Experiments with rare isotopes

The limits of experiments at the limits of stability

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Joint Institute for Heavy Ion Research, Oak Ridge, Tennessee, USA
Oak Ridge National Laboratory
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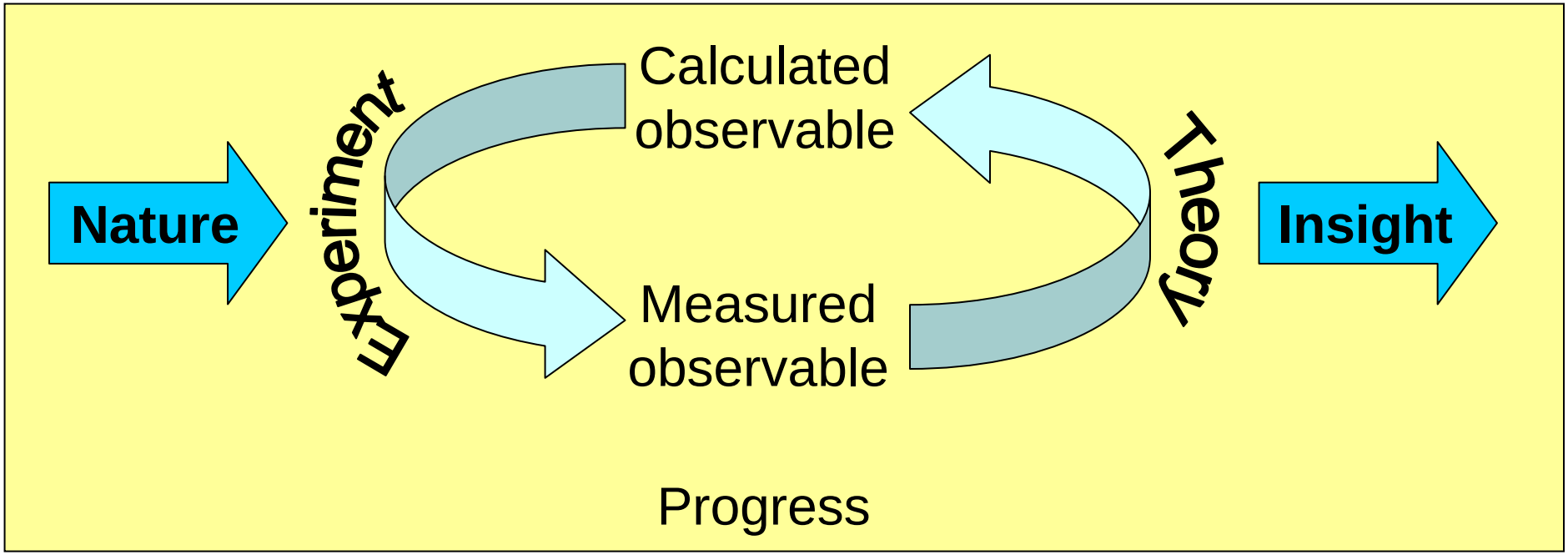
Our shared goal: To develop a predictive theory of atomic nuclei and their reactions

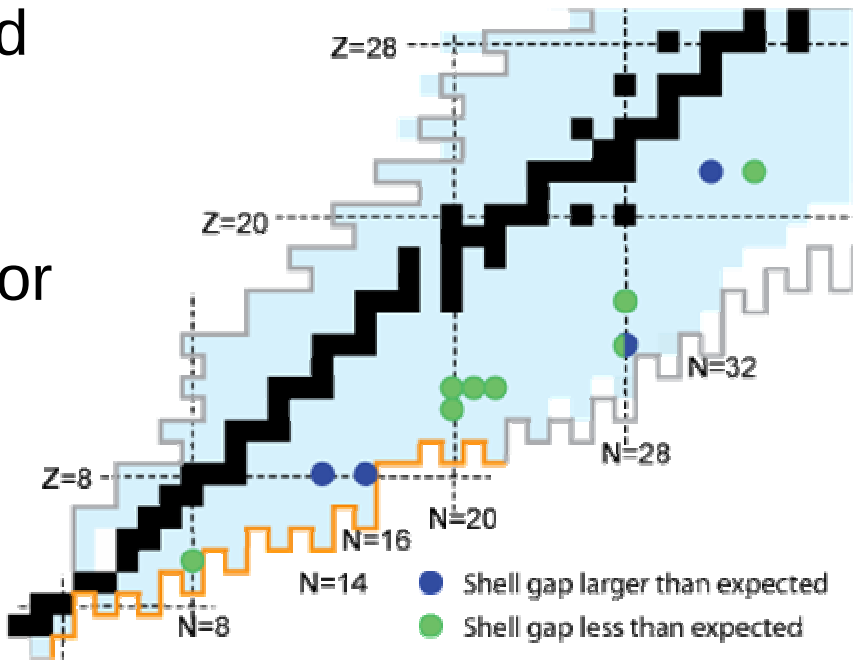


Optimize progress by investing resources wisely:

- Measure observables that can (in principle) be calculated
- Calculate observables that (in principle) can be checked in experiments

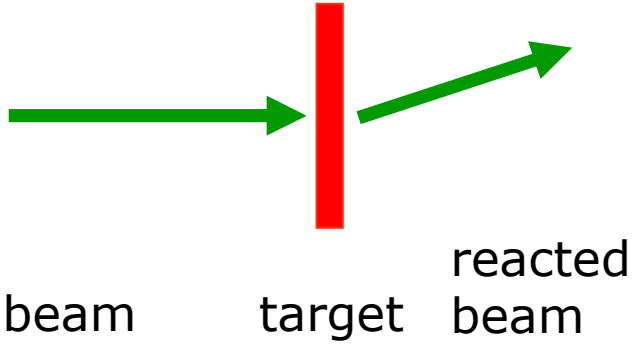
Rare isotopes are a wise investment and Tasks for experimenters

- Stable nuclei are well-described with closed-shell nuclei as key benchmarks
- Rare isotopes show evidence for
  - disappearance of canonical shell gaps,
  - appearance of new shell gaps,
  - reduction of spin-orbit force,
  - influence of continuum states



- Experimental task: Quantify changes encountered in rare isotopes and measure with defined certainty observables that are calculable and can be used to discriminate between theories

Facts of life for experimentalists

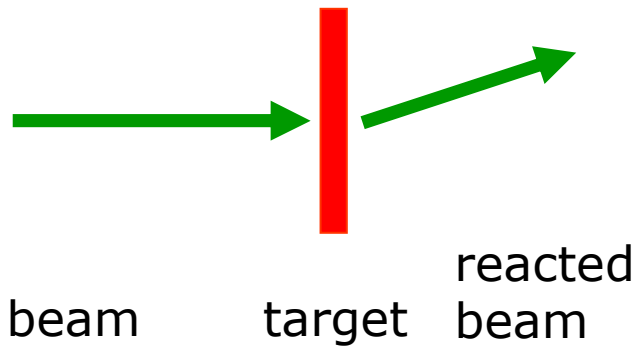


$$N_{obs}/\varepsilon = N_R = N_T \times N_B \times \sigma$$

N_{obs} observed reactions
N_R reaction rate
N_B beam rate

ε detection efficiency
N_T atomic density of target
σ cross section

Facts of life for experimentalists



Build more efficient detectors

Make more beam

Given by nature

$$N_{obs}/\varepsilon = N_R = N_T \times N_B \times \sigma$$

Use targets with more scattering centers

N_{obs} observed reactions
N_R reaction rate
N_B beam rate

ε detection efficiency
N_T atomic density of target
σ cross section

Experimental observables in experiments with in-flight produced rare isotope beams

Stopped beam experiments

- Possible experiments and quality of observables depend on number of beam particles
- Discovery
  (few particles total)
- Half live
  (few ten particles)
- Mass
  (few hundred particles)

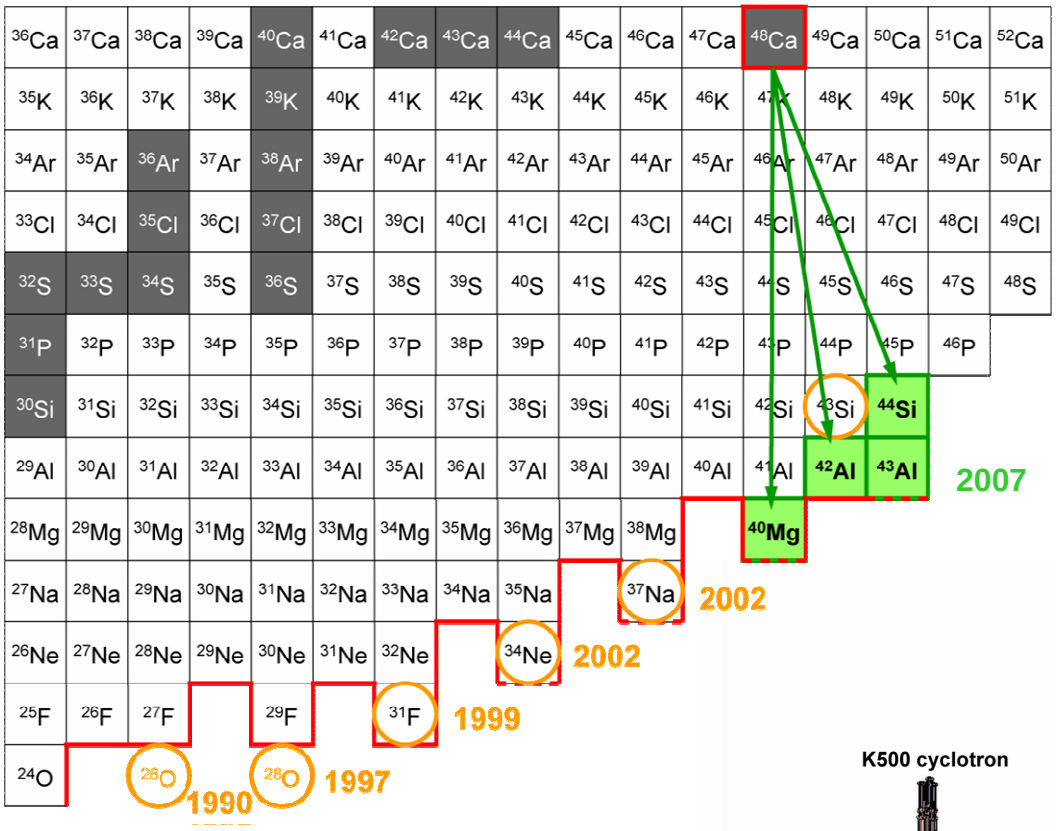
Fast beam experiments

- Possible experiments and quality of observables depend on luminosity
- Interaction radii
  (few particles per hour)
- g-factors
  (hundreds of particles per second)

Fast beam experiments (cont'd)

- Excited state energies, transition matrix elements
  - Elastic and inelastic scattering
    (ten particles per second)
    - Electromagnetic
    - Hadronic
  - Lifetimes from γ-ray line shapes
    (hundreds of particles per second)
- Occupation numbers
  - Nucleon removal
    - Single nucleon
      (particles per second)
    - Two-nucleon
      (hundreds of particles per second)
    - Multi-nucleon
      (hundreds of particles per second)
  - Nucleon addition
    (hundreds of particles per second)

Stopped beam experiment: Discovery of new isotopes near the *n*-dripline: ^{40}Mg, ^{42}Al, ^{43}Al, ^{44}Si



1990: **GANIL** Guillemaud-Mueller *et al*., Z. Phys. A 332, 189

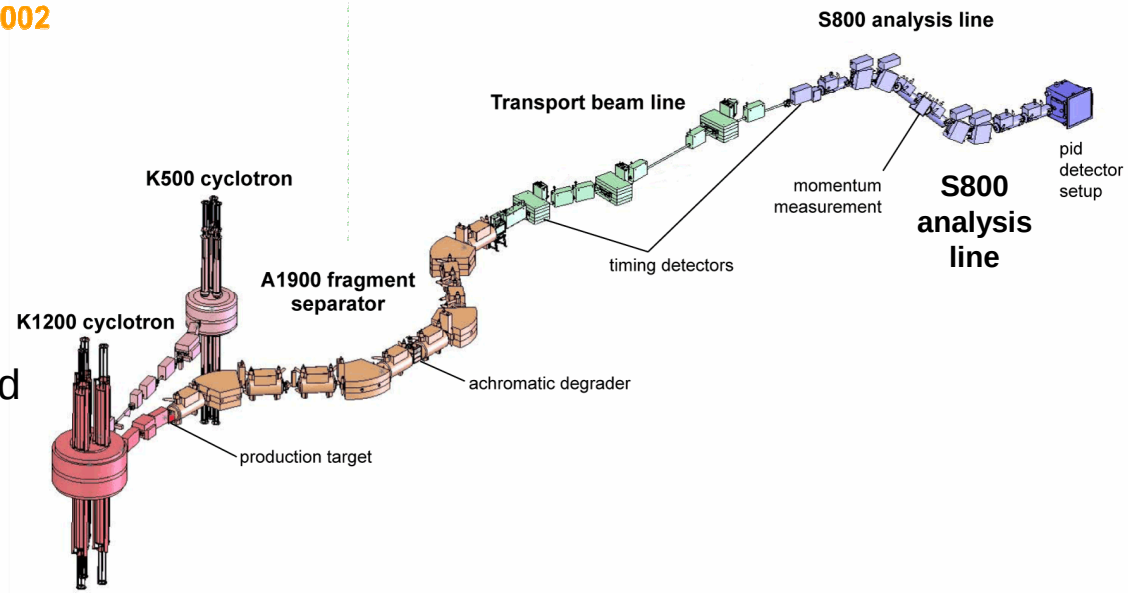
1997: **GANIL** Tarasov *et al*., Phys. Lett. B 409, 64

1999: **RIKEN** Sakurai *et al*., Phys. Lett. B 448, 180

2002: **RIKEN** Notani *et al*., Phys. Lett. B 542, 49
GANIL Lukyanov *et al*., J. Phys. G 28, L41

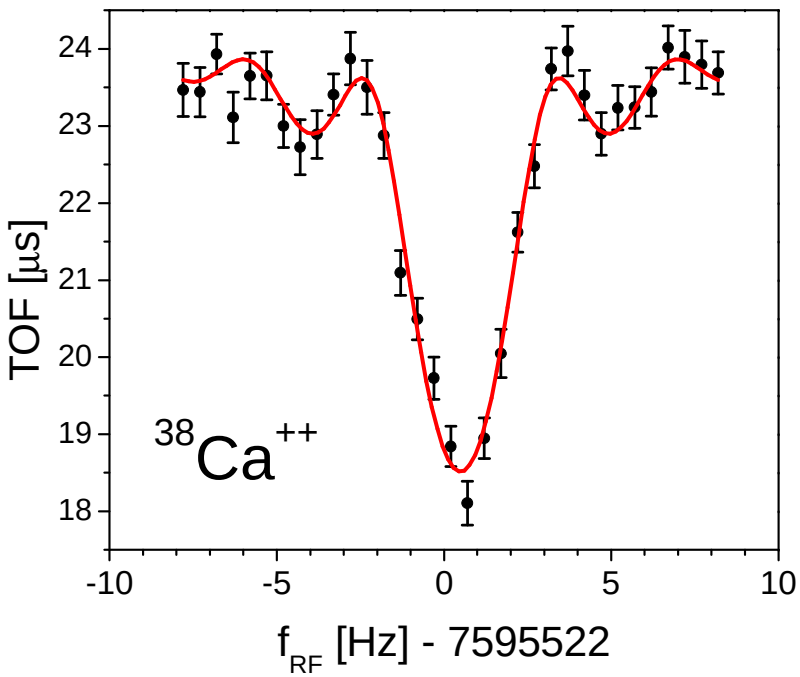
2007: **NSCL** Tarasov *et al*, Phys. Rev. C 75 (2007) 064613; Baumann *et al*, Nature 449 (2007) 1022

- 4×10^{17} ^{48}Ca beam particles
- Two-stage separator (one-stage did not provide sufficient clean-up)
- First observation of ^{40}Mg (3 events), ^{42}Al, ^{43}Al



Stopped beam experiment: Mass measurement

Stop fast exotic beams in gas cell, extract, and use in experiments



^{38}Ca: $T_{1/2}$ = 440 ms, $0^+ \rightarrow 0^+$ β^+-emitter

- new candidate for the test of the conserved vector current (CVC) hypothesis

ME_{LEBIT} = -22058.53(28) keV

δm = 280 eV, $\delta m/m = 8 \cdot 10^{-9}$

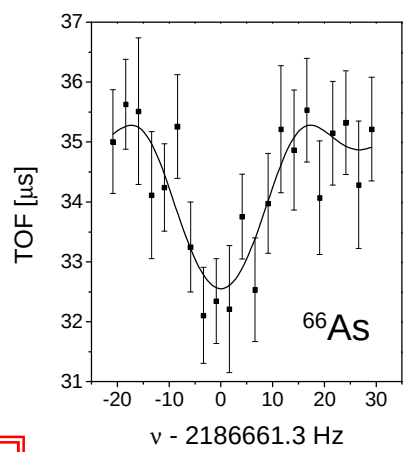
- AME 03: δm = 5 keV

G. Bollen *et al*. Phys. Rev. Lett. **96** (2006) 152501

Penning trap mass measurements of rare isotopes produced in-flight:

Since Summer 2005:

^{33}Si, ^{29}P, ^{34}P
^{37}Ca, ^{38}Ca
^{40}S, ^{41}S, ^{42}S, ^{43}S, ^{44}S
^{63}Ga, ^{64}Ga
^{64}Ge, ^{65}Ge, ^{66}Ge
^{66}As, ^{67}As, ^{68}As, ^{80}As
^{68}Se, ^{69}Se, ^{70}Se, ^{81}Se, ^{81m}Se
^{70m}Br, ^{71}Br



^{66}As: $T_{1/2}$ = 96 ms

LEBIT: $\delta m \approx$ 20 keV, $\delta m/m \approx 3 \times 10^{-7}$

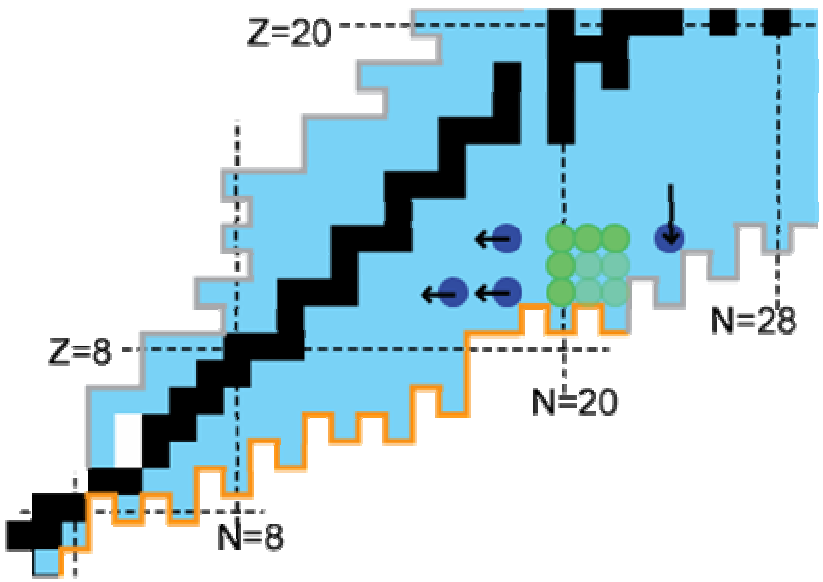
- 20-fold improved masses in region critical to rp process

Exploring the boundaries of Island of Inversion

- C. Thibault *et al*: PRC 12 (1975) 646
  ^{31,32}Na, local increase of S_{2n} → *N=20* shell gap decreased
- X. Campi *et al*: NPA 251(1975) 193
  explained by deformation via filling of $\nu(f_{7/2})$
- C. Detraz *et al*: PRC19 (1979) 164
  ^{32}Na → ^{32}Mg β–decay, low 2^+ in ^{32}Mg
- E. Warburton *et al*: PRC 41 (1990) 1147
  Z=10-12 and *N=20-22* have ground state wavefunctions dominated by $\nu(sd)^{-2}(fp)^{+2}$ configurations
- T. Motobayashi *et al*: PLB 346 (1995) 9
  large B(E2;0^+→ 2^+) in ^{32}Mg

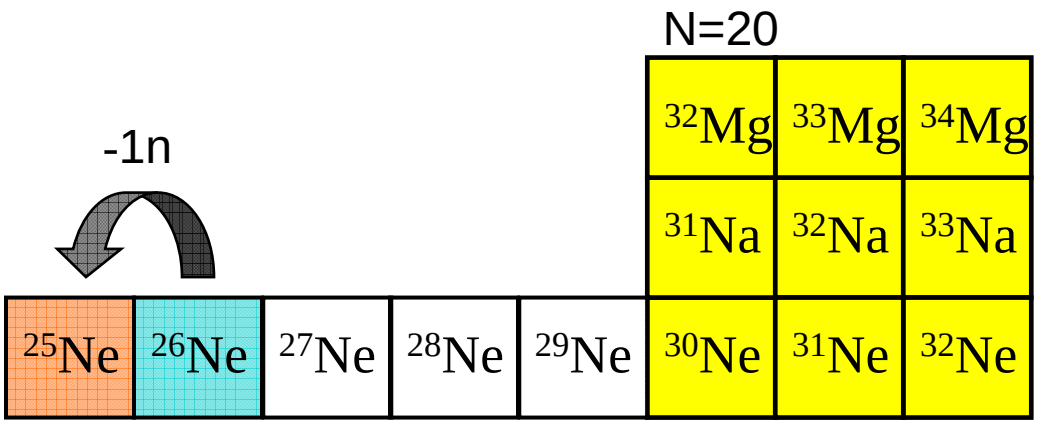
See also

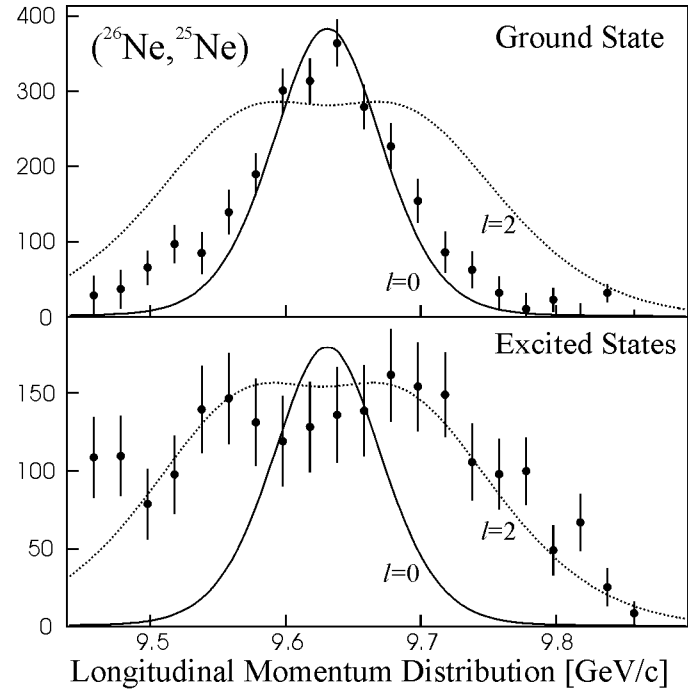
- ^{29}Na V. Tripathi *et al*. Phys. Rev. Lett. **94** (2005) 162501 (2005)
- ^{31}Mg G. Neyens *et al*. Phys. Rev. Lett. **94** (2005) 022501 (2005)
- ^{27}Ne A. Obertelli *et al*., Phys. Lett **B 633** (2006) 33
- ^{28}Ne H. Iwasaki *et al.*, Phys.Lett. **B 620** (2005) 118
- ^{34}Al P. Himpe, G. Neyens *et al*. Phys.Lett. **B 658** (2008) 203

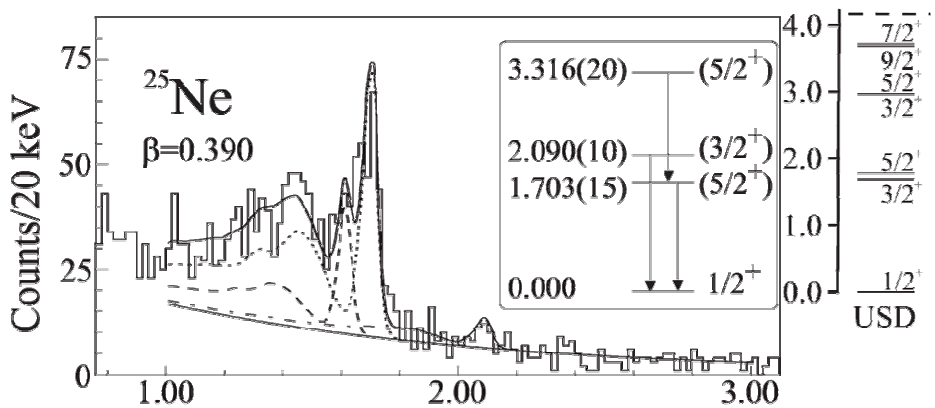


- Single-neutron removal to look for negative parity states, indicating the presence of $f_{7/2}$ intruder configurations in the ground state of the parent:
  (^{30}Mg,^{29}Mg+γ)
  (^{26}Ne,^{25}Ne+γ)
  (^{28}Ne,^{27}Ne+γ)
- (^{38}Si,^{36}Mg+γ) two-proton removal

Single-neutron removal from ^{26,28}Ne and ^{30}Mg







- ^{25}Ne is well-described in *sd* shell with no evidence for intruder states below 3 MeV

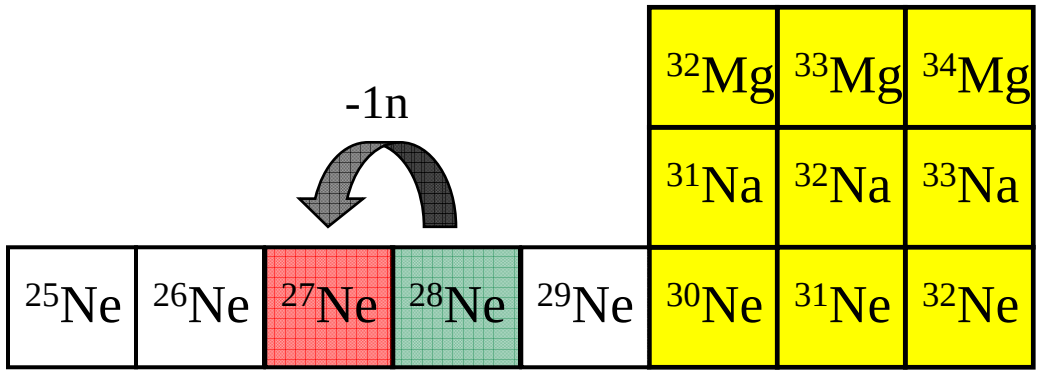
→ No evidence for intruder configurations in the ground state wave function of ^{26}Ne

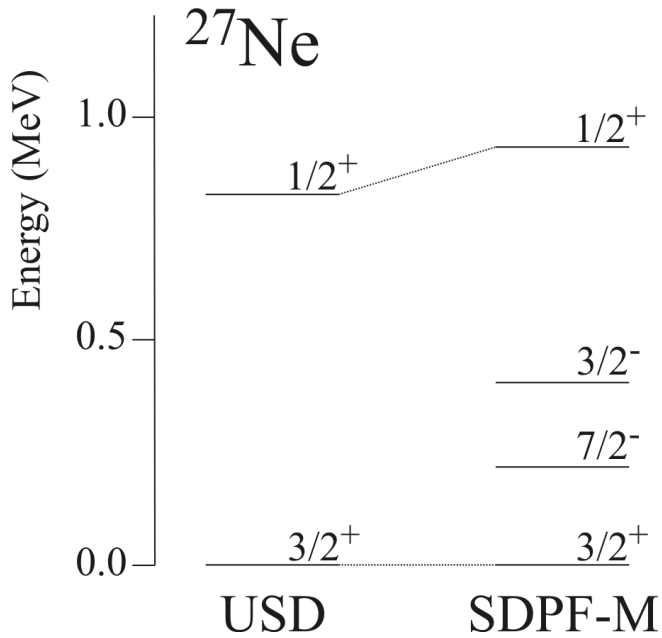
^{25}Ne level structure known

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

J.R. Terry *et al.*, Phys. Lett. **B 640** (2006) 86

Single-neutron removal from ^{26,28}Ne and ^{30}Mg

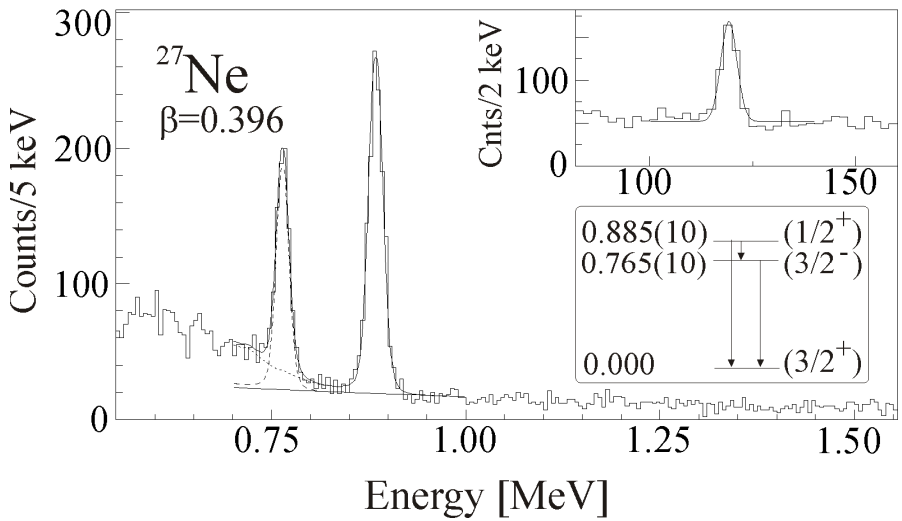


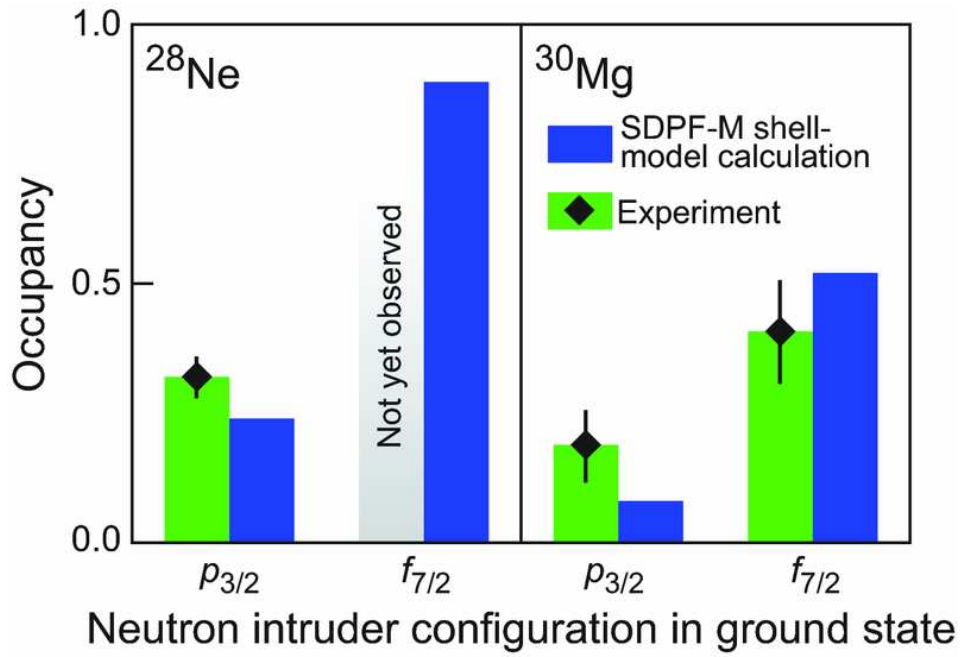


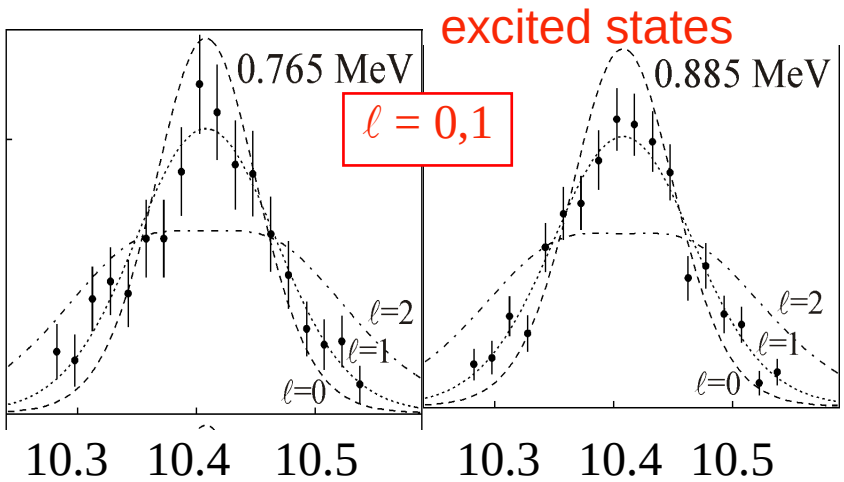
sd shell only

allows for intruder configurations

Single-neutron removal from ^{26,28}Ne and ^{30}Mg





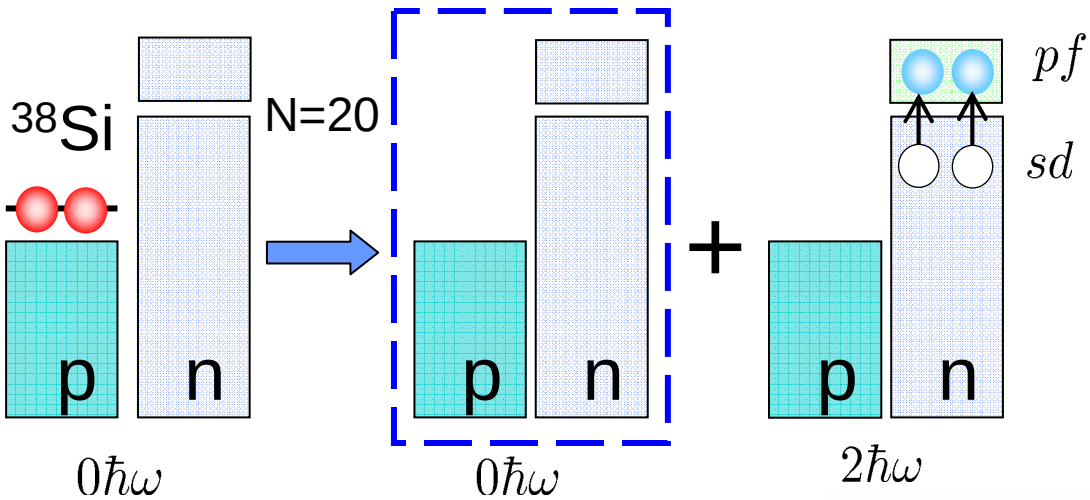


→ Ground states for ^{28}Ne, ^{30}Mg have significant 2hω $f_{7/2}$ intruder configurations

- See also
  ^{31}Mg G. Neyens *et al*. Phys. Rev. Lett. **94** (2005) 022501 (2005)
  ^{27}Ne A. Obertelli *et al*., Phys. Lett **B 633** (2006) 33

J.R. Terry *et al.*, Phys. Lett. **B 640** (2006) 86

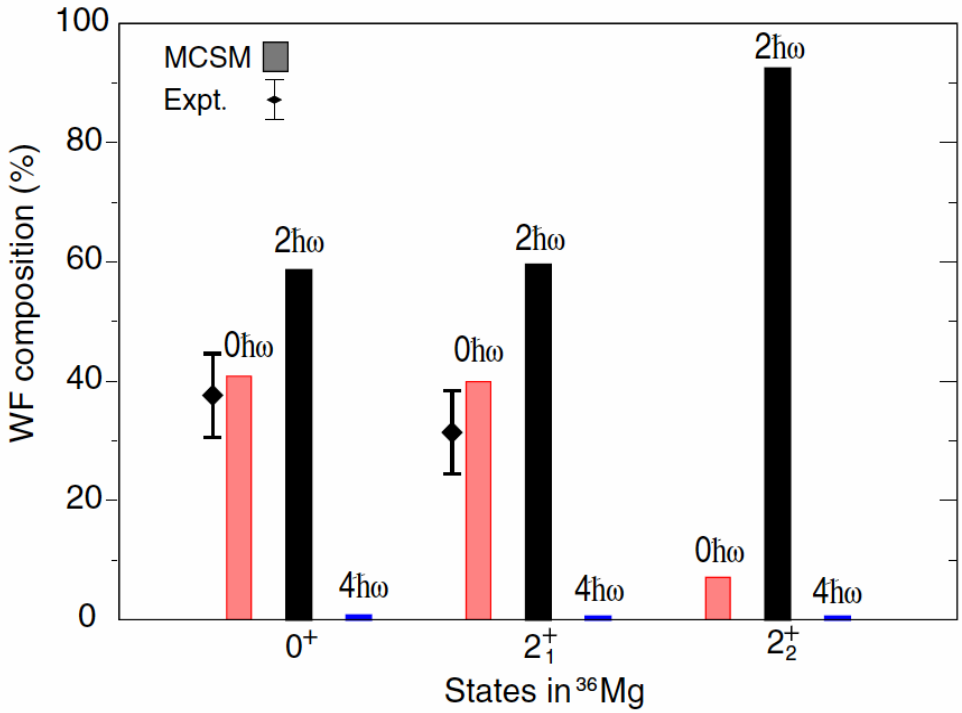
^{36}Mg g.s. dominated by 2hω configurations



Monte-Carlo Shell Model (MCSM) calculations:
SDPF-M interaction of
Y. Utsuno, T. Otsuka *et al*.

Reaction theory: J.A. Tostevin and B.A. Brown, PRC 74, 064604 (2006),

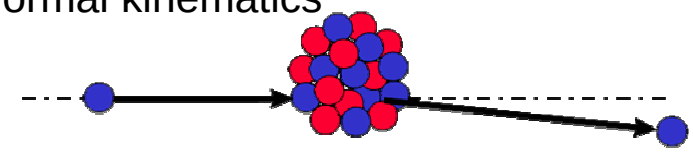
- ^{38}Si: no significant intruder configurations in g.s. ^{36}Mg: MCSM predicts strong intruder admixtures for the low-lying states
- 2p knockout from ^{38}Si reaches only 0hω components in ^{36}Mg
- Comparison of measured cross sections and those calculated assuming the population of 0hω components of the final states by the direct 2p knockout reaction: Only 32(8)% and 38(8)% of the w.f. of the g.s. and 2^+ state, respectively, are 0hω components, the rest is proposed to be of intruder character
- Intruder domination places ^{36}Mg inside the "Island of Inversion"



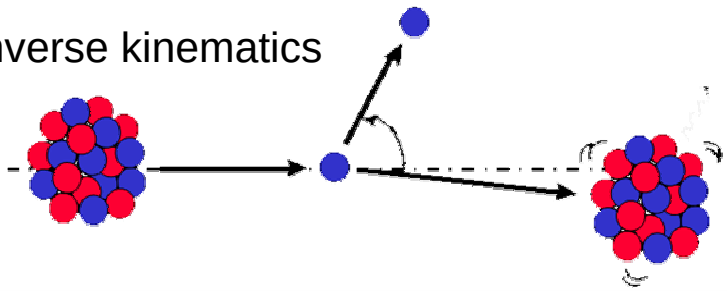
A Gade *et al*., Phys. Rev. Lett. 99, 072502 (2007)

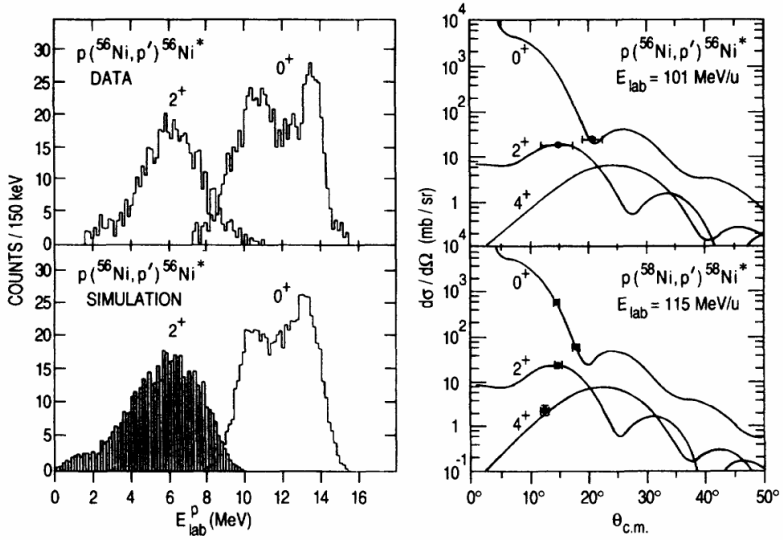
Proton scattering in inverse kinematics

Normal kinematics

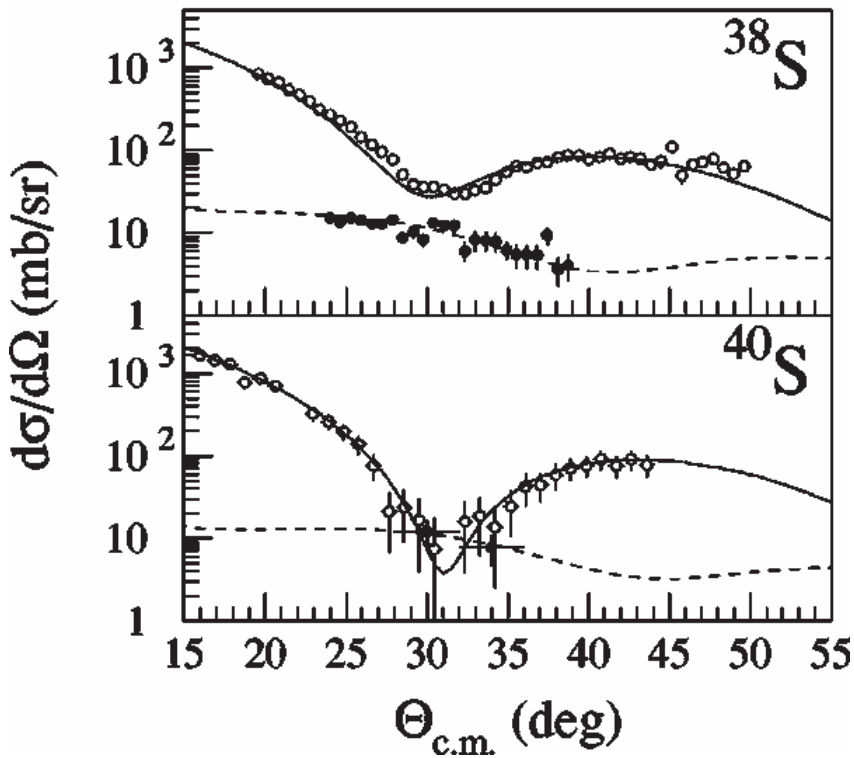


Inverse kinematics





p(^{56}Ni,p') at GSI
G. Kraus *et al.*, PRL **73** (1994) 1773



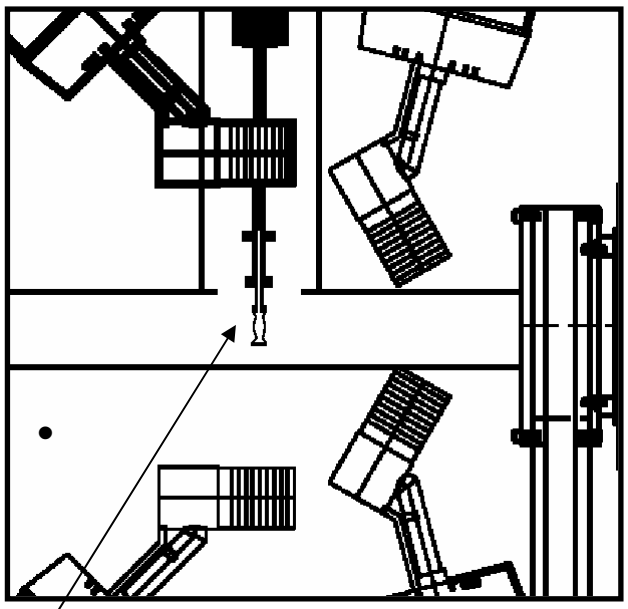
F. Maréchal *et al.*, PRC **60** (1999) 034615

- Many experiments at GANIL (MUST detector)
- Some experiments at MSU
- Thin target to avoid angular and energy straggeling of low-energy protons

Inelastic scattering to measure transition rates: Thick-target γ-tagged inelastic proton scattering

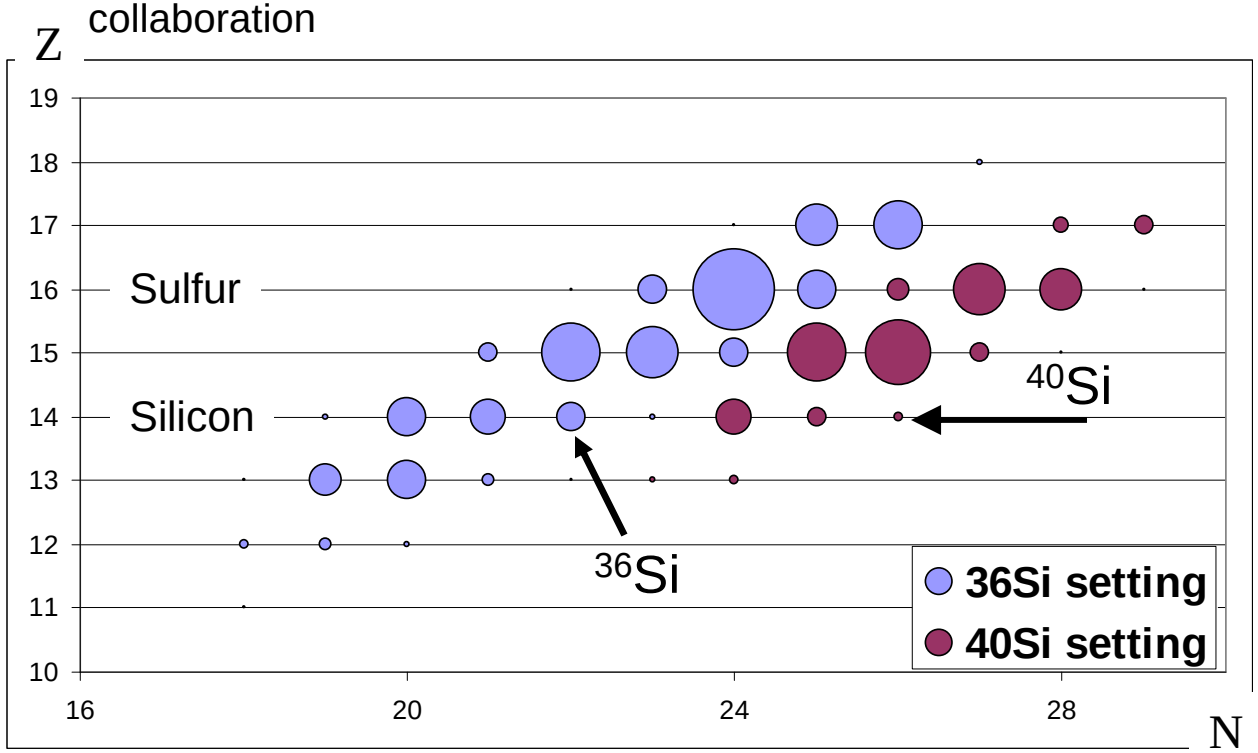
Pioneering experiment at RIKEN $p(^{30}Ne,^{30}Ne\gamma)$

Y. Yanagisawa *et al*. PLB 566 (2003) 84

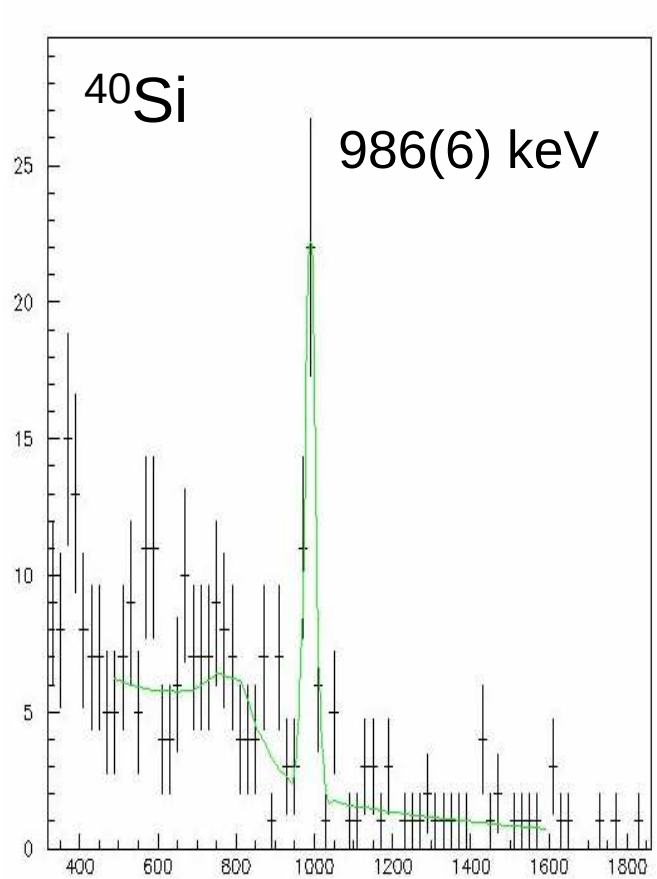


RIKEN/Kyushu/Rikkyo LH_2 target:
H. Ryuto *et al*., NIM **A 555** (2005) 1
30 mm diameter
9 mm thick, nominal
Negligible contaminant reactions

- Hydrogen has the most scattering centers per energy loss
- Inelastic *p* scattering using two cocktail beam settings to study chains of isotopes accessible in a consistent approach
- Determine excited state energies and collectivity towards *N*=28
- Univ. Tokyo, RIKEN, Rikkyo Univ., Michigan State Univ. collaboration

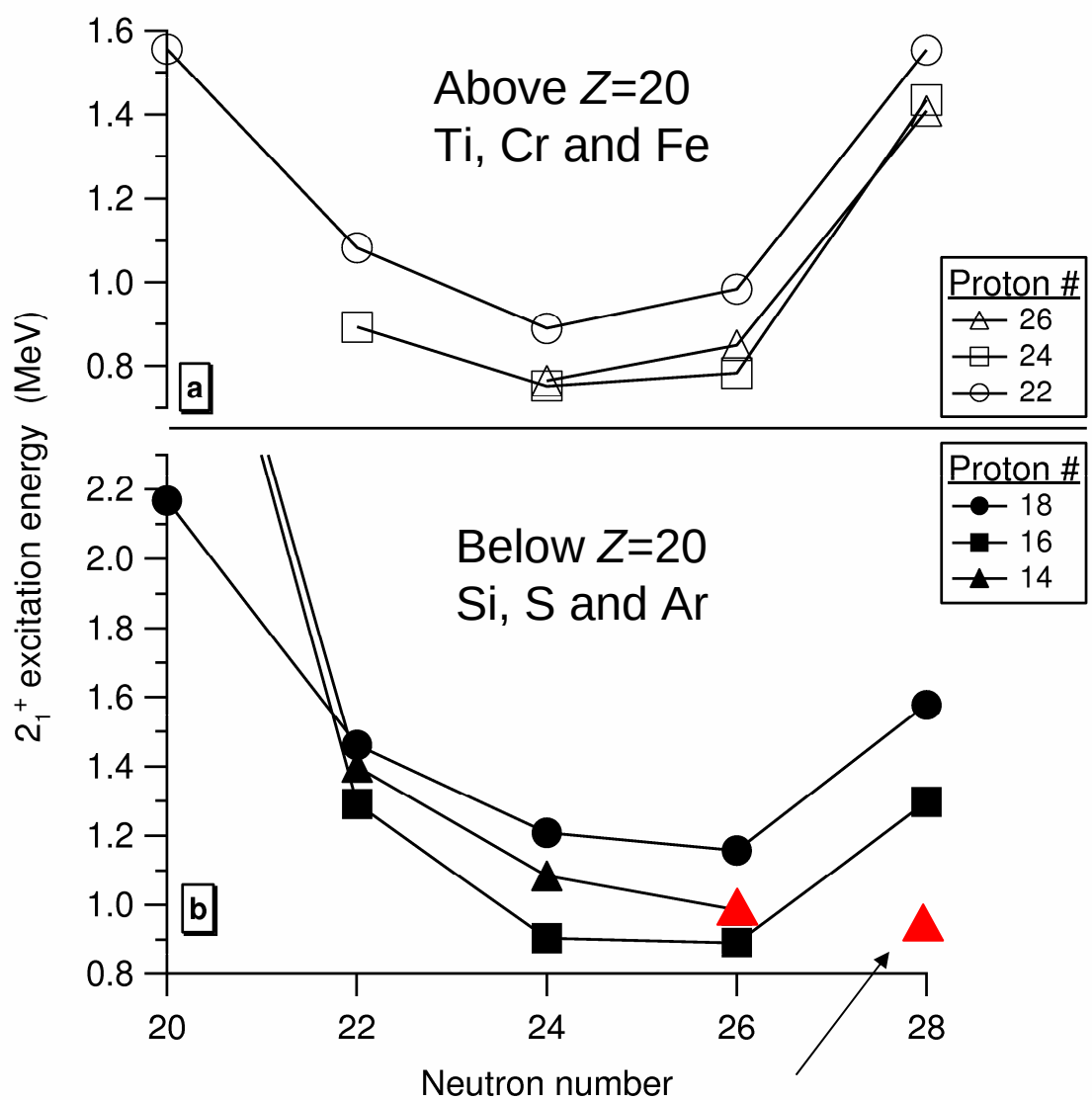


Evolution of 2^+ energies towards N=28



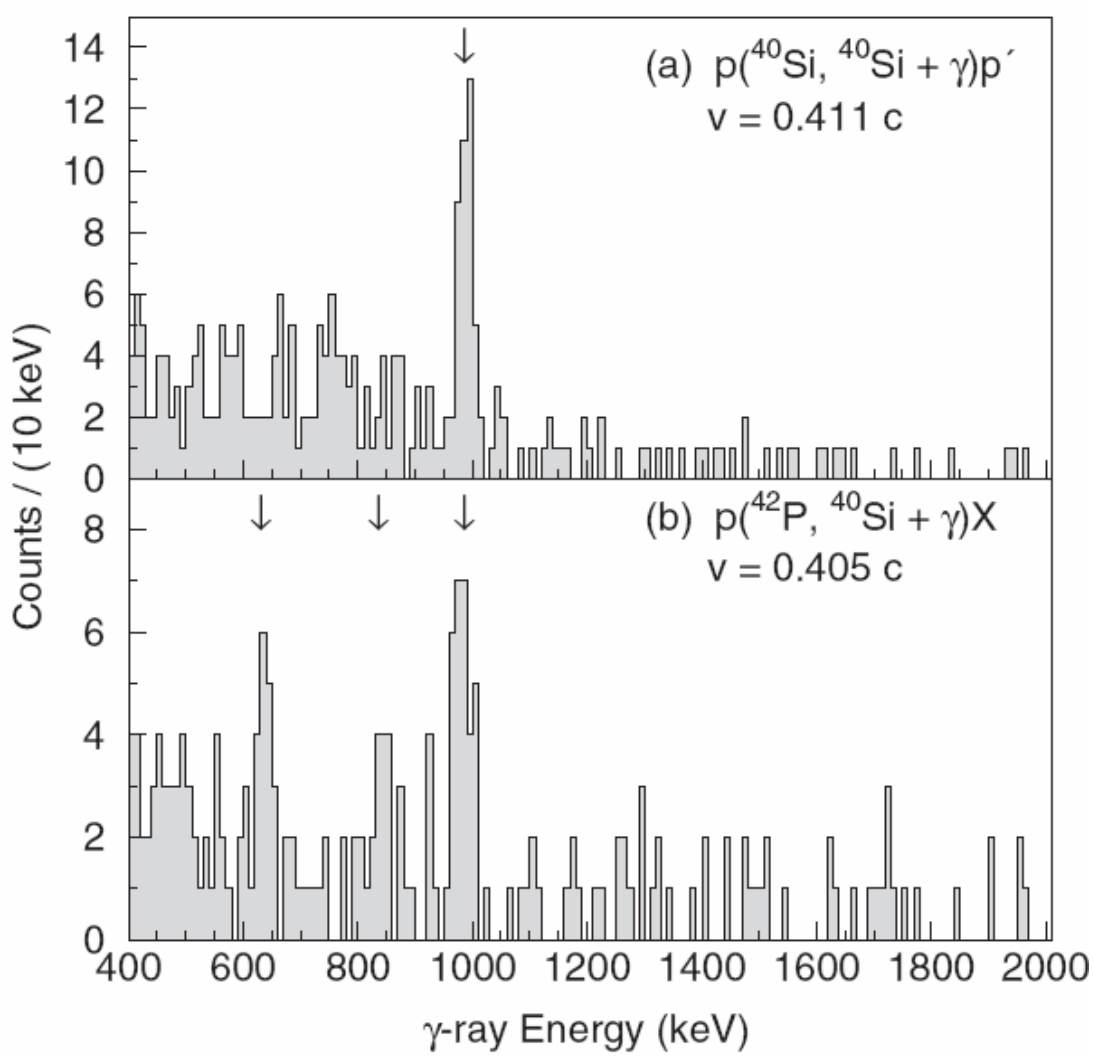
- 1.5 million ^{40}Si beam particles
- $\sigma_{p,p'}$ = 20(3) mb
- ~30 counts in the photopeak
- Low energy indicative of neutron collectivity in ^{42}Si

C.M. Campbell *et al.*, PRL **97** (2006) 112501

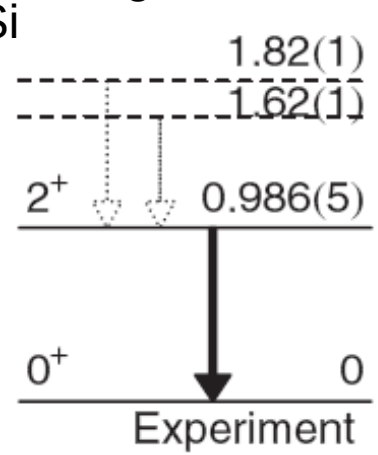


Discovery of low-lying 2^+ state in ^{42}Si at GANIL
B. Bastin, S. Grévy *et al.* PRL **99**, 022503 (2007)

Higher excited states in ^{40}Si

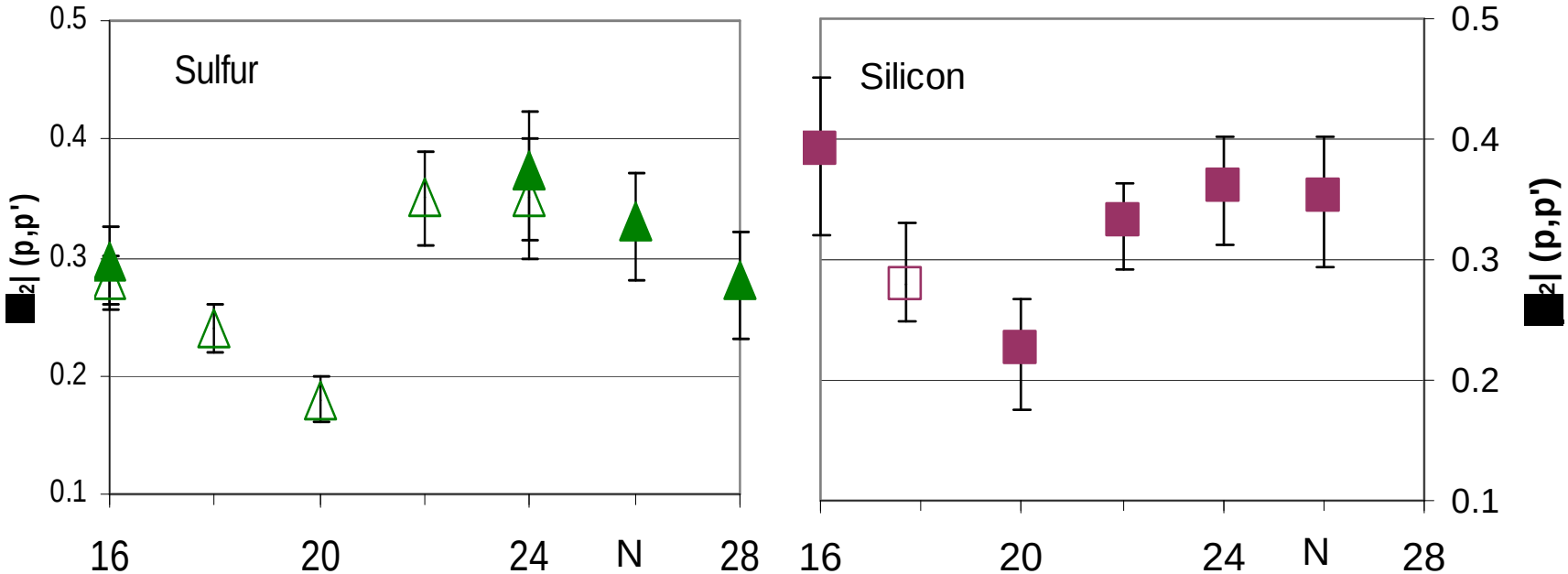


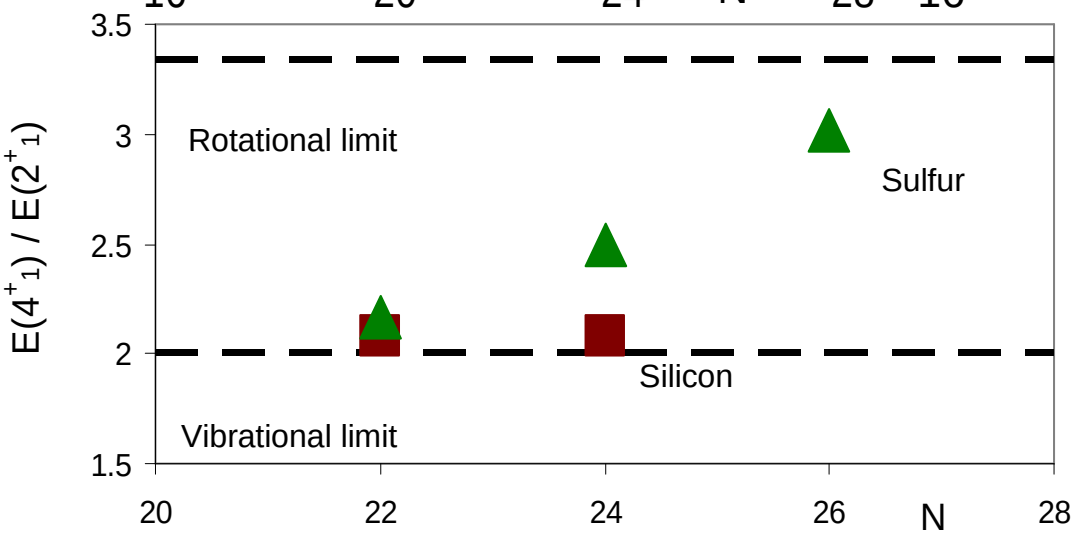
- Two additional γ-rays in fragmentation channel 42P-*p*-*n*
  - States at 1.62(1) MeV and 1.82(1) MeV?
- Not enough statistics to test if the two transitions are in coincidence
- Independent of the sequence, the second excited state is low in energy
- In the shell model second excited state is *ph*-excitation across *N*=28
- Low energy supports narrowing of the *N*=28 gap in ^{40}Si



C.M. Campbell *et al.*, PRL **97** (2006) 112501

Evolution and character of collectivity





- Enhanced collectivity towards N=28 in silicon
- Sulfur transitions from vibrational mid-shell to rotational towards N=28
- Silicon vibrational mid-shell

Prior data from F. Maréchal *et al*, PRC **60**, 034615 (1999)
P.D. Cottle *et al*., PRL **88**, 172502 (2002)

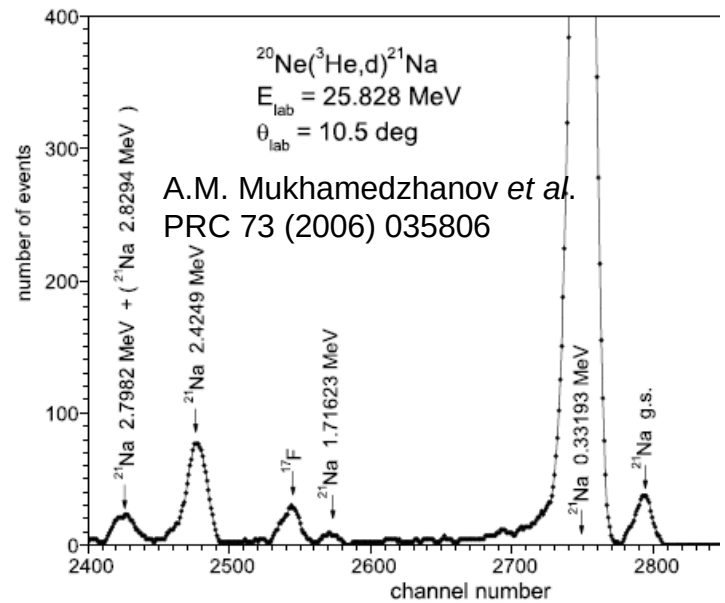
C.M. Campbell Ph.D. PLB **652** (2007) 169

Nucleon addition complements knockout

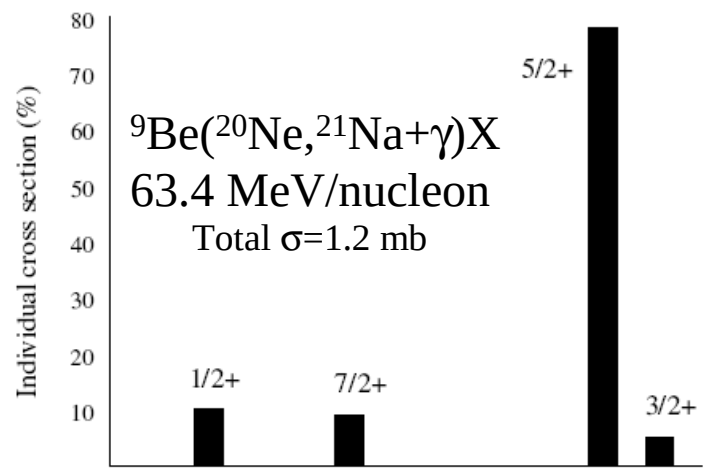
Inverse-kinematics proton-adding direct reactions with fast beams

- Traditionally performed in normal kinematics at lower beam energies, e.g. (*d*,*n*), (^{3}He,*d*), (α,*t*), …
- At higher energies momentum less well matched
- Trick: Pickup of a strongly-bound nucleon S. Shimoura *et al*., JPG 31, S1759
- Pioneering inverse kinematics experiment at RIKEN, (α,*t*) reaction at 60 MeV/nucleon
  S. Michimasa *et al*., PLB 638, 146 (2006)
- Few mb cross sections observed at intermediate energies
- NSCL: Pickup of a well-bound proton from ^{9}Be [S_p(^{9}Be) = 16.9 MeV]
  First test case: ^{9}Be(^{20}Ne,^{21}Naγ)X

A. Gade *et al*., PRC **76** (2007) 061302(R)



Population pattern broadly consistent with low-energy transfer reactions (and shell model)



Summary and Outlook

- Measurements and interpretation go hand-in-hand to advance knowledge
- For experiments with rare isotopes, beam rates limit which observables can be measured, even after we
  - Build more efficient detectors
  - Use targets with more scattering centers
  - Make more beam
- Beam rate is the “Limit of experiments at the limits of stability”

- New robust experimental techniques have been developed that allow sensitive experiments with much decreased beam rates required
- New theoretical approaches are enabled by compute power and ingenuity
- New facilities are operational, under construction, and envisioned

➢ A dawn for discovery in science of atomic nuclei

Collaborators

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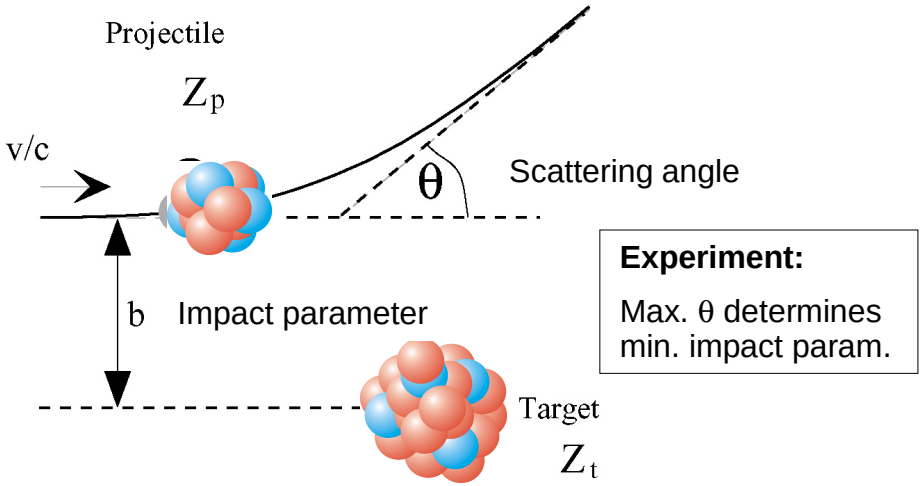
e) Department of Physics, Rikkyo University
f) Department of Physics and Astronomy, Ursinus College
g) Center for Mathematical Sciences, University of Aizu
h) Department of Physics, University of Tokyo
i) Department of Physics, University of Surrey
j) Japan Atomic Energy Research Institute
k) Physics Department, Florida State University

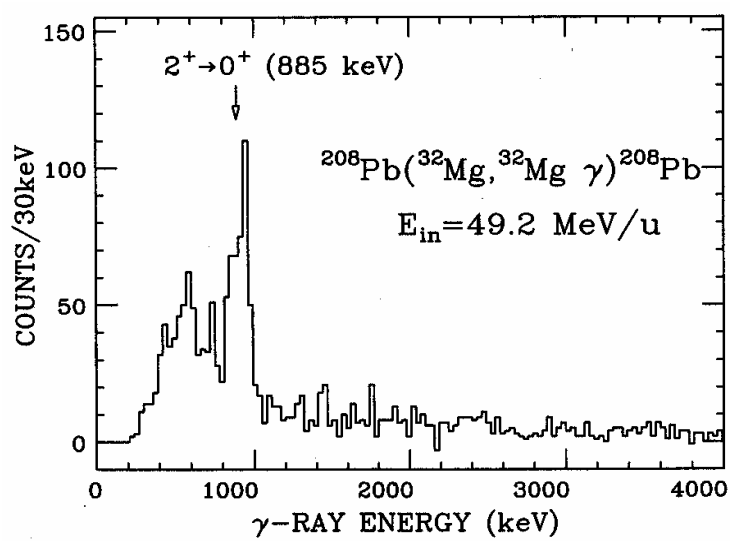
Intermediate-energy Coulomb excitation of ^{32}Mg

Large transition matrix element indicates breakdown of the *N*=20 shell gap

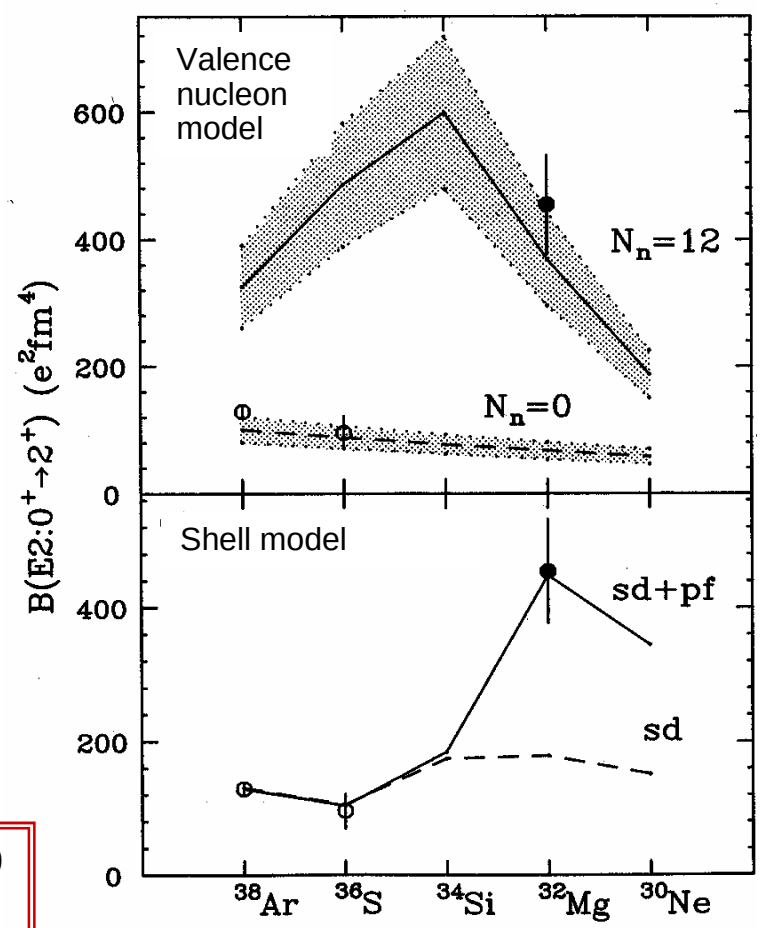


Experiment:

Max. θ determines min. impact param.



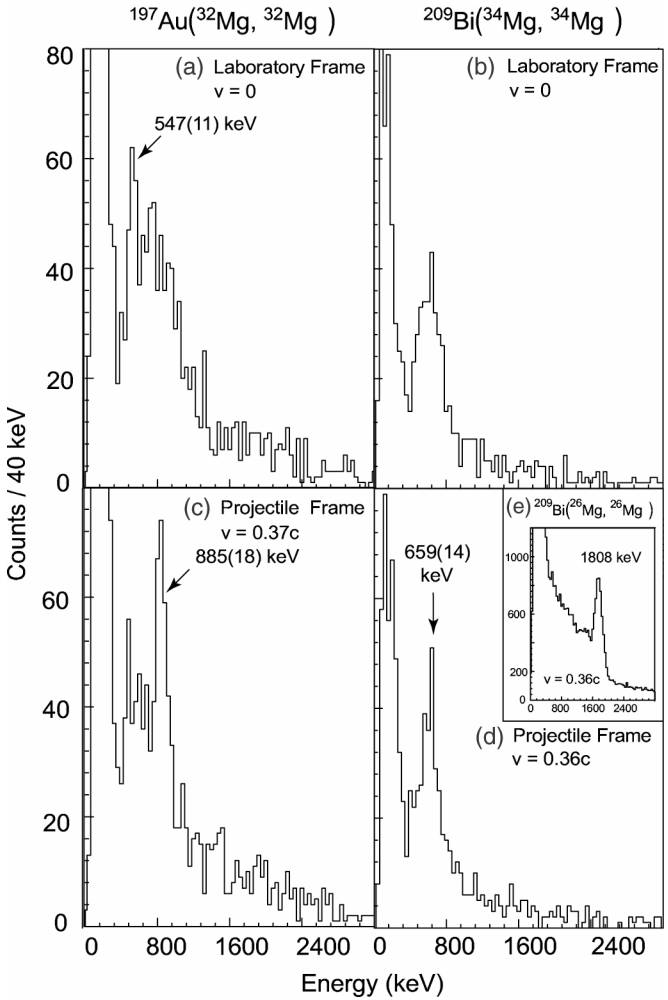
- σ_{Coul} = 87 mb
- B(E2↑) = 454(78) e^2fm^4 = $\langle 0^+ || \mathbf{O}(2) || 2^+ \rangle$
- $|\beta_2|$ = 0.49(4)

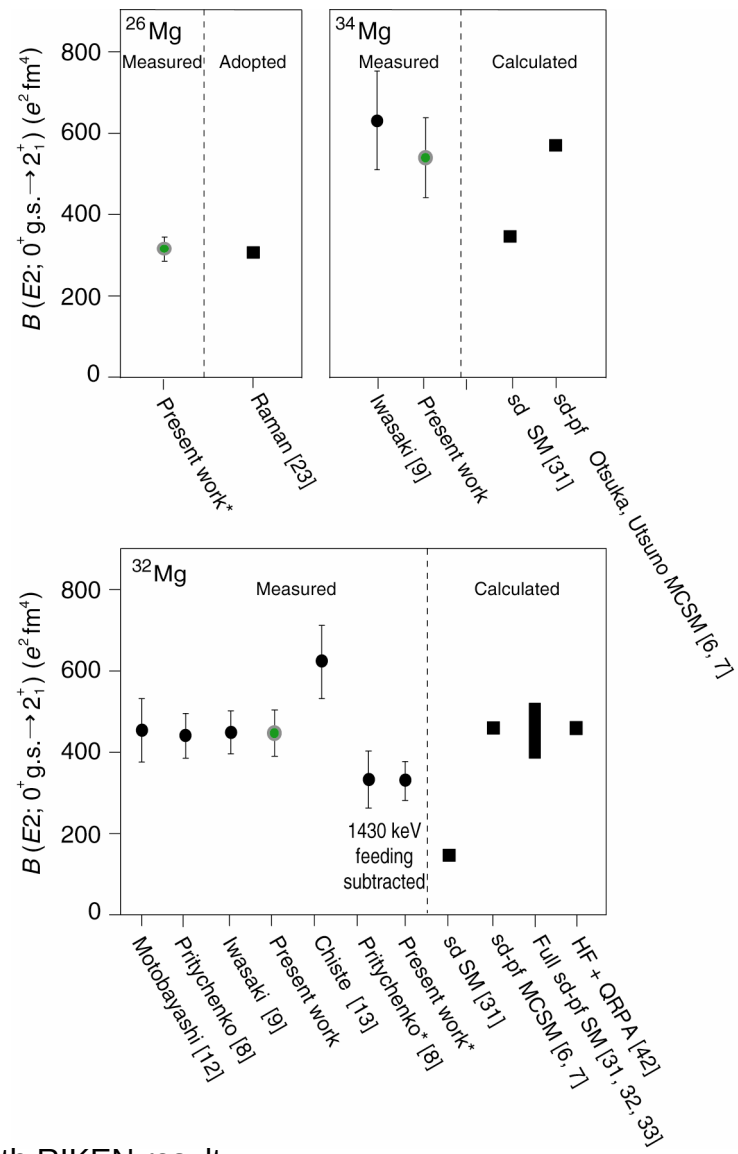


T. Motobayashi, R. Casten *et al.*, Phys. Lett. **B 346** (1995) 9

T.G. Ann. Rev. Nucl. Part. Sci. **48** (1998) 1

E2 transition strengths in ^{32,34}Mg





- ^{34}Mg Rate 10 atoms/s, run time 96 hrs, APEX detector
- ^{32}Mg B(E2↑) in agreement with RIKEN, MSU results
- ^{26}Mg B(E2↑) in agreement with adopted value
- ^{34}Mg E(2$^+$) and B(E2↑)=541(102) e^{2}fm^4 in agreement with RIKEN result

J. Church *et al.*, Phys. Rev. C **72** (2005) 054320

Intermediate-energy Coulomb excitation

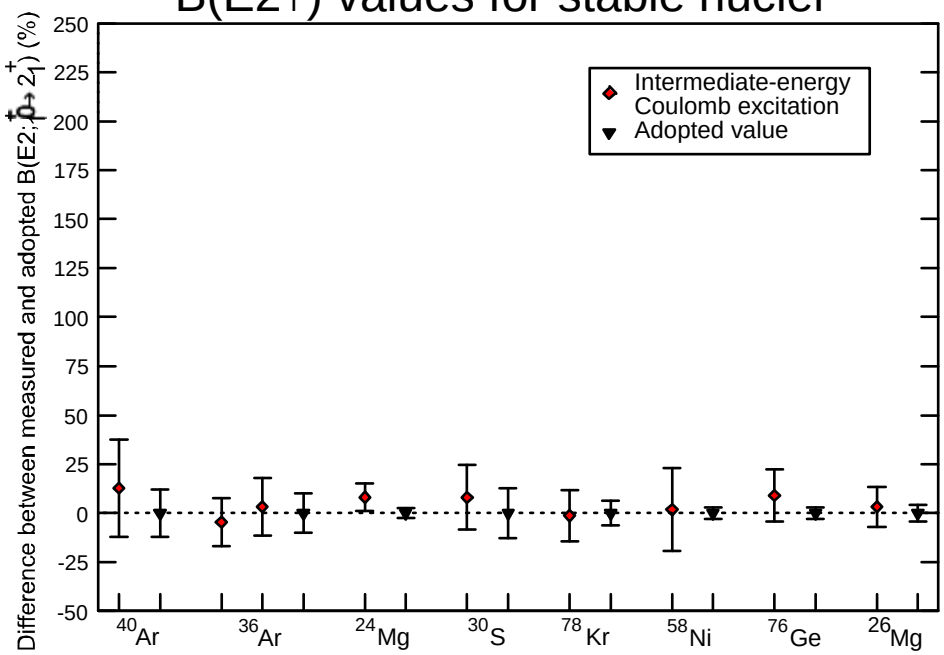
An accurate technique that allows for absolute B(E2) measurements

J. Cook *et al.*, Phys. Rev. **C 73** (2006) 024315

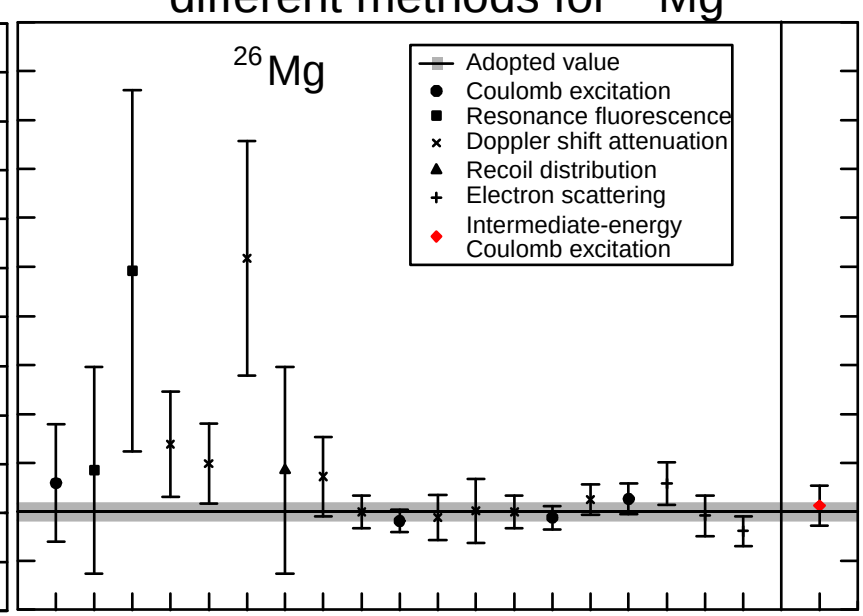
Scheit, Gade, Glasmacher, Motobayashi, Phys. Lett. **B 659** (2008) 515

- Active programs at GANIL, GSI, MSU and RIKEN
- One-step process
- Sensitive to *E*1, *E*2, *E*3 excitations

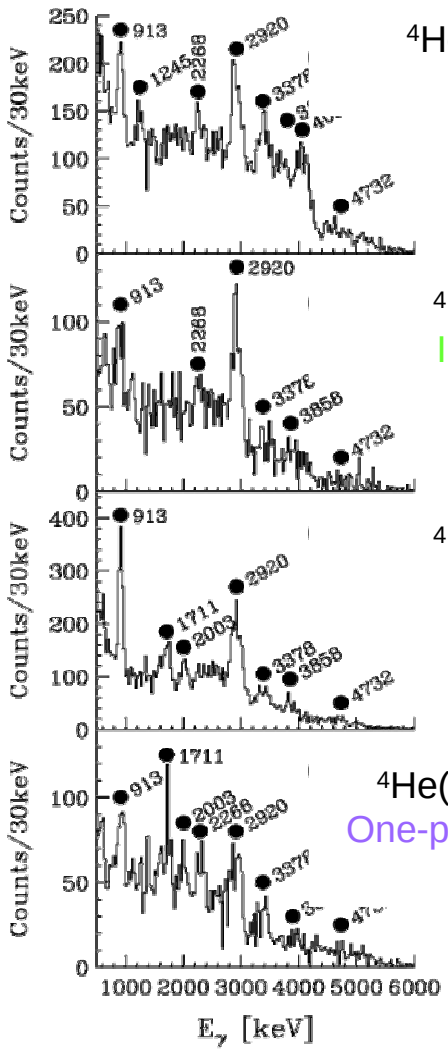
Adopted and measured B(E2↑) values for stable nuclei



B(E2↑) values from different methods for ^{26}Mg



Structure of ^{23}F: Multiple reactions in one experiment
~35 MeV/nucl,100 mg/cm^2 liquid helium target at RIKEN

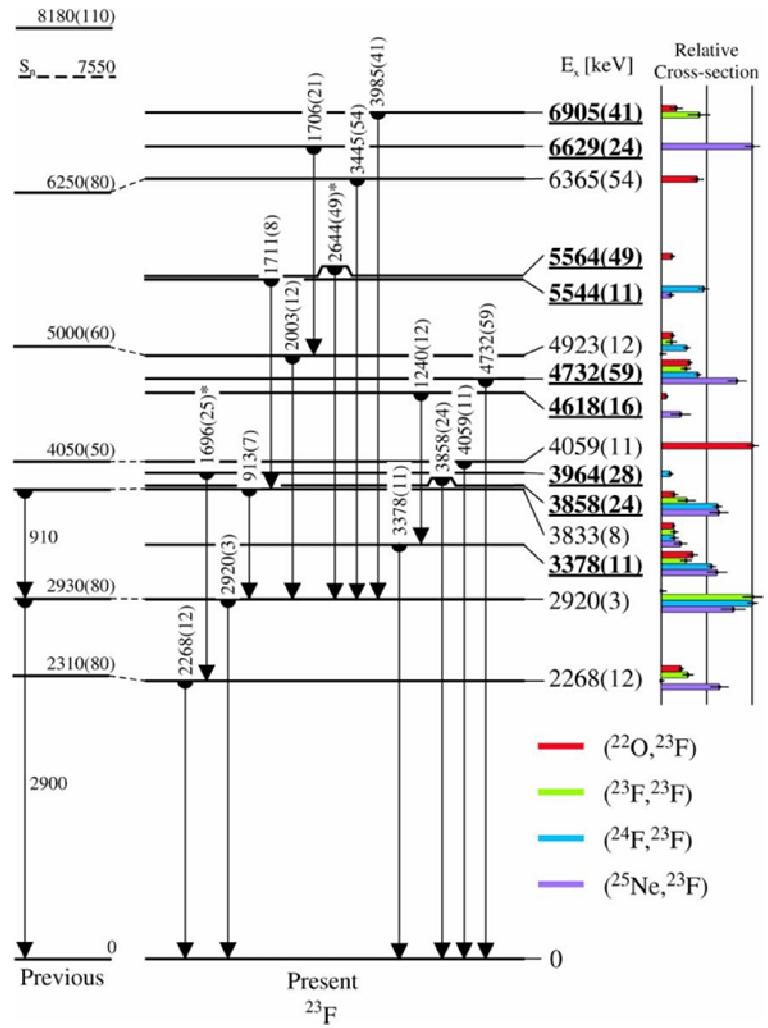


^{4}He(^{22}O,^{23}Fγ) 2000/s
Proton addition

^{4}He(^{23}F,^{23}Fγ) 550/s
Inelastic scattering

^{4}He(^{24}F,^{23}Fγ) 470/s
neutron-knockout

^{4}He(^{25}Ne,^{23}Fγ) 1200/s
One-proton one-neutron knockout

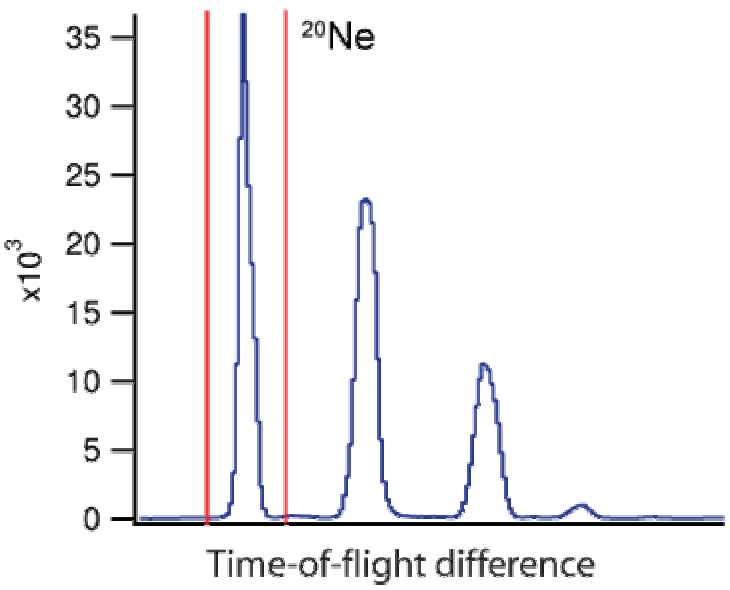


A. Michimasa *et al*. Phys. Lett. **B 638** (2006) 146

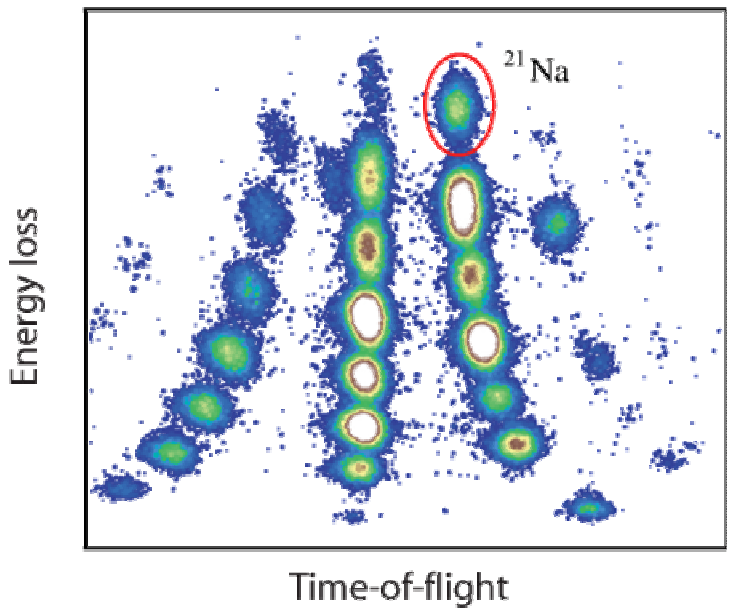
Single-proton addition

- Traditionally performed in normal kinematics at lower beam energies, e.g. (*d*,*n*), (^{3}He,*d*), (α,*t*), …
- Few mb cross sections observed at intermediate energies

- Proton well-bound in ^{9}Be $S_p(^9\text{Be}) = 16.9$ MeV
- ^{8}Li has only one bound excited state

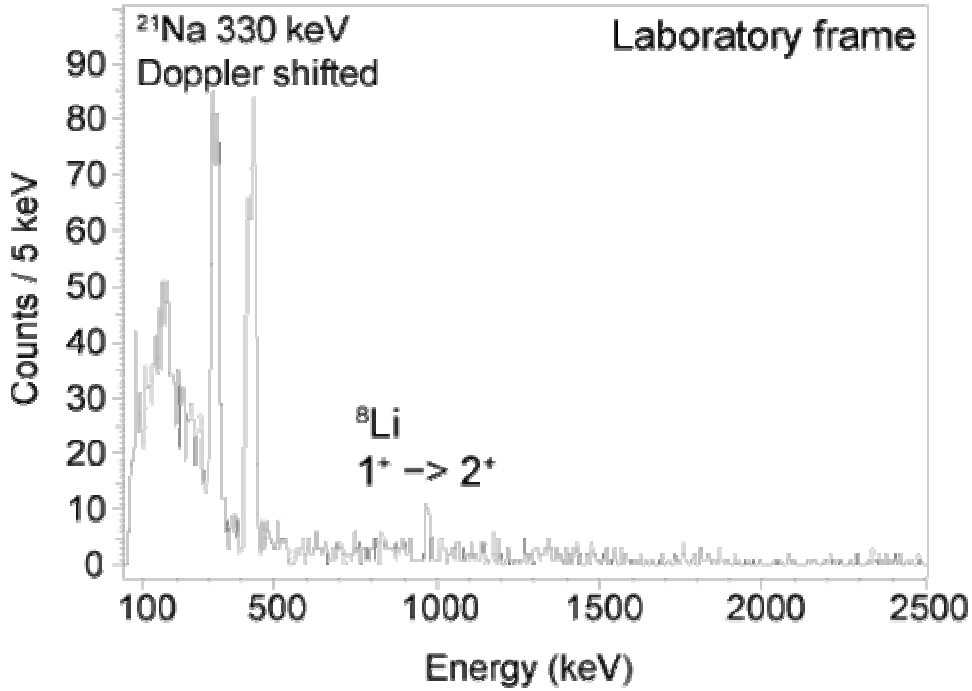


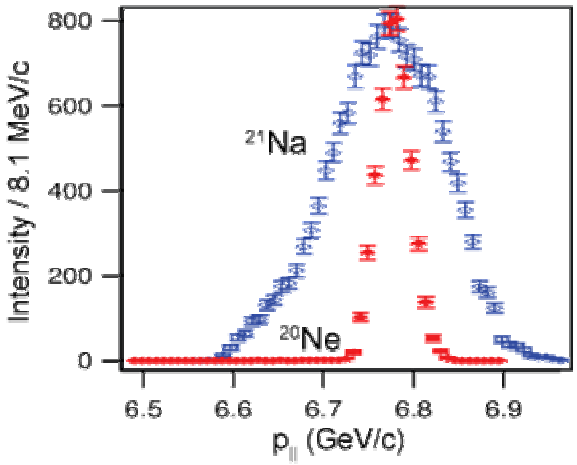
Beam identification

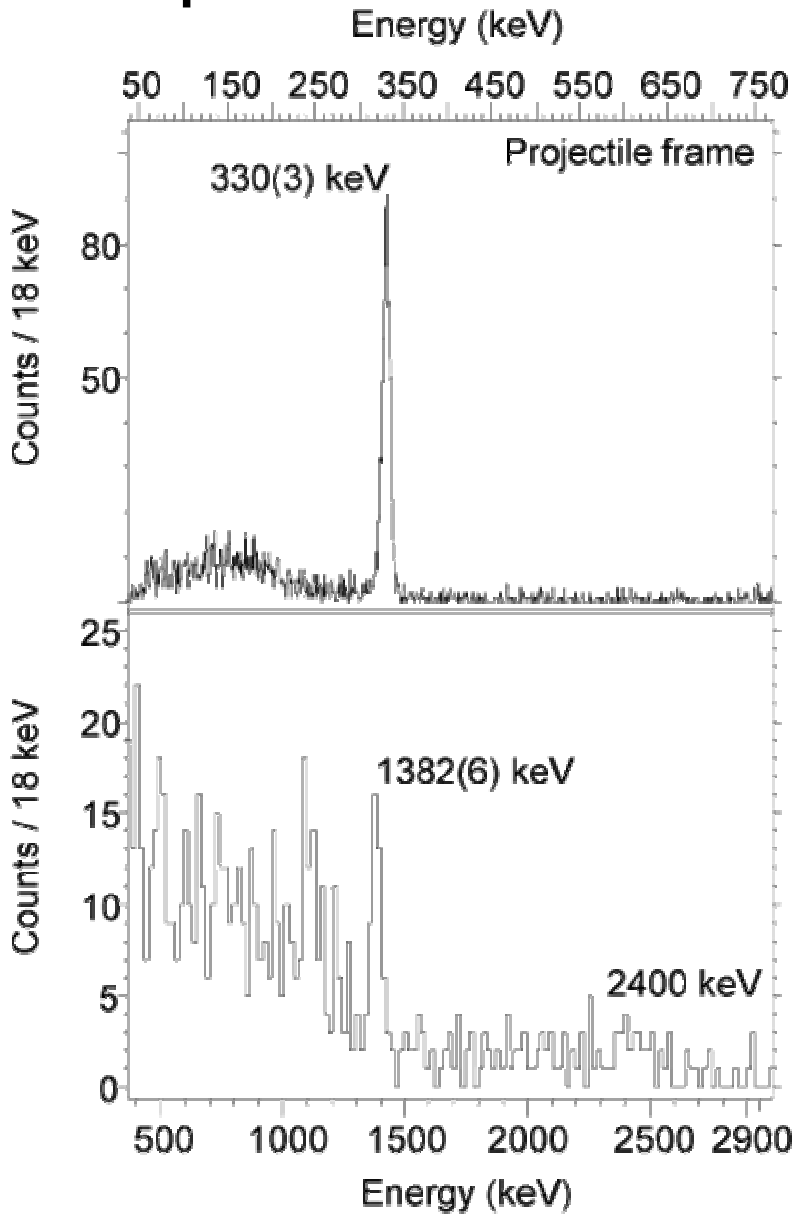


Reaction product identification

Measure coincident γ-rays and particle momenta







Approaching the "Island": $^{9}Be(^{30}Mg,^{29}Mg)X$

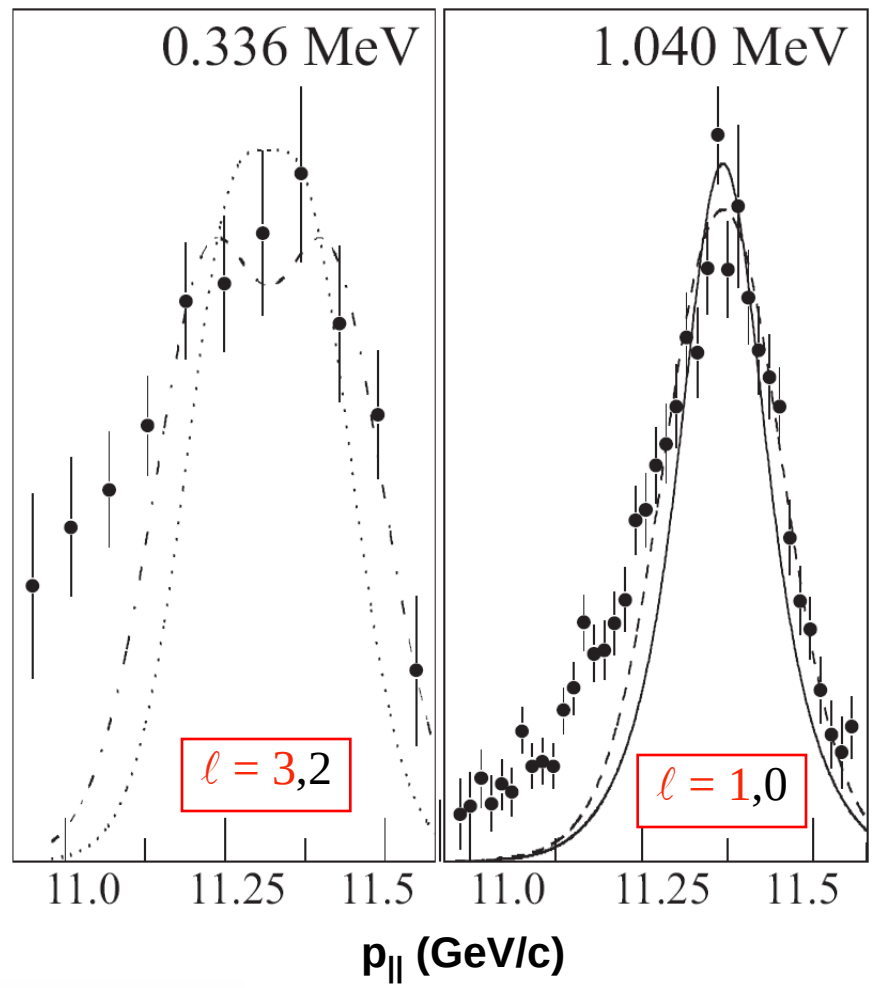
Level scheme of ^{29}Mg is known
β decay and β-n decay:
P. Baumann et al., PRC 36, 765 (1987)
PRC 39, 626 (1989)
$^{30}Si(^{13}C,^{14}O)^{29}Mg$ and $^{28}Si(^{13}C,^{14}O)^{27}Mg$:
C.L. Woods et al., NPA 476, 392 (1988)

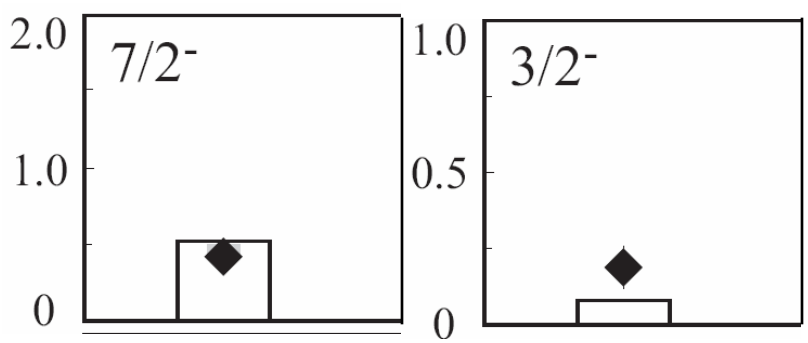
Levels at 1.431 and 1.095 MeV are assigned as 7/2- and 3/2-.

Our experiment: Momentum distributions are consistent with these previous ℓ assignments and the states are directly populated in the knockout.

Spectroscopic factors extracted from our data quantify intruder content in the gs of ^{30}Mg

J. Russ Terry et al., PRC, in press

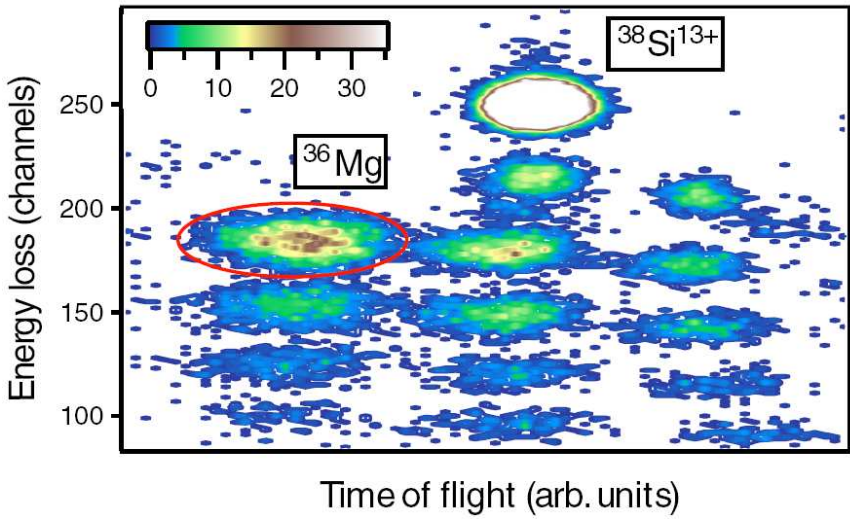


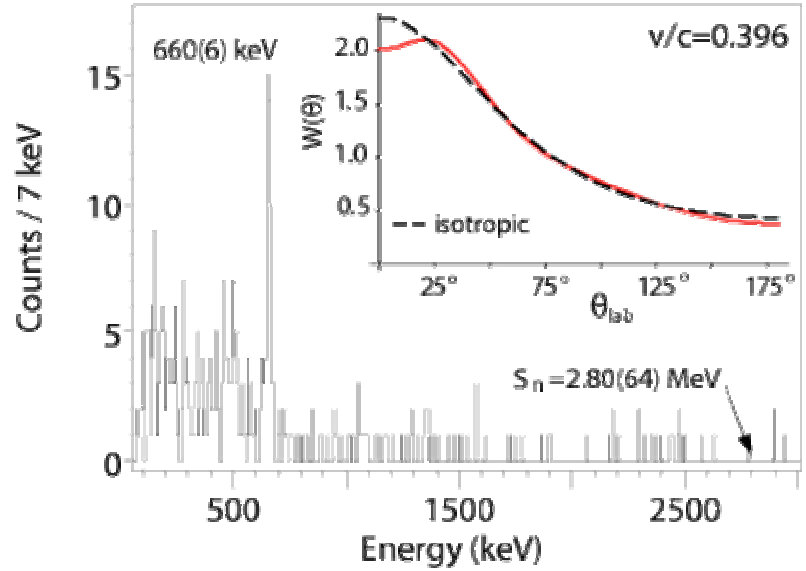


$\langle n \rangle_{SDPF-M}$

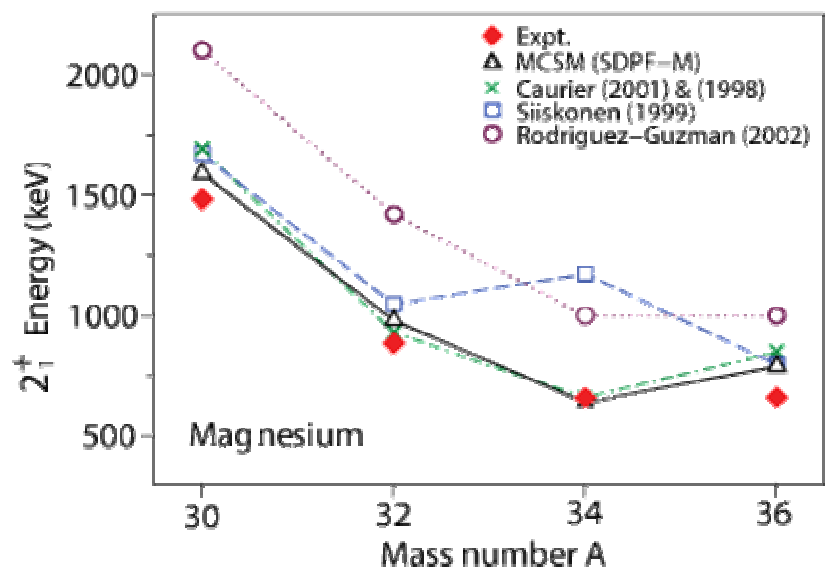
C^2S extracted from experiment

The structure of ^{36}Mg via ^{38}Si $\rightarrow$ ^{36}Mg+γ





- Beam rate too low for ^{36}Mg inelastic scattering and β-decay impossible (^{36}Na *n*-unbound)
- ^{48}Ca primary beam, 1500 ^{38}Si per second secondary projectile beam (purity exceeded 95%)
- 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



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