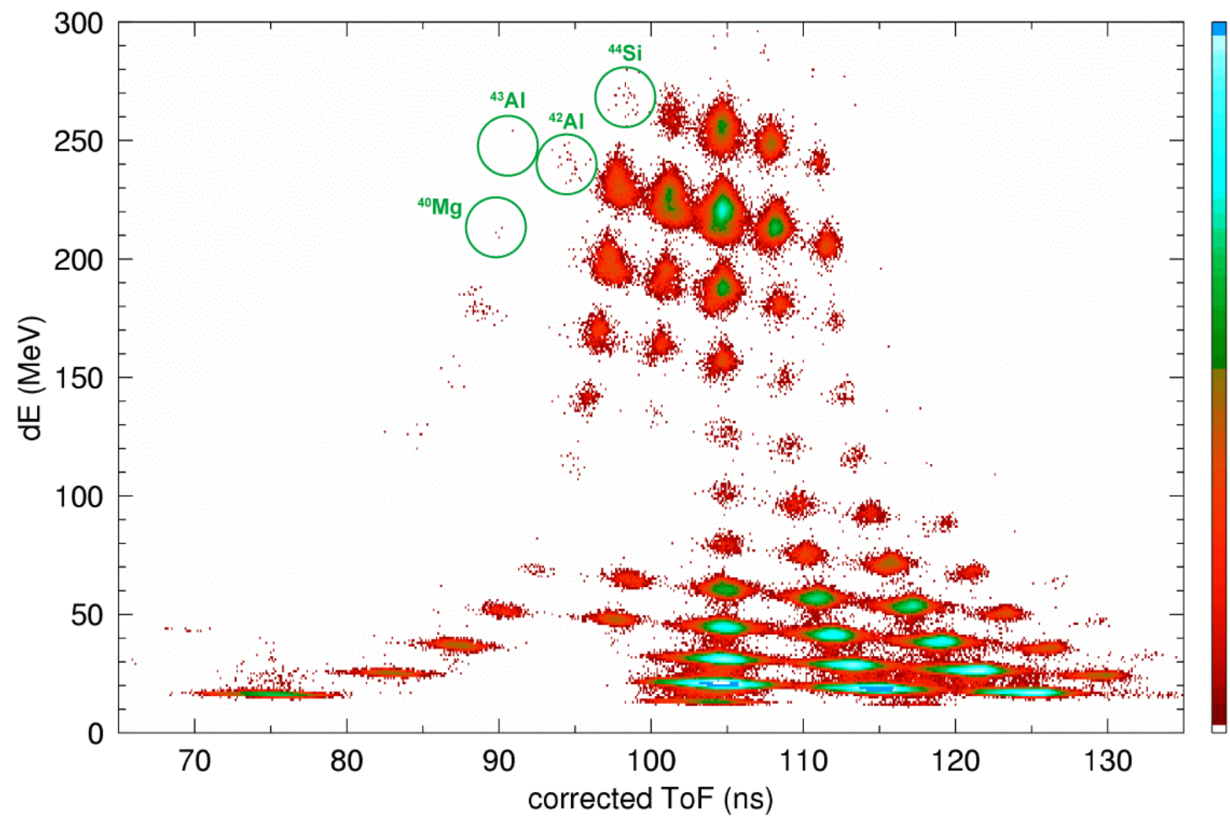
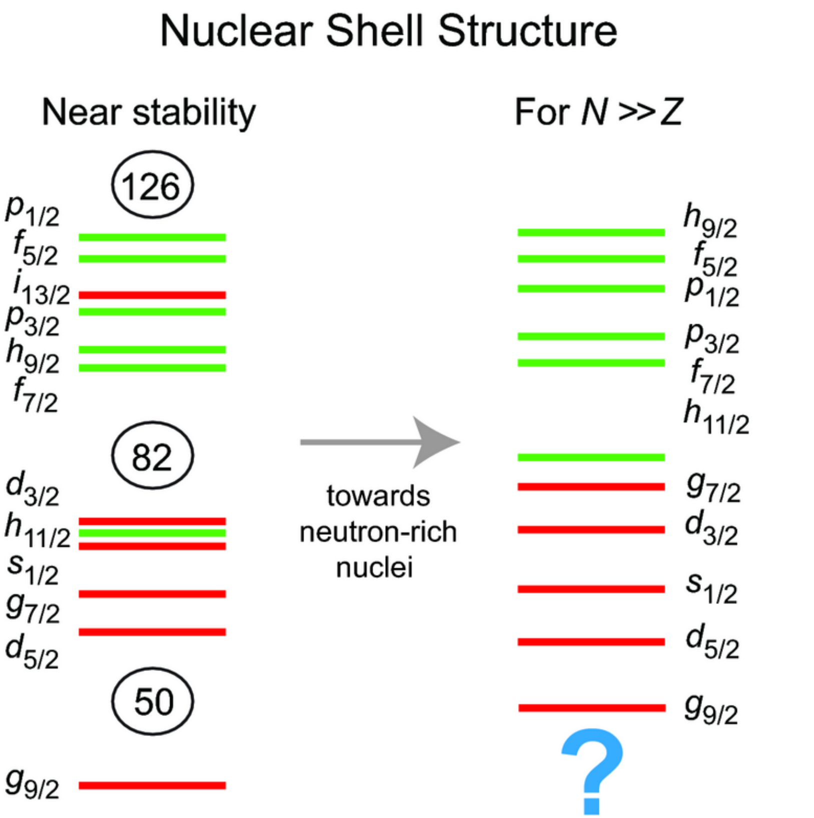


The existence of ^{42,43}Al indicates that the neutron dripline might be much further out than predicted by most of the present theoretical models, certainly out of reach at present generation facilities.



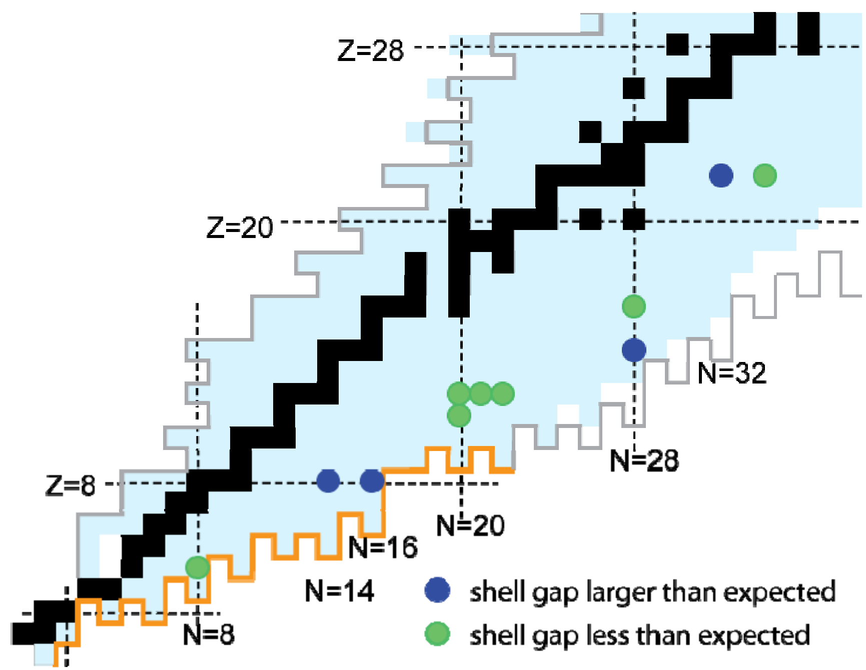
Evolution of nuclear shell structure in ground state configurations



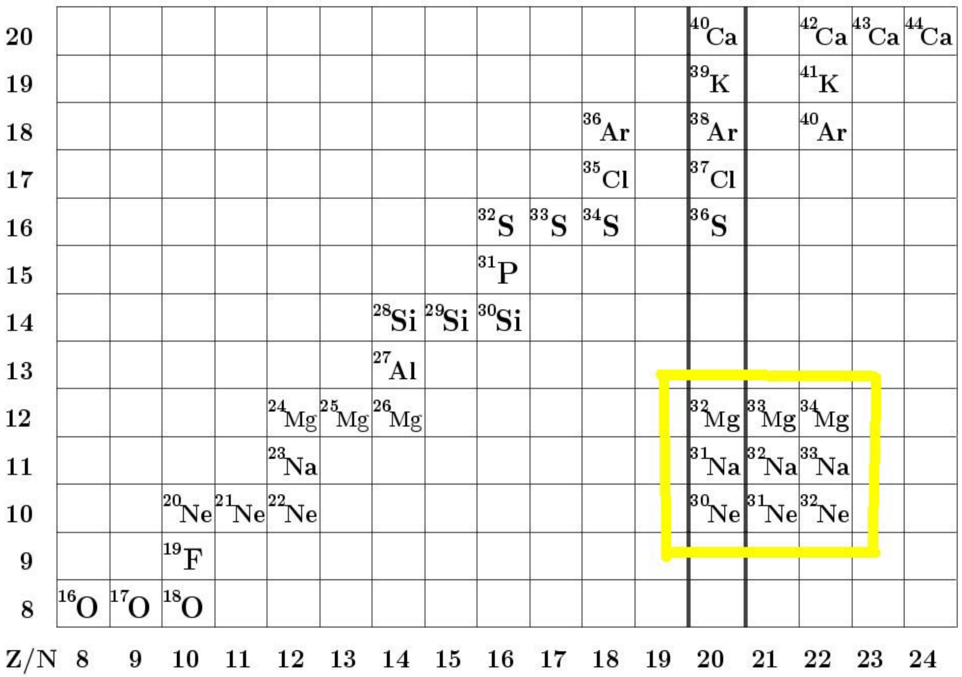
- Mean field near stability
- Strong spin-orbit term

- Mean field for $N >> Z$?
- Reduced spin-orbit
- Diffuse density
- Tensor force

- First experiments – with light neutron-rich nuclei, which are the only ones accessible far enough away from stability – indicate significant changes:
  - Reduced shell gaps
    - » N=8, N=20
  - New shell gaps at
    - » N=14, Z=14, N=16, N=32



The "Island of Inversion"… or what is wrong with N=20 in Ne, Na and Mg isotopes?



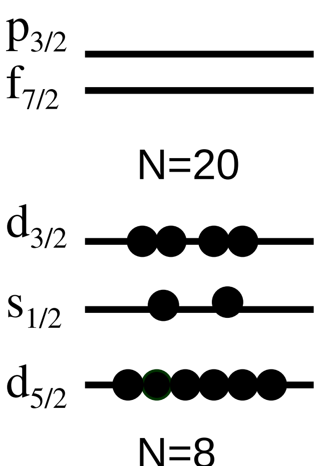
A trail of evidence:

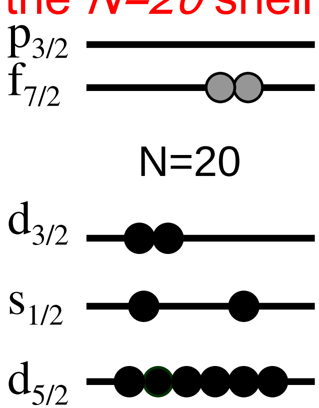
C. Thibault et al. (1975): ^{31,32}Na, local increase of S_{2n}, *N=20* shell closure would lead to a decrease Phys. Rev. C 12, 646 (1975)

C. Detraz et al. (1979): ^{32}Na → ^{32}Mg β-decay, found low-lying 2^+ in ^{32}Mg (885 keV), *N=20* shell closure would lead to a high-lying 2^+ Phys. Rev. C 19, 164 (1979)

T. Motobayashi et al. (1995): Coulomb excitation, ^{32}Mg is deformed, *N=20* shell closure would indicate spherical shape Phys. Lett. B 346, 9 (1995)

neutron-*ph* excitations across the *N=20* shell gap





E. Warburton et al:
Z=10-12 and *N=20-22* have intruder configurations $(sd)^{-2}(fp)^{+2}$

Phys. Rev. C 41, 1147 (1990)

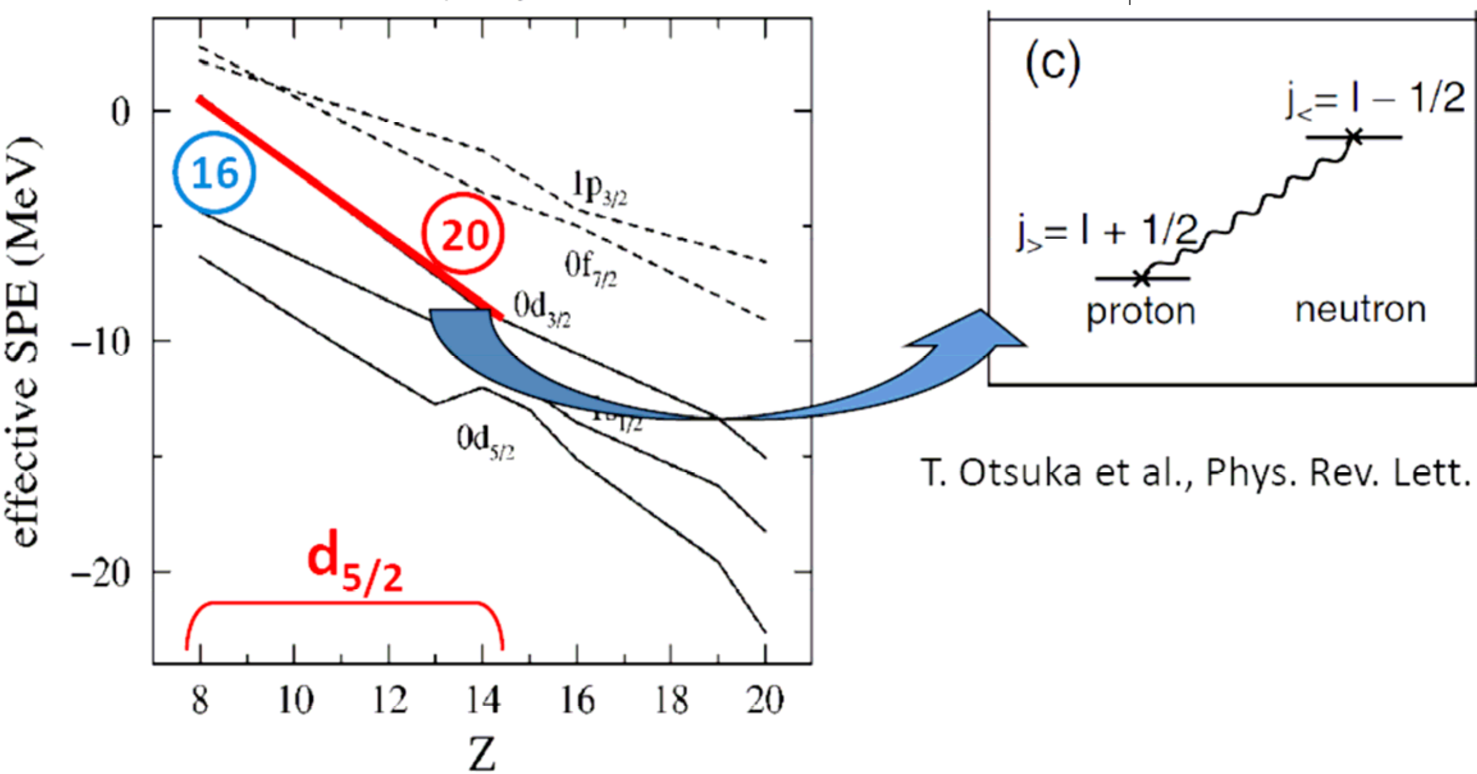
The driving force behind? Spin-isospin parts of the NN interaction

PRL 95, 232502 (2005) PHYSICAL REVIEW LETTERS week ending 2 DECEMBER 2005

Evolution of Nuclear Shells due to the Tensor Force

Takaharu Otsuka,[1,2,3,*] Toshio Suzuki,[4] Rintaro Fujimoto,[1] Hubert Grawe,[5] and Yoshinori Akaishi[6]
[1]*Department of Physics, University of Tokyo, Hongo, Bunkyo-ku, Tokyo 113-0033, Japan*
[2]*Center for Nuclear Study, University of Tokyo, Hongo, Bunkyo-ku, Tokyo 113-0033, Japan*
[3]*RIKEN, Hirosawa, Wako-shi, Saitama 351-0198, Japan*
[4]*Department of Physics, Nihon University, Sakurajosui, Setagaya-ku, Tokyo 156-8550, Japan*
[5]*GSI, D-64291, Darmstadt, Germany*
[6]*KEK, Oho, Tsukuba-shi, Ibaraki 305-0801, Japan*
(Received 22 February 2005; published 30 November 2005)

Attraction between proton-neutron spin-orbit partners. For the “Island of Inversion”: proton $d_{5/2}$ and neutron $d_{3/2}$



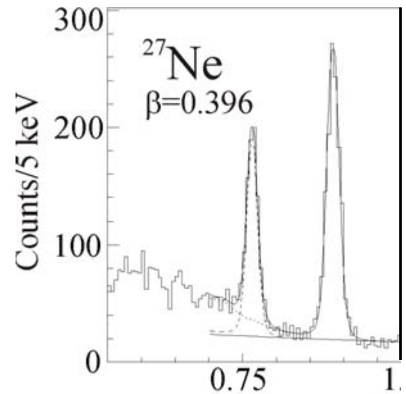
T. Otsuka et al., Phys. Rev. Lett. 87, 082502 (2001).

Y. Utsuno et al., Phys. Rev. C 60, 054315 (1999) and following MCSM papers.

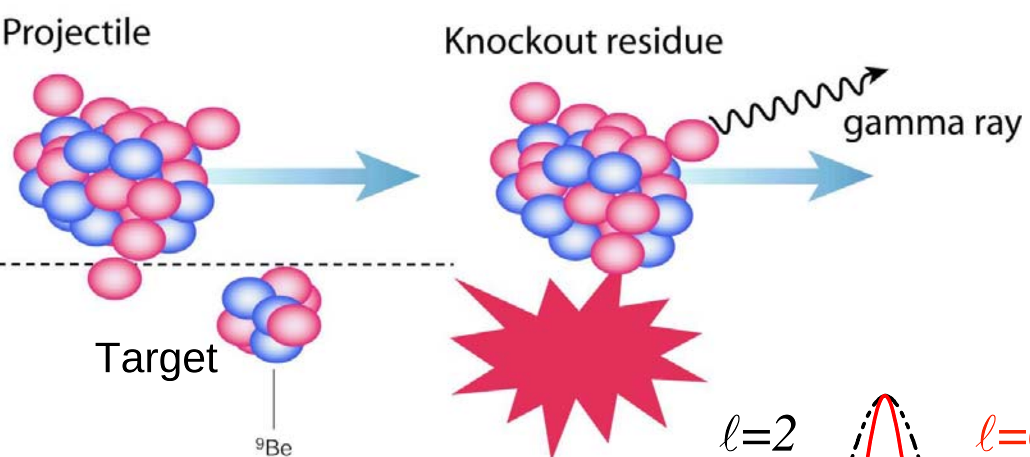
Figures from Y. Utsuno, talk at the ECT* meeting (2007)

Spectroscopy of the wave function – One-nucleon knockout

Mission: Figure out if neutrons occupy f or p orbits (above the N=20 shell gap)

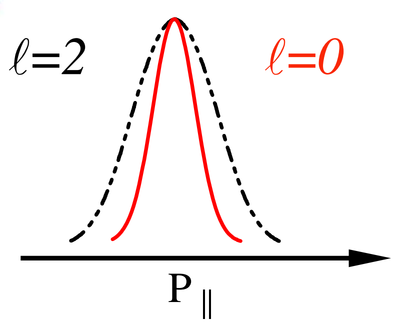


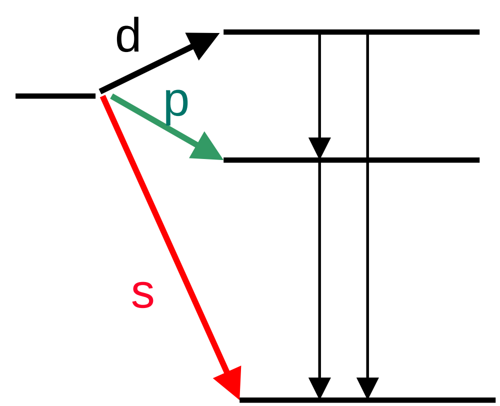
- Cross section for the reaction to occur (inclusive cross section)
- Transition energies from γ-ray spectroscopy (**relative location of single-particle states**)
- γ-ray intensities (**cross section for the reaction to proceed to a specific final state**)
- Longitudinal momentum distribution of the projectile-like knockout residue (**obital angular momentum of the knockout-out nucleon**)



P.G. Hansen and J. A. Tostevin, Annu. Rev. Nucl. Sci. 53, 219 (2003)

P.G. Hansen, PRL 77, 1016 (1996)





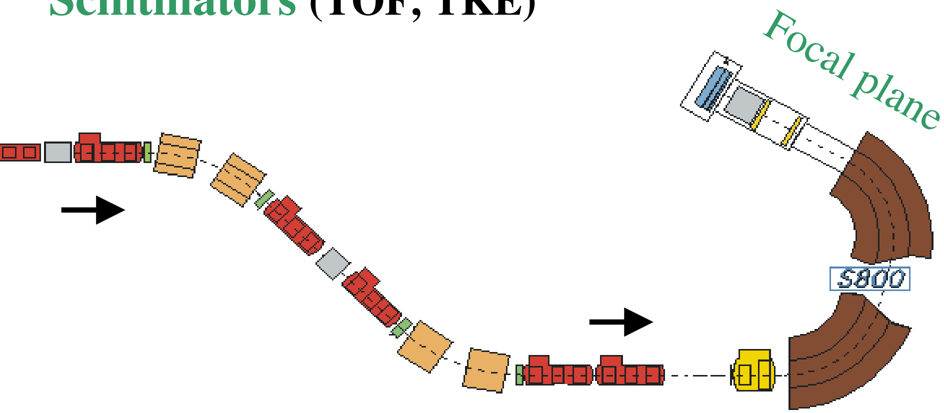
S800 Spectrograph and SeGA at the NSCL

Focal plane detectors:

Ion chamber **(energy loss)**

2 CRDC's **(angle, position (-> momentum))**

Scintillators **(TOF, TKE)**



Target

Momentum: ± 2.5%

Angle: ±3.5° (vertical)

±5° (horizontal)

Event-by-event PID in entrance and exit channel

J. Yurkon *et al.*, Nucl. Instr. Meth. A422, 291 (1999)

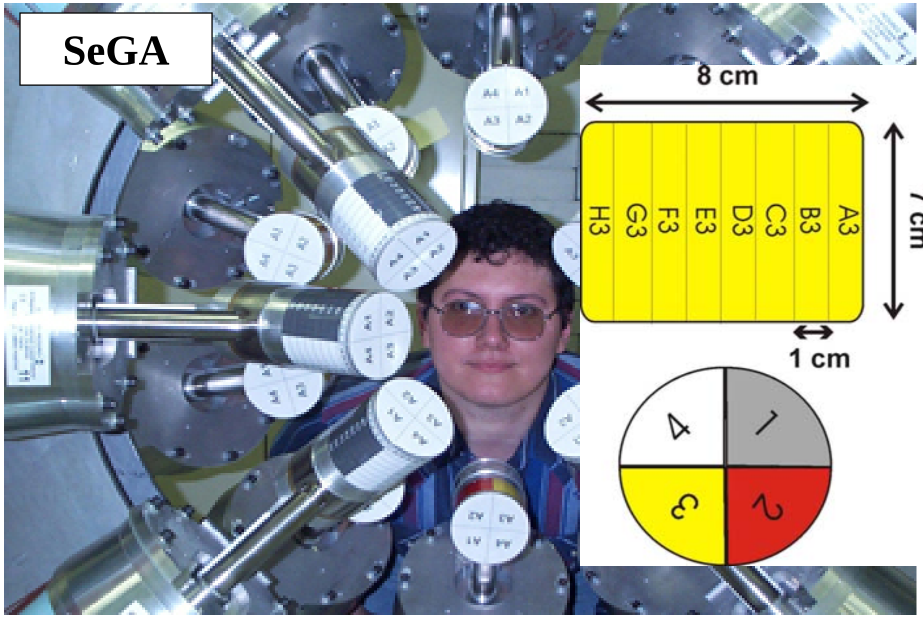
D. Bazin *et al.*, Nucl. Instr. Meth. B204, 629 (2003)

SeGA (Segmented Germanium Array)—Eighteen 32-fold segmented HP germanium detectors

2 rings: 37° and 90° with respect to the beam axis

With 7 detectors per ring:

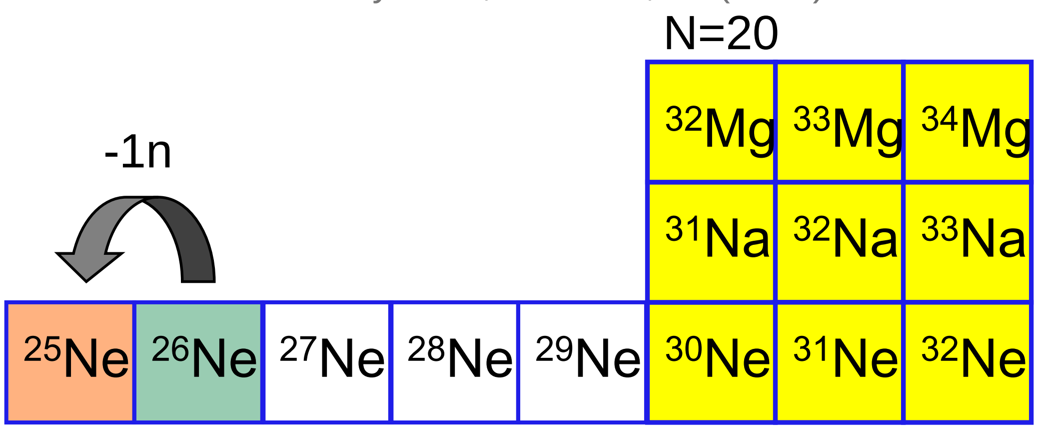
Efficiency (source): 2% @ 1.3MeV

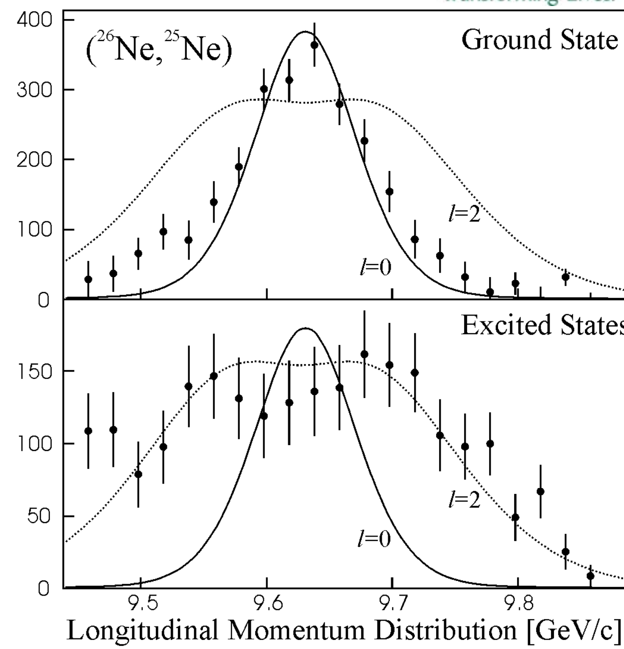


W.F. Mueller et al, Nucl. Instr. Meth. A 466, 492 (2001)

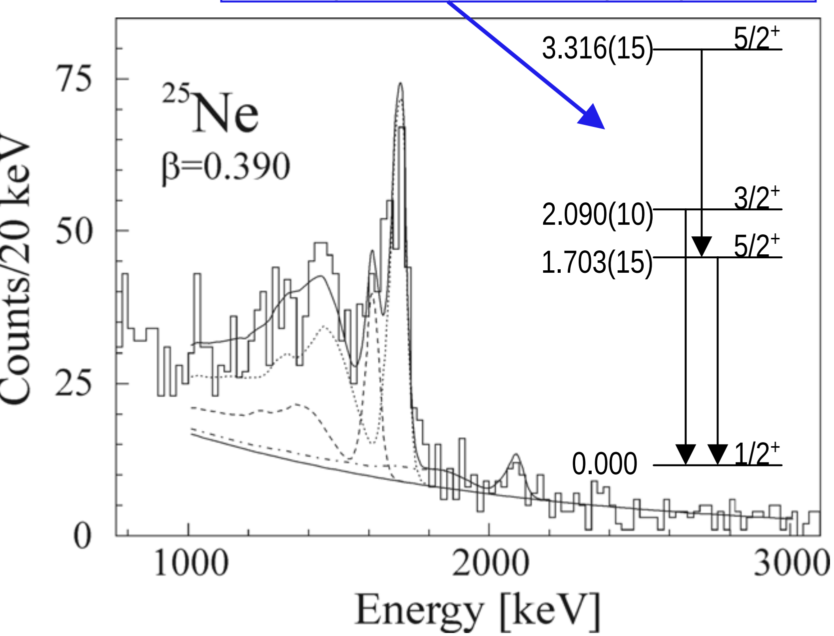
Approaching the "Island"
One-neutron removal from ^{26}Ne

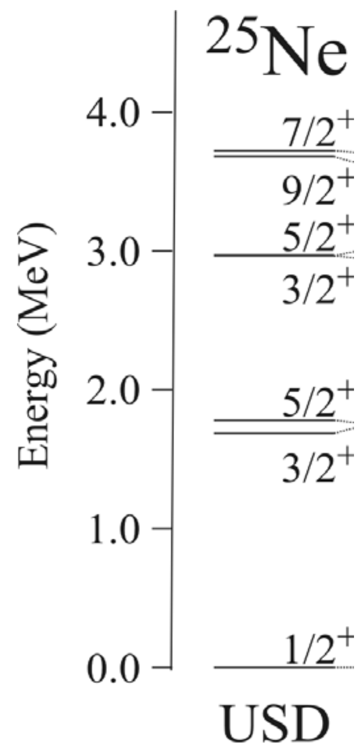
J. Russ Terry et al., PLB 640, 86 (2006)





A.T. Reed *et al.*, PRC 60 (1999) 024311
S. Padgett et al., PRC 72 (2005) 064330

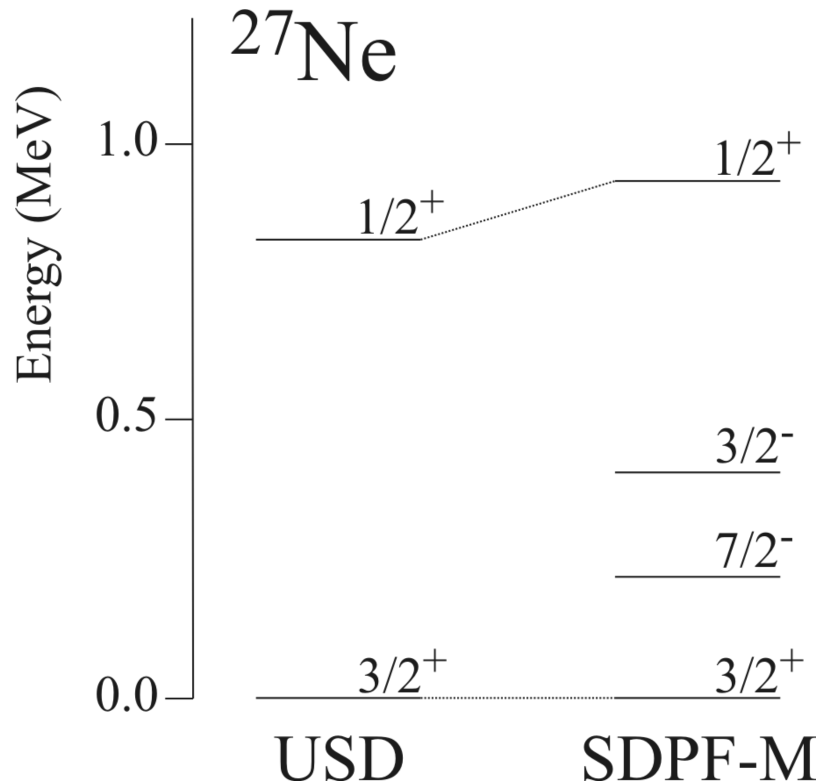




- ^{25}Ne is a well-behaved *sd* shell nucleus
- No evidence for intruder states below 3 MeV in ^{25}Ne
- No evidence for intruder configurations in the gs wave function of ^{26}Ne

Closer to the Island …

J. Russ Terry et al., PLB 640, 86 (2006)



(Tokyo group)

sd shell only

allows for intruder configurations

^{27}Ne

- SDPF-M interaction predicts higher level density than USD at low excitation
- SDPF-M predicts near degeneracy of normal and intruder states

Coming closer!
One-neutron removal from ^{28}Ne

NSCL NSF

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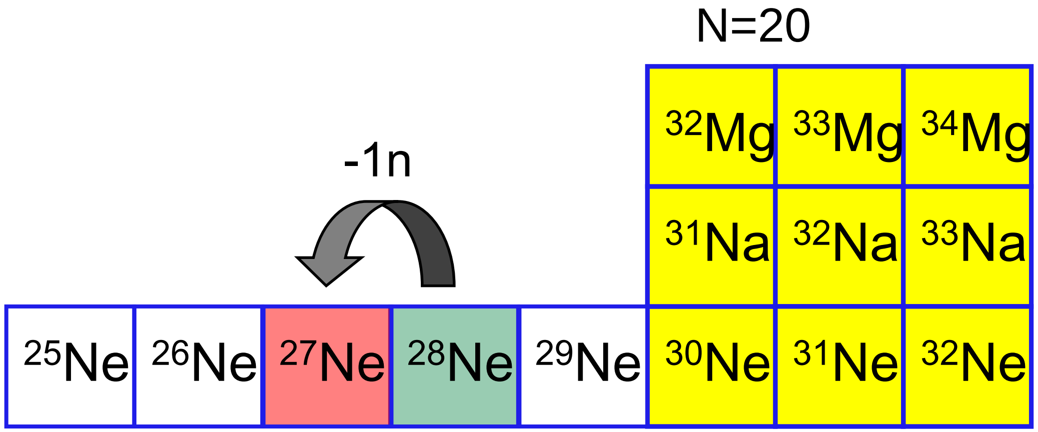
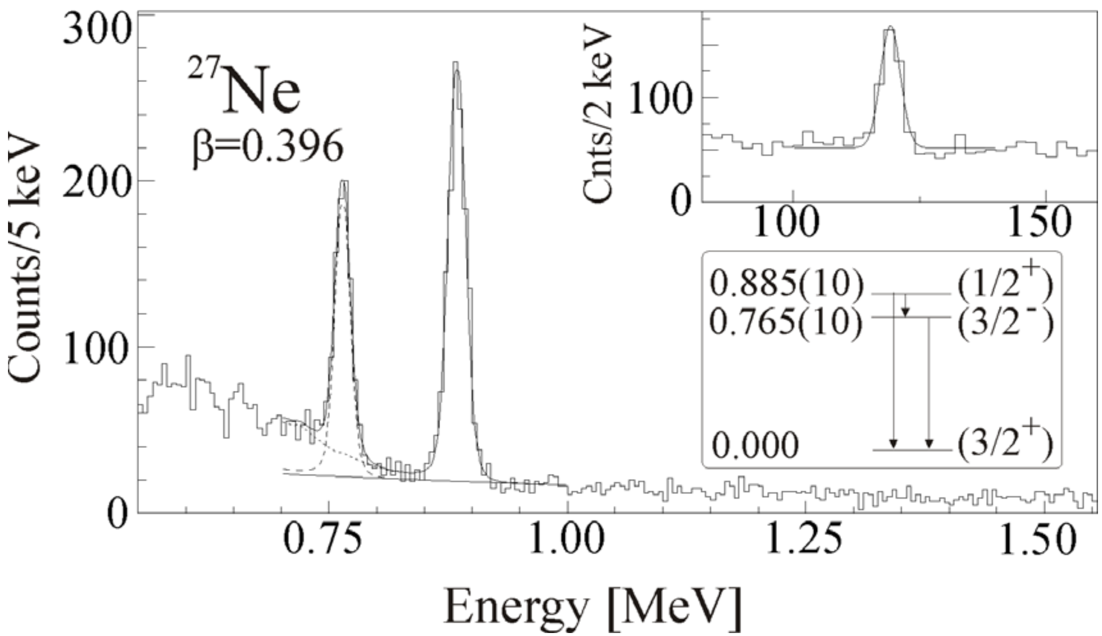
J. Russ Terry et al., PLB 640, 86 (2006)





See also: A. Obertelli et al., PLB 633, 33 (2006)
H. Iwasaki et al., PLB 620, 118 (2005)

^{25}Ne — no low-lying intruder states

^{26}Ne — no intruder configurations in gs

^{27}Ne — low-lying intruder state (~800 keV)

^{28}Ne — $\nu p_{3/2}$ intruder configuration in gs

J. Russ Terry et al., PLB 640, 86 (2006)

Not an "Island" with hard outlines …
… rather a gradual onset of intruder states

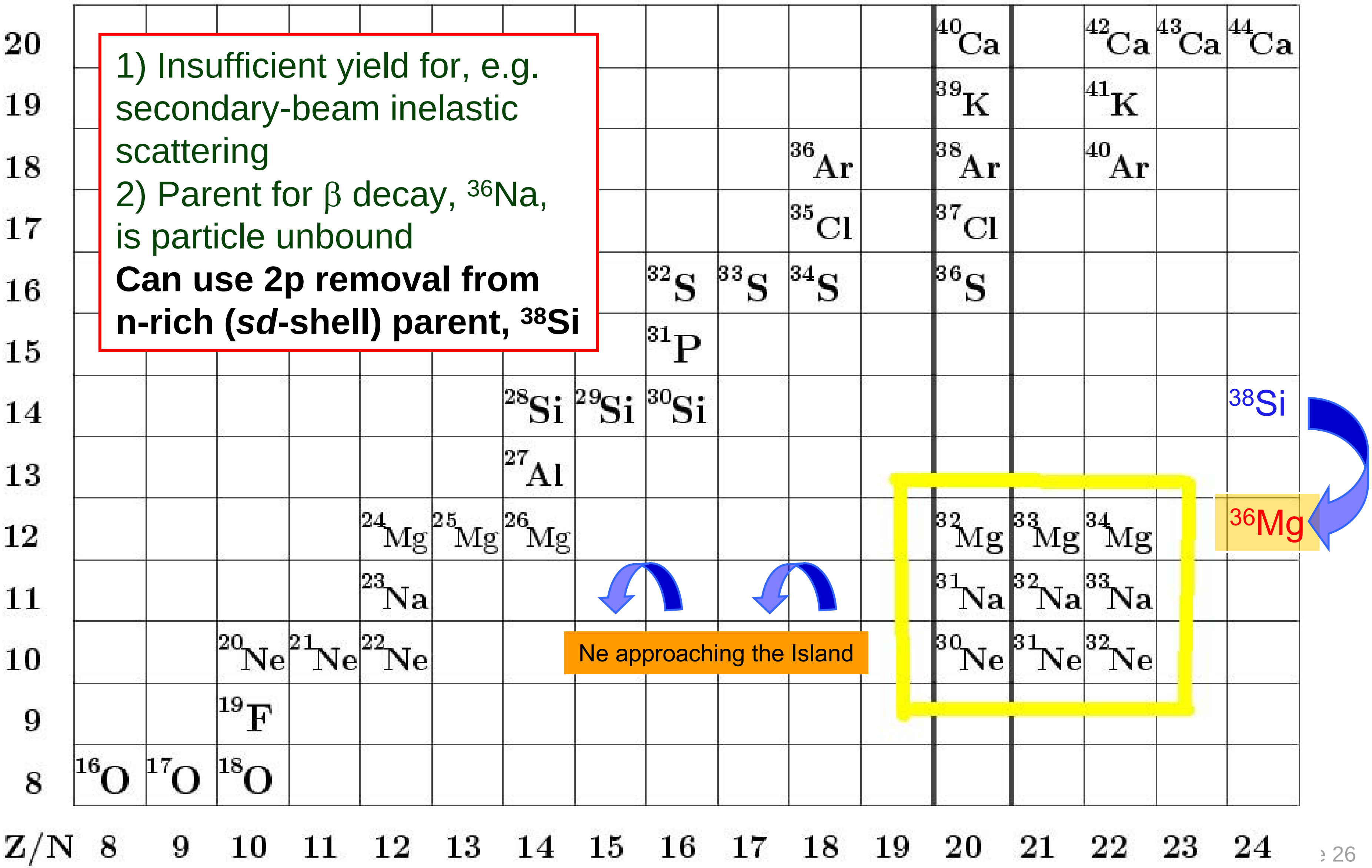
Going East …
^{36}Mg and the “Island of Inversion”

Figure: Warburton, Becker and Brown, PRC 41, 1147 (1990)

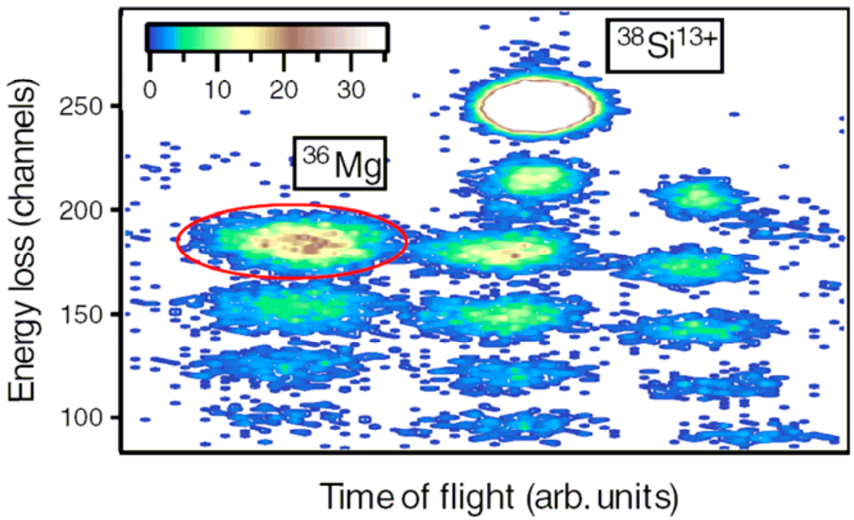
1) Insufficient yield for, e.g. secondary-beam inelastic scattering

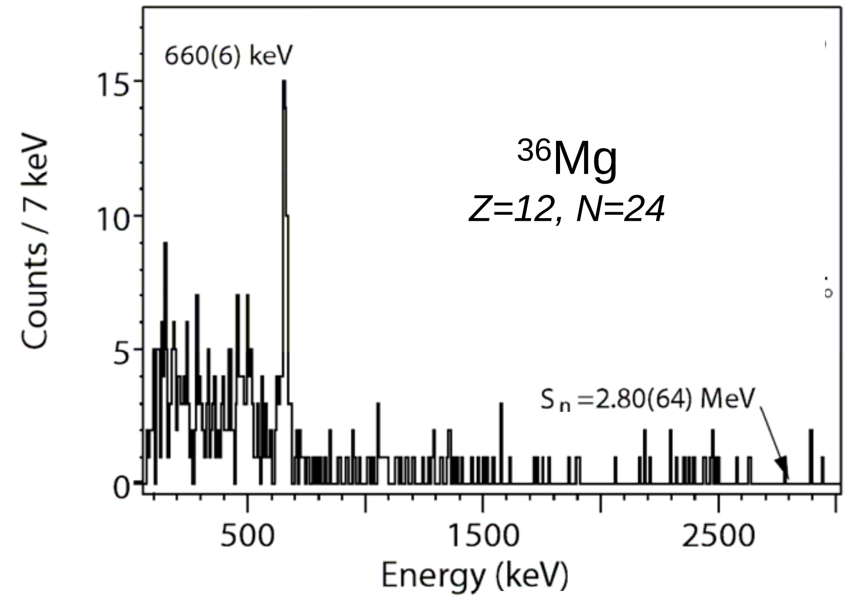
2) Parent for β decay, ^{36}Na, is particle unbound

Can use 2p removal from n-rich (*sd*-shell) parent, ^{38}Si



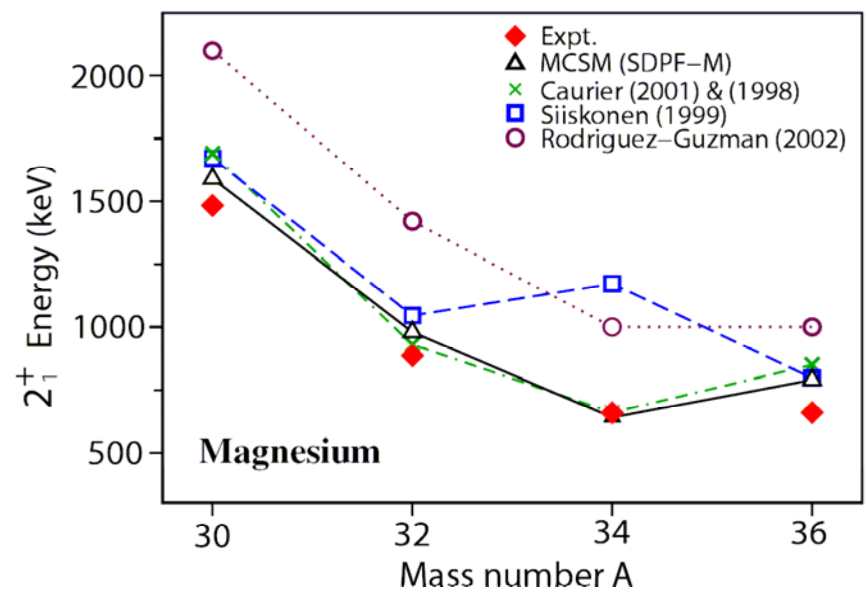
Tour de Force … or reaching ^{36}Mg





^{38}Si-2p

- ^{48}Ca primary beam
- 1500 ^{38}Si per second secondary projectile beam
- cross section: σ=0.10(1)mb (~1 out of 400,000 ^{38}Si)
- 42(6)% of the cross section to 2^+, 58(6)% to the ground state
- In comparison to theory, ^{36}Mg has intruder-dominated ground state



A. Gade et al., Phys. Rev. Lett. 99, 072502 (2007)

Low-energy transfer reactions

A. H. Wuosmaa et al., PRL 94, 082502 (2005)

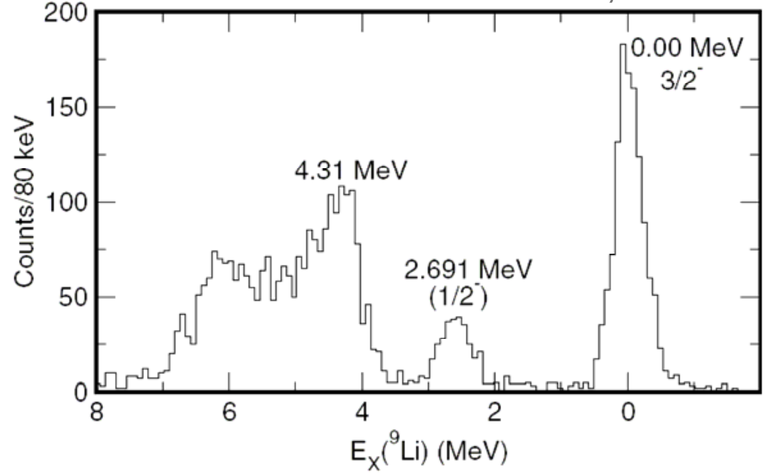


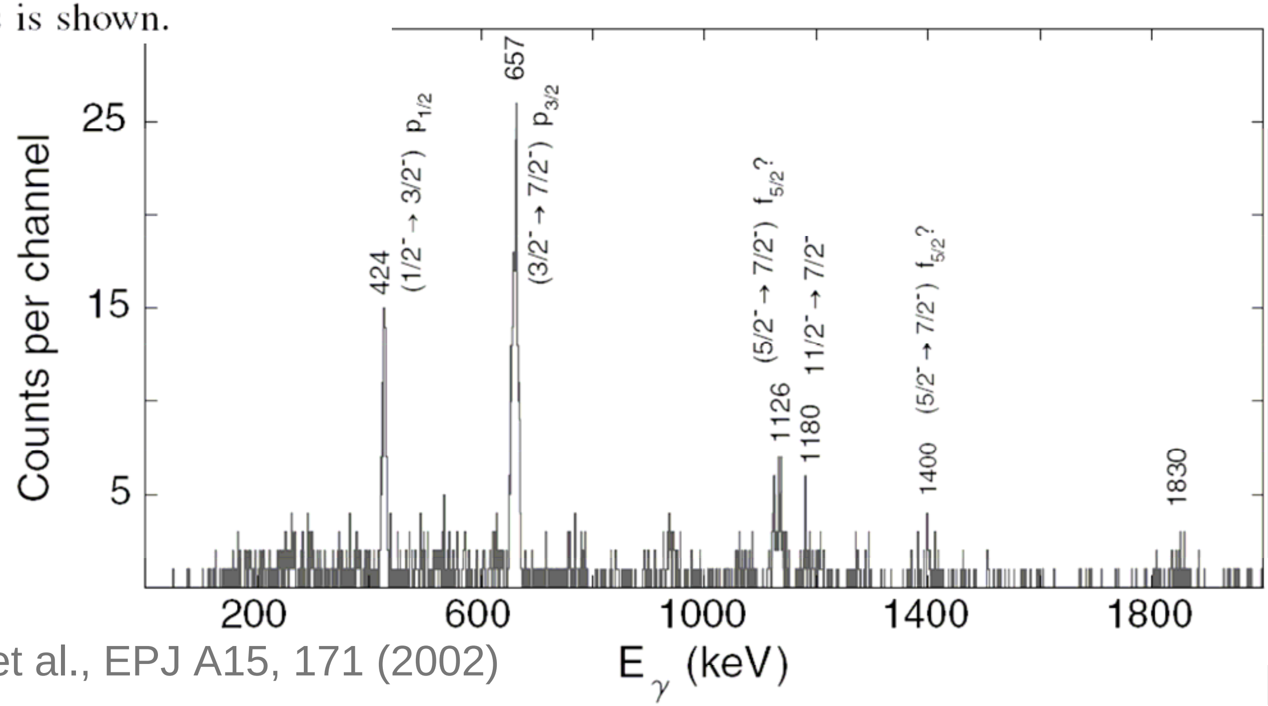
FIG. 2. Excitation-energy spectrum for ^{2}H(^{8}Li, p)^{9}Li. The sum of coincidences at all laboratory angles is shown.

Low-energy inverse-kinematics transfer experiment

- ^{2}H(^{8}Li,p)^{9}Li at ANL
- Proton angular distribution measured
- Quantitative spectroscopic information obtained

Heavy-ion induced transfer

- ^{9}Be(^{134}Te,^{8}Be)^{135}Te at HRIBF@ORNL
- Gamma-ray detection in coincidence with 2α clusters



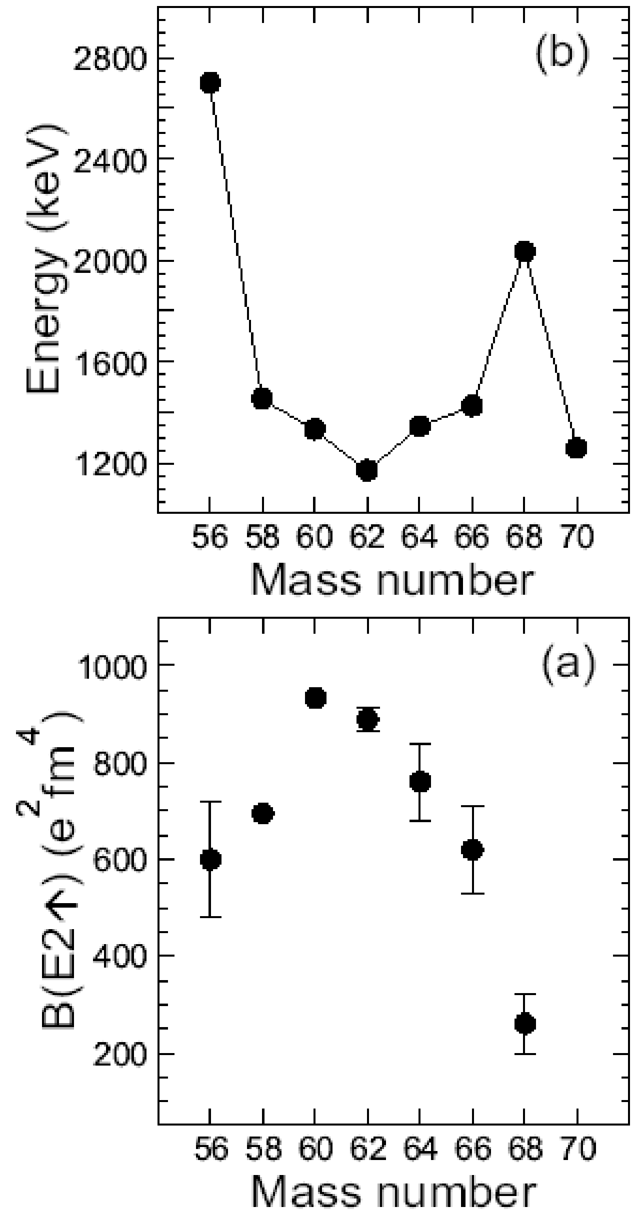
D.C. Radford et al., EPJ A15, 171 (2002)

Traditional Coulomb excitation

NUCLEAR SHAPES STUDIED BY COULOMB EXCITATION

Douglas Cline

Nuclear Structure Research Laboratory,[1] University of Rochester, Rochester, New York 14627



Nuclear excitation caused by the long-ranged electric field acting between colliding atomic nuclei is called Coulomb excitation. For bombarding energies well below the Coulomb barrier, the colliding nuclei remain sufficiently far apart to ensure the finite-range nuclear interaction is insignificant and the interaction is dominated by the well-known electromagnetic force.

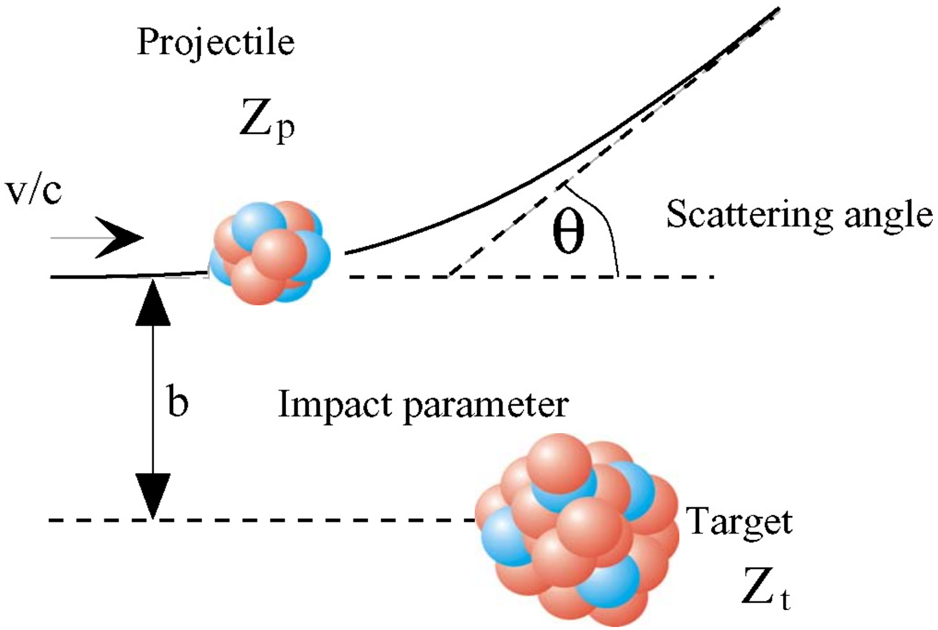
D. Cline, **“Nuclear shapes studied by Coulomb excitation”** Annu. Rev. Part. Sci. 36, 683 (1986)

Houston … we have a problem

At NSCL, RIKEN, GSI … the collision between target and projectile happens above the Coulomb barrier for every target-projectile combination

$$U_{coul} = \frac{k\, Z_1\, Z_2\, e^2}{r}$$

But: electromagnetic interaction dominates for $b > R_{int}$



For given v/c:

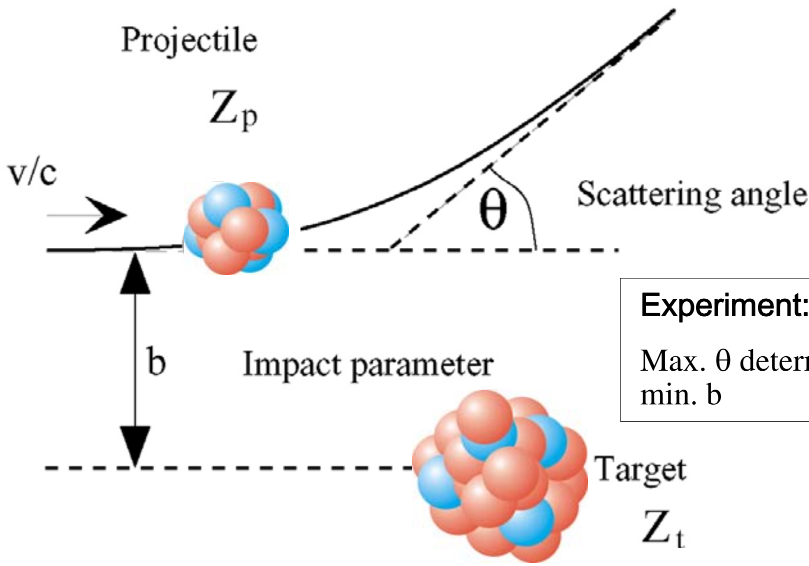
impact parameter $b=b(\theta)$

Experiment:

Maximum scattering angle determines minimum b. Restrict analysis to events at the most forward scattering angles so that $b(\theta) > R_{int}$

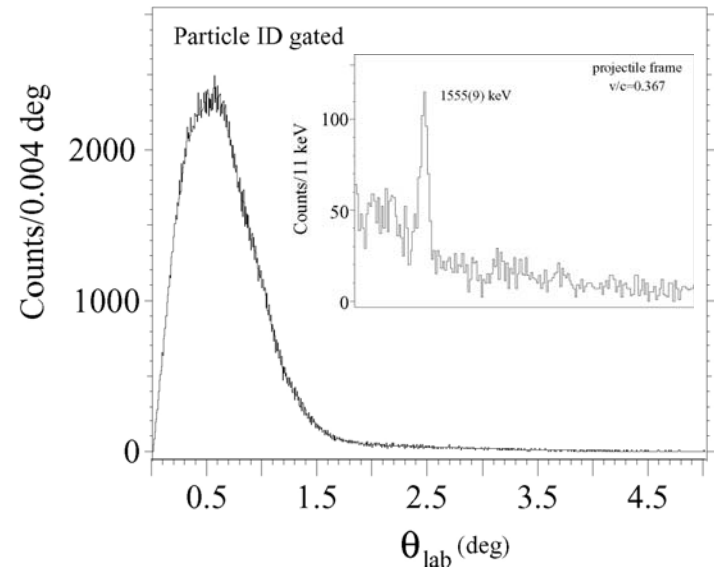
Intermediate-energy Coulomb excitation
Example: $^{46}Ar + ^{197}Au$

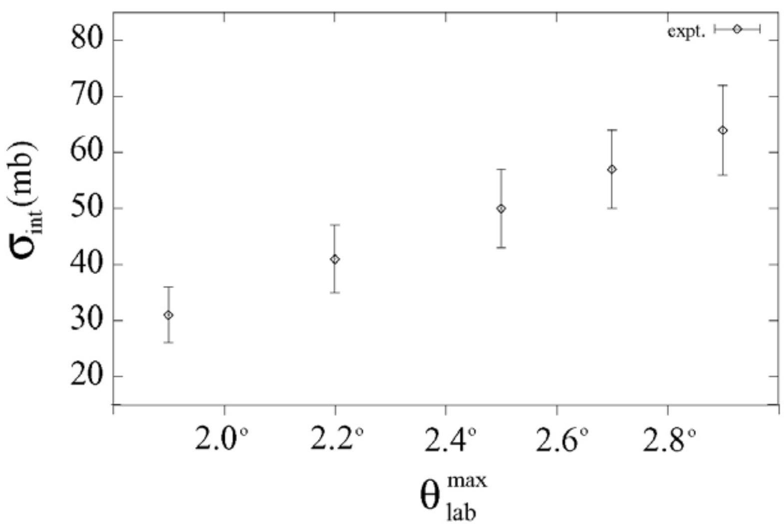
A. Gade *et al.*, Phys. Rev. C 68, 014302 (2003)

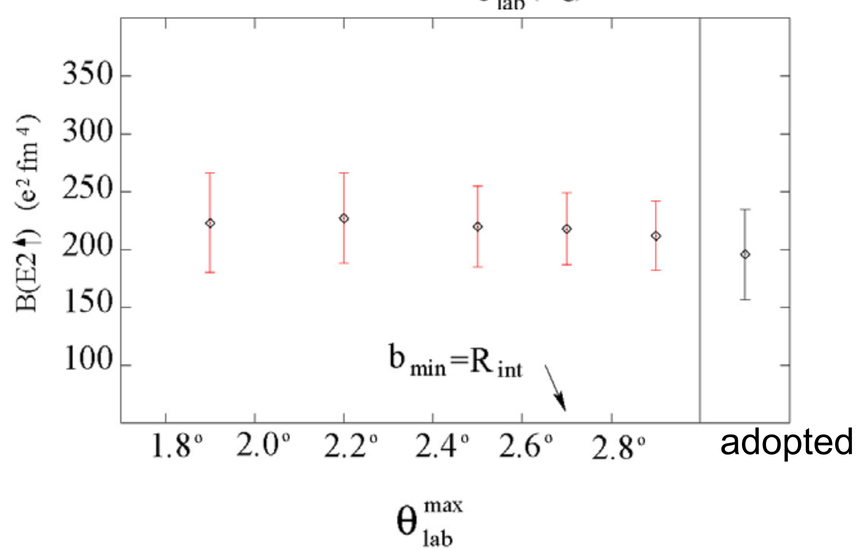


Experiment:

Max. θ determines min. b

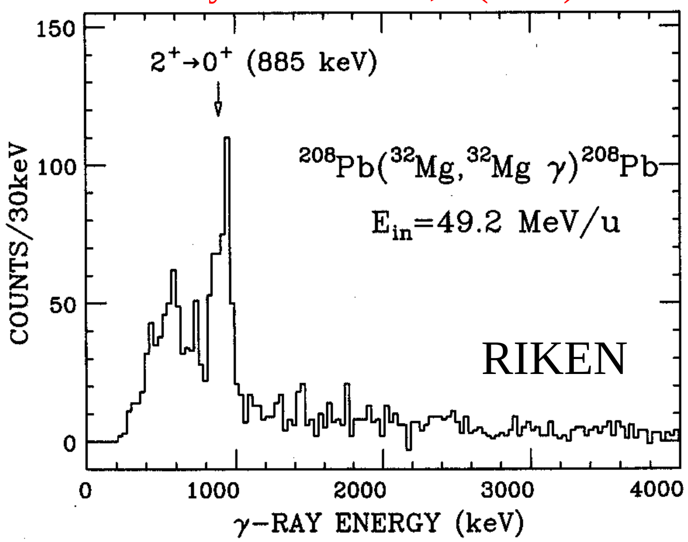




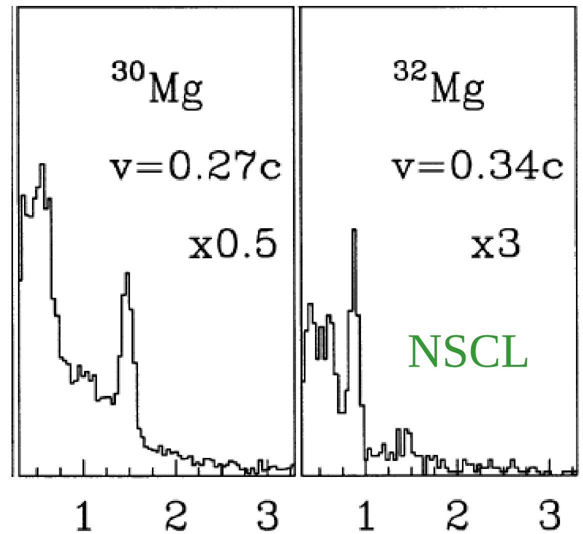


Collectivity inside the Island of Inversion

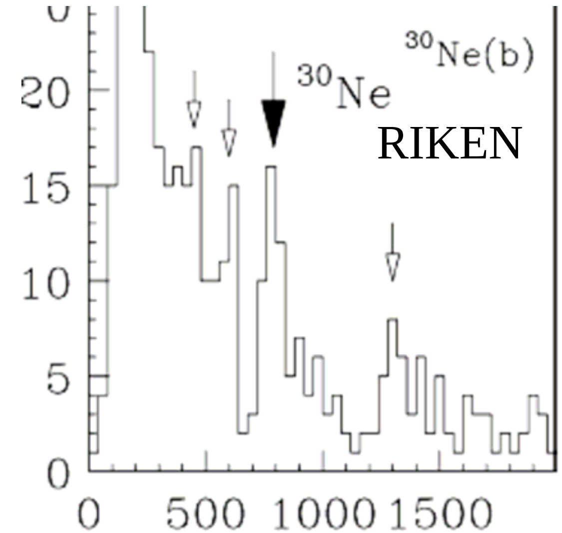
Phys. Lett. B 346, 9 (1995)



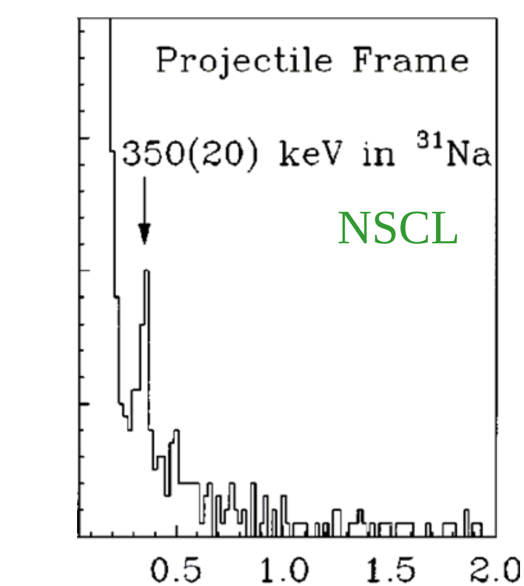
Phys.Lett. 461B, 322 (1999)



Phys.Lett. B 566, 84 (2003)



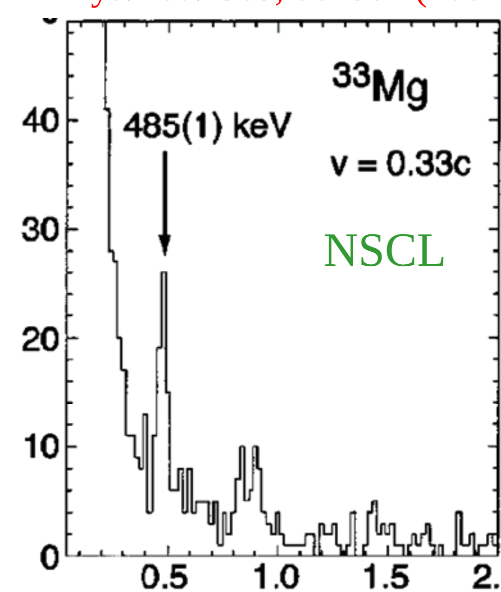
Phys.Rev. C63, 011305 (2001)



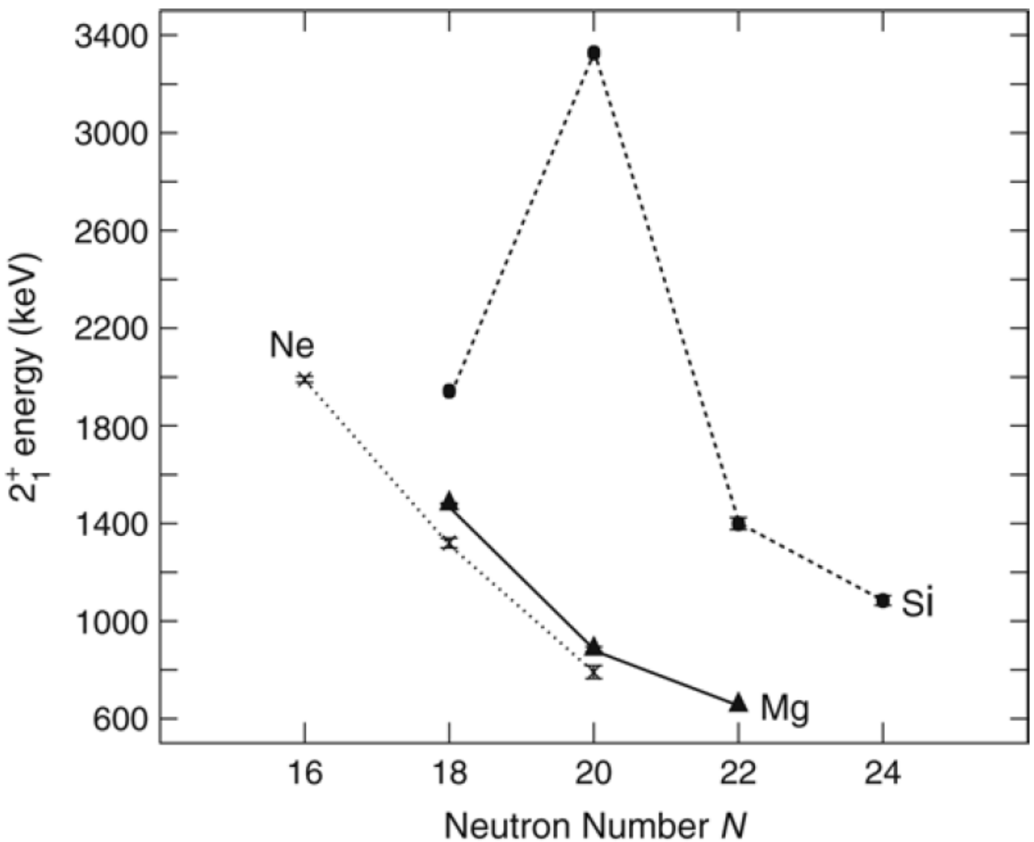
^{32}Mg	^{33}Mg	^{34}Mg
^{31}Na	^{32}Na	^{33}Na
^{30}Ne	^{31}Ne	^{32}Ne

RIKEN
NSCL

Phys.Rev. C65, 061304 (2002)



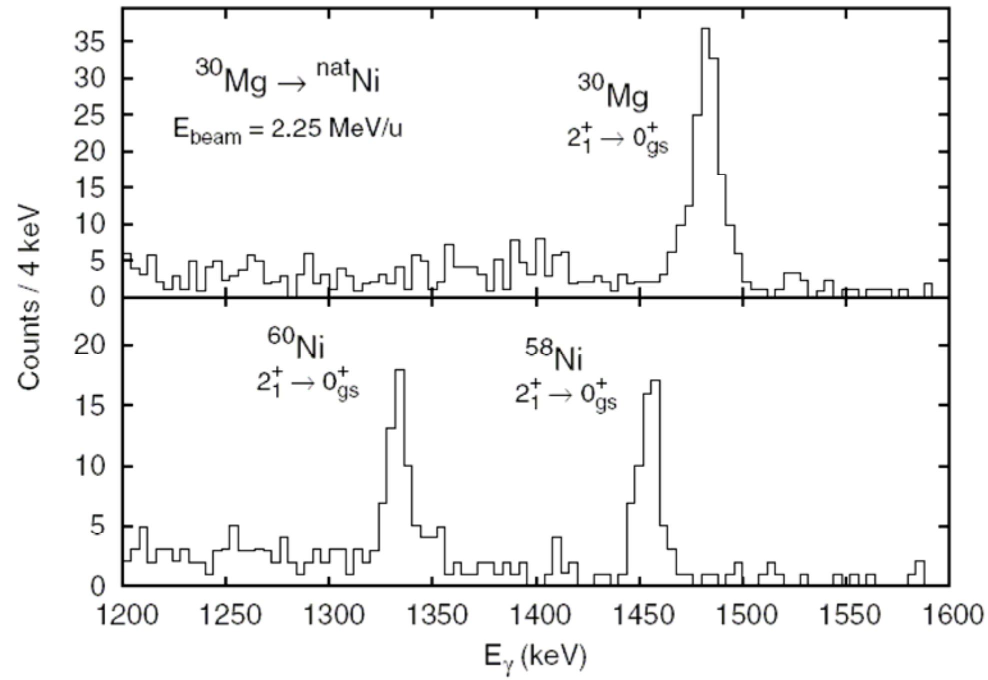
The first 2^+ state as signature

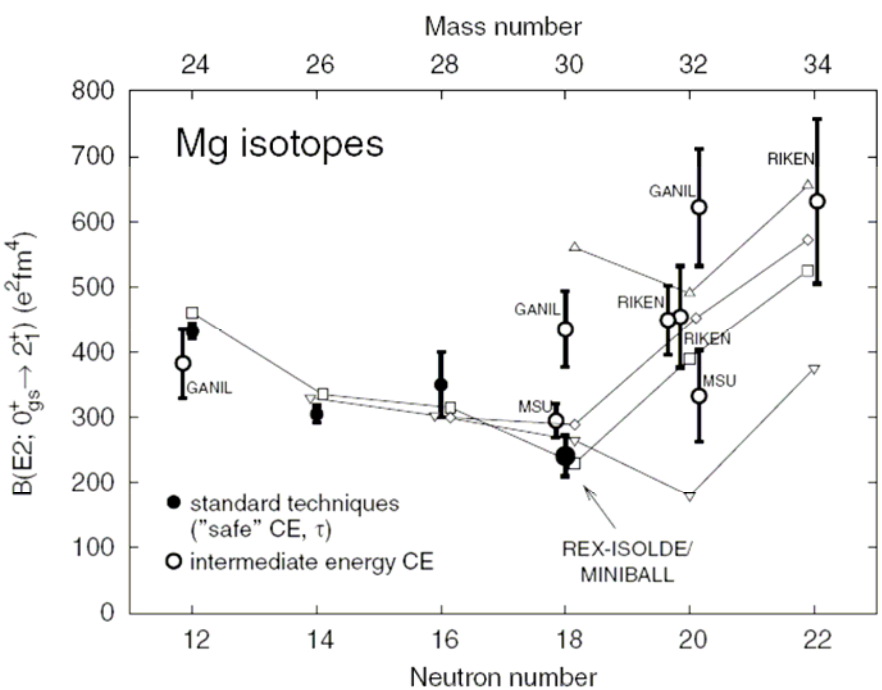


Low-energy Coulomb excitation
Example: ^{30}Mg + ^{58,60}Ni

^{30}Mg at 2.25 MeV/nucleon on natural Ni target (1.0 mg/cm^2)
From REX-ISOLDE at CERN
γ-ray detection with MINIBALL.
Particle detection with CD-shaped double-sided Si strip detector

O. Niedermaier *et al.*, Phys. Rev. Lett. 94, 172501 (2005)





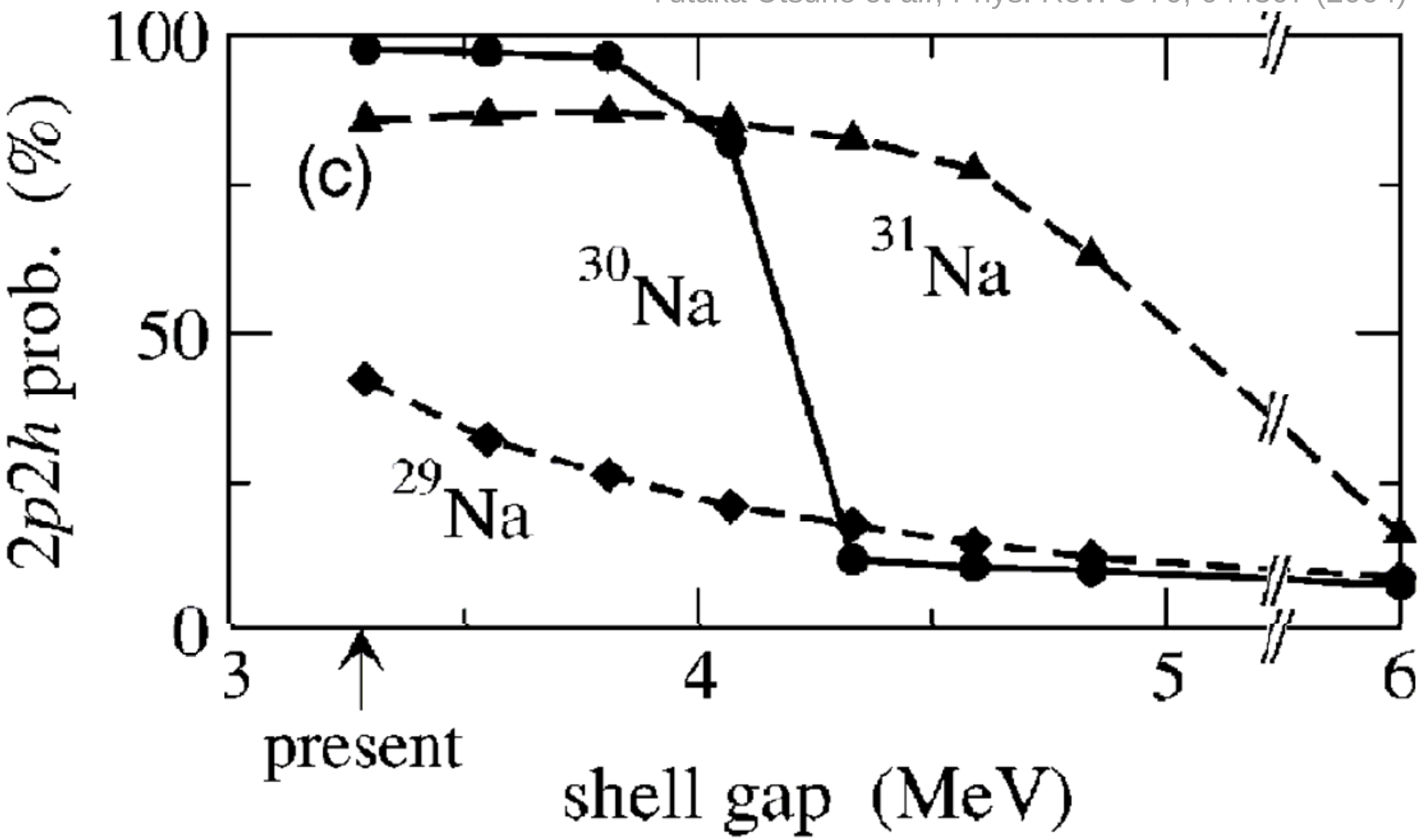
$$\frac{\sigma_{CE}(^{30}\mathrm{Mg})}{\sigma_{CE}(^{58,60}\mathrm{Ni})} = \frac{\epsilon_\gamma(^{58,60}\mathrm{Ni})}{\epsilon_\gamma(^{30}\mathrm{Mg})} \frac{W_\gamma(^{58,60}\mathrm{Ni})}{W_\gamma(^{30}\mathrm{Mg})} \frac{N_\gamma(^{30}\mathrm{Mg})}{N_\gamma(^{58,60}\mathrm{Ni})},$$

Why in the world ^{30}Na?

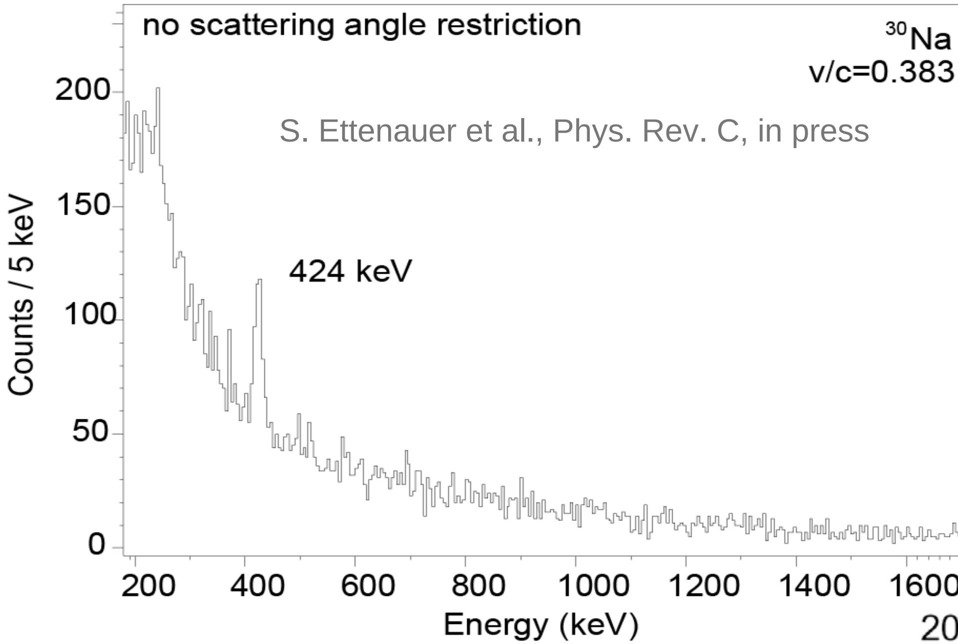
Or: My PhD thesis advisor used to tell me that odd-odd nuclei are a bit messy … but I did not listen

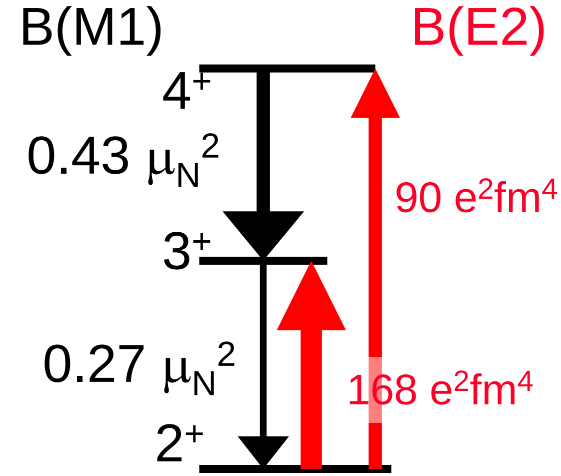
^{30}Na is more sensitive to the size of the N=20 shell gap than any other Na isotope

Yutaka Utsuno *et al.*, Phys. Rev. C 70, 044307 (2004)



A puzzle for theory … ^{30}Na Coulomb excitation

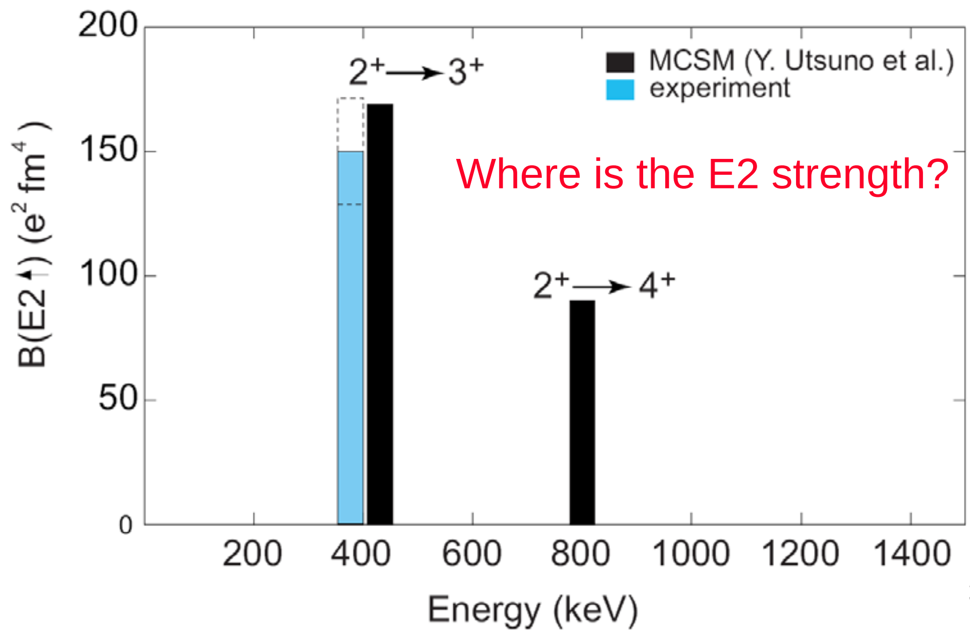




Yutaka Utsuno *et al.*,
Phys. Rev. C 70, 044307 (2004)

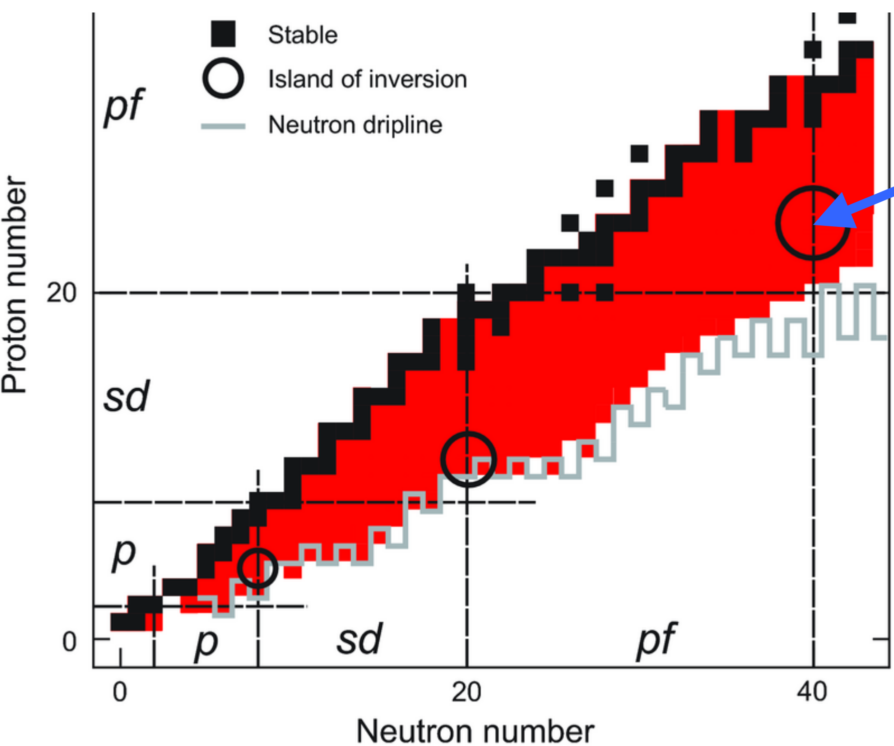
^{30}Na + ^{209}Bi at 80 MeV/nucleon

- Target: 737 mg/cm^2 ^{209}Bi
- Few hundred ^{30}Na per second projectile beam
- cross section: σ=41(5) mb
  (~1 out of 268,000 ^{30}Na emits a γ-ray that is detected)
- B(E2; $2^+ \rightarrow 3^+$)=147(21) e^2fm^4



Summary and outlook

- Exotic nuclei are qualitatively different from stable nuclei
- Predictive power on exotic nuclei is limited
  - Nuclear existence, modifications to magic numbers, …
- New generation of experiments measures observables that can be compared to theory



Other “Islands of Inversion”?

Prediction: Around ^{62}Ti (B.A. Brown)

Needed to reach this: A new facility …

The Nuclear Shell Model Towards the Drip Lines *

B. Alex Brown
Department of Physics and Astronomy
and National Superconducting Cyclotron Laboratory, Michigan State University,
East Lansing, Michigan 48824-1321, USA

July 12, 2002

I apologize …

… for not giving you more details about

- Nuclear halo states, K. Riisager, Rev. Mod. Phys. 66, 1105 (1994).
- Radioactive nuclear beam facilities based on projectile fragmentation, D.J. Morrissey and B.M. Sherrill, Proc. Royal Soc. A 356, 1985 (1998).
- Mass measurements of short-lived nuclides with ion traps, G. Bollen, NPA 693, 3 (2001).
- Nuclear magnetic and quadrupole moments for nuclear stricture research on exotic nuclei, G. Neyens, Rep. Prog. Phys. 66, 633 (2003).
- Radioactive beam facilities of North America, J. A. Nolen, NPA 746 (2004) 9c.
- Physics of a Rare Isotope Accelerator, D.F. Geesaman, C.K. Gelbke et al., Prog. Part. Nucl. Phys. 56, 53 (2006).
- In-beam nuclear spectroscopy of bound states with fast exotic ion beams, A. Gade and T. Glasmacher, Prog. Part. Nucl. Phys. 60, 161 (2008).

- Report of the Isotope Separation On-Line (ISOL) task force to the Nuclear Science Advisory Committee (NSAC), URL http://srfsrv.jlab.org/isol/ISOLTaskForceReport.pdf.

but 1 hour only has 60 minutes …

Partners in Crime …

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NSCL's drip-line hunters

LETTERS nature

Nature 449, 1022 (2007)

Discovery of ^{40}Mg and ^{42}Al suggests neutron drip-line slant towards heavier isotopes

T. Baumann[1], A. M. Amthor[1,2], D. Bazin[1], B. A. Brown[1,2], C. M. Folden III[1], A. Gade[1,2], T. N. Ginter[1], M. Hausmann[1], M. Matoš[1], D. J. Morrissey[1,3], M. Portillo[1], A. Schiller[1], B. M. Sherrill[1,2], A. Stolz[1], O. B. Tarasov[1,4] & M. Thoennessen[1,2]