Exotic Nuclei

Outline

Shell Structure – Collective Structure:

- *Experimental methods:*

Coulomb excitation

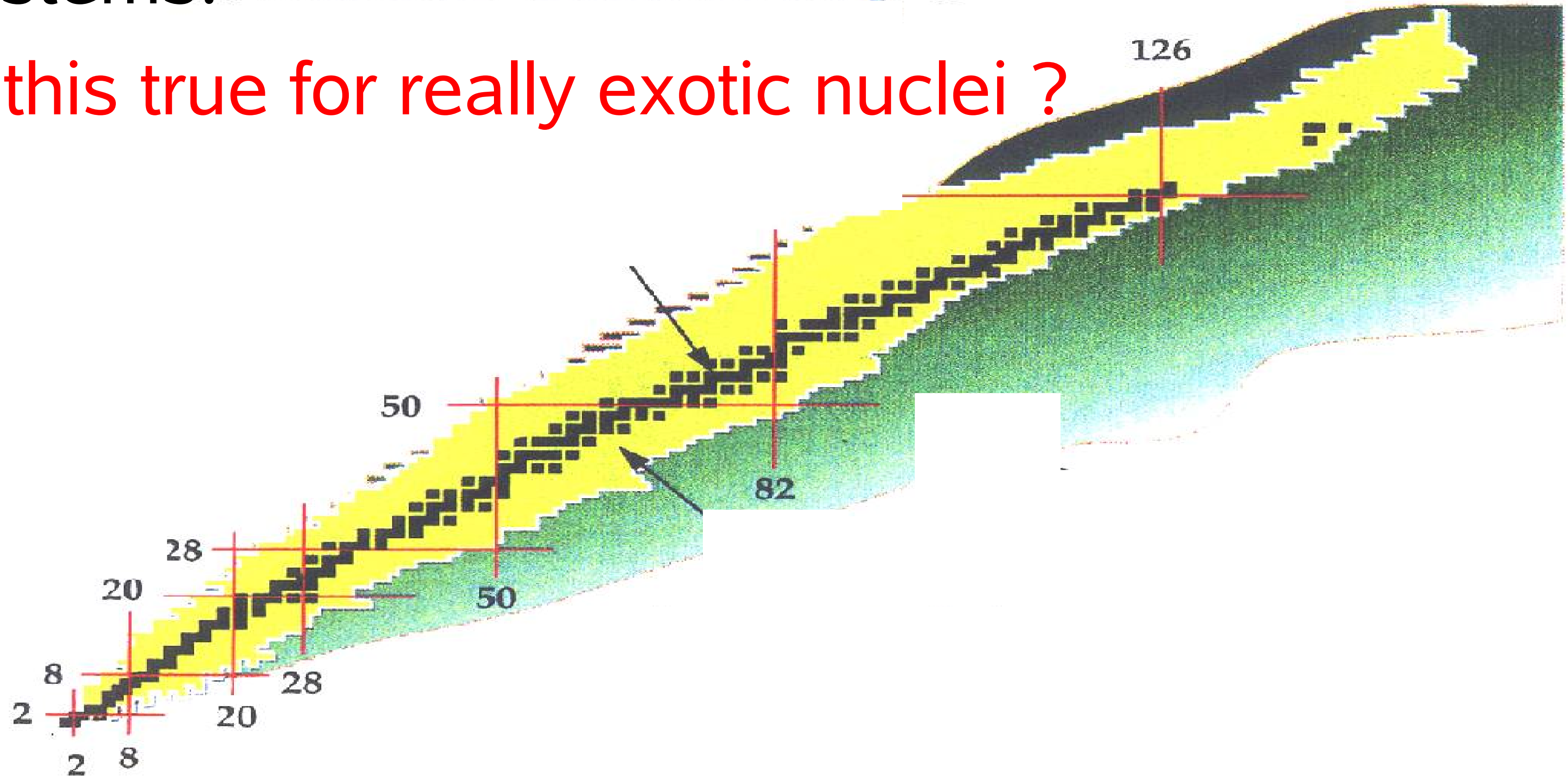
Knockout reactions

- *Magic Numbers in exotic nuclei*
- *New modes of collectivity ?*

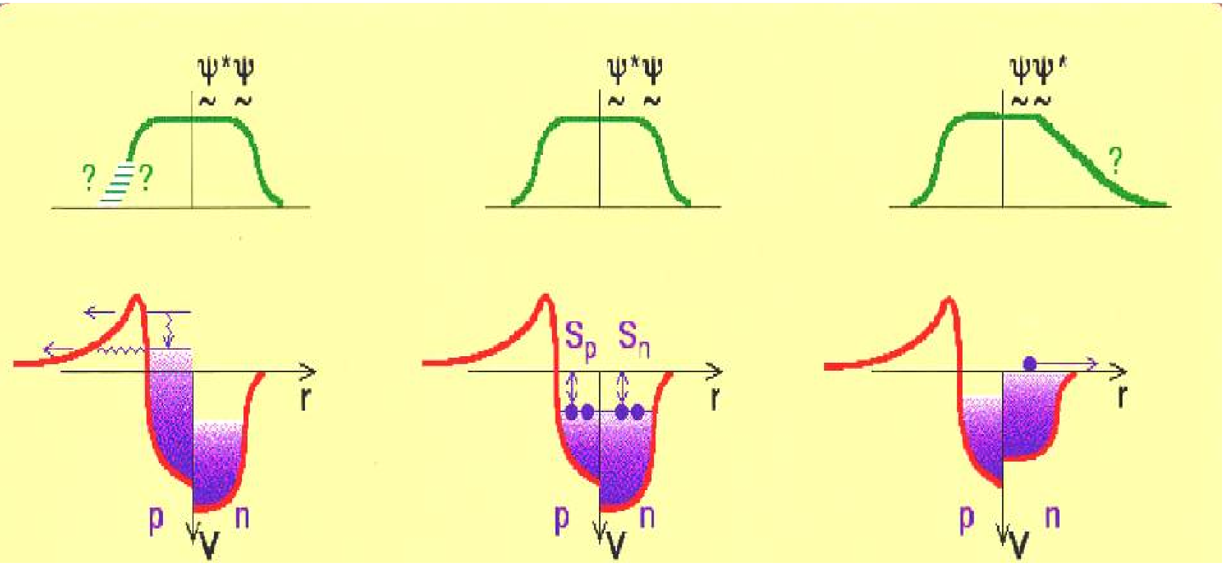
Ingo Wiedenhöver,
National Nuclear Physics Summer School
7/16/2007 Tallahassee, Florida

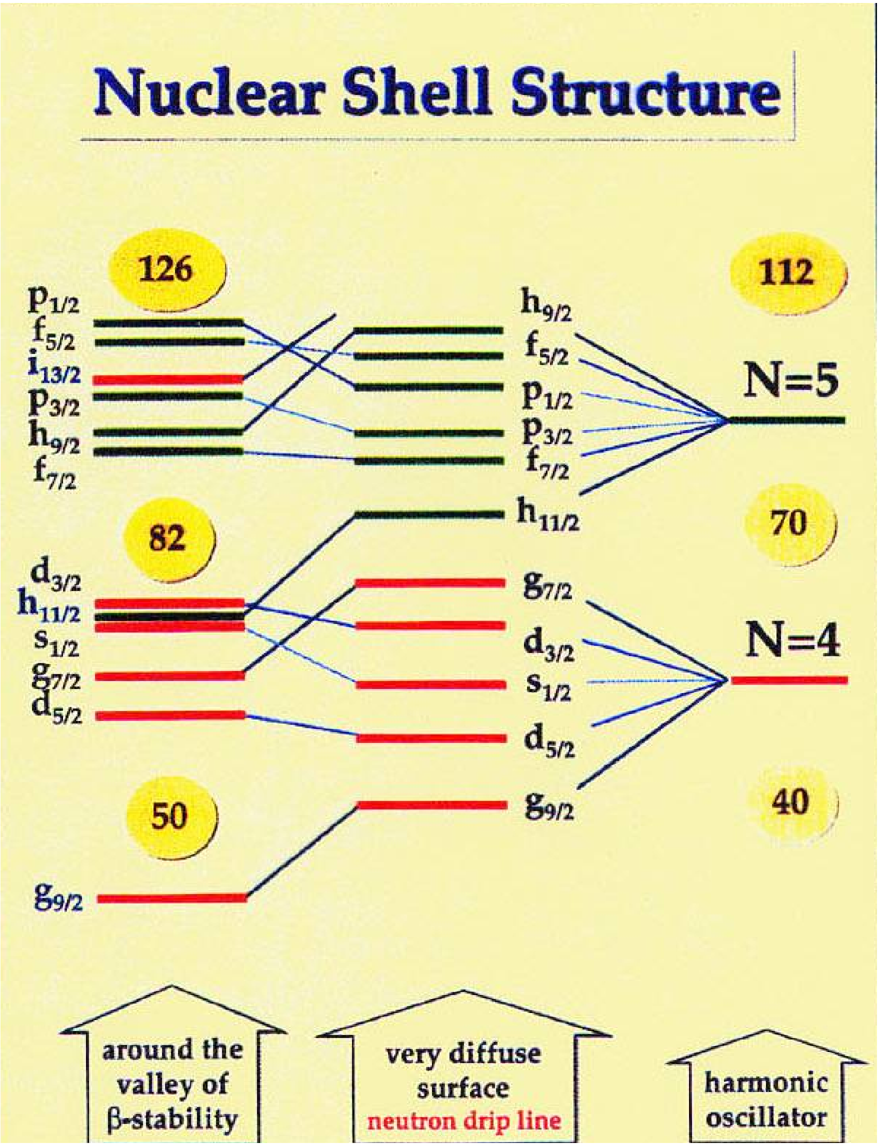
Magic Numbers

- The existence of magic numbers is the most important thing to know about atomic nuclei.
- Protons and neutrons act almost like independent systems.
- Is this true for really exotic nuclei ?



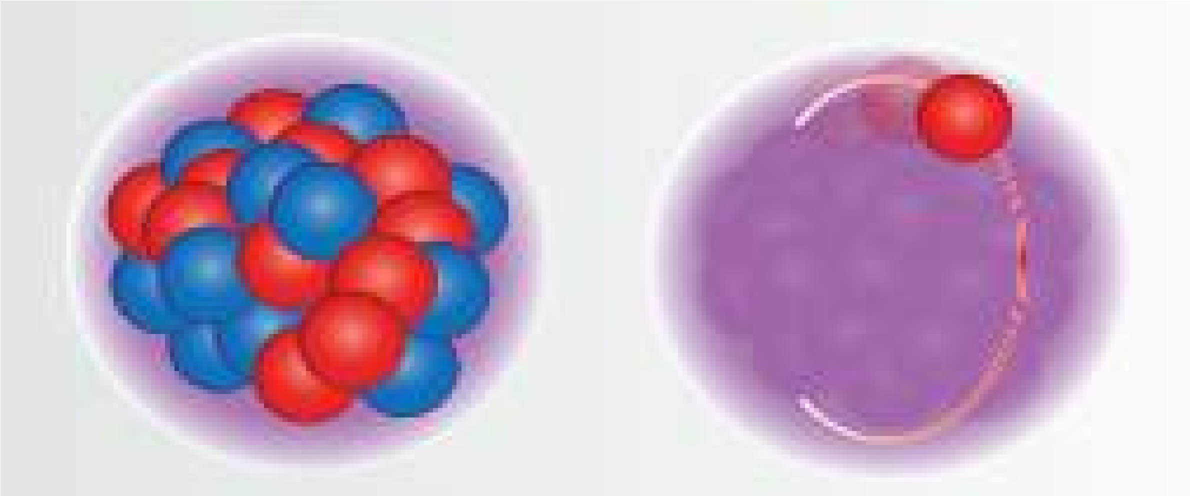
Shell Structure of Neutron-Rich Nuclei





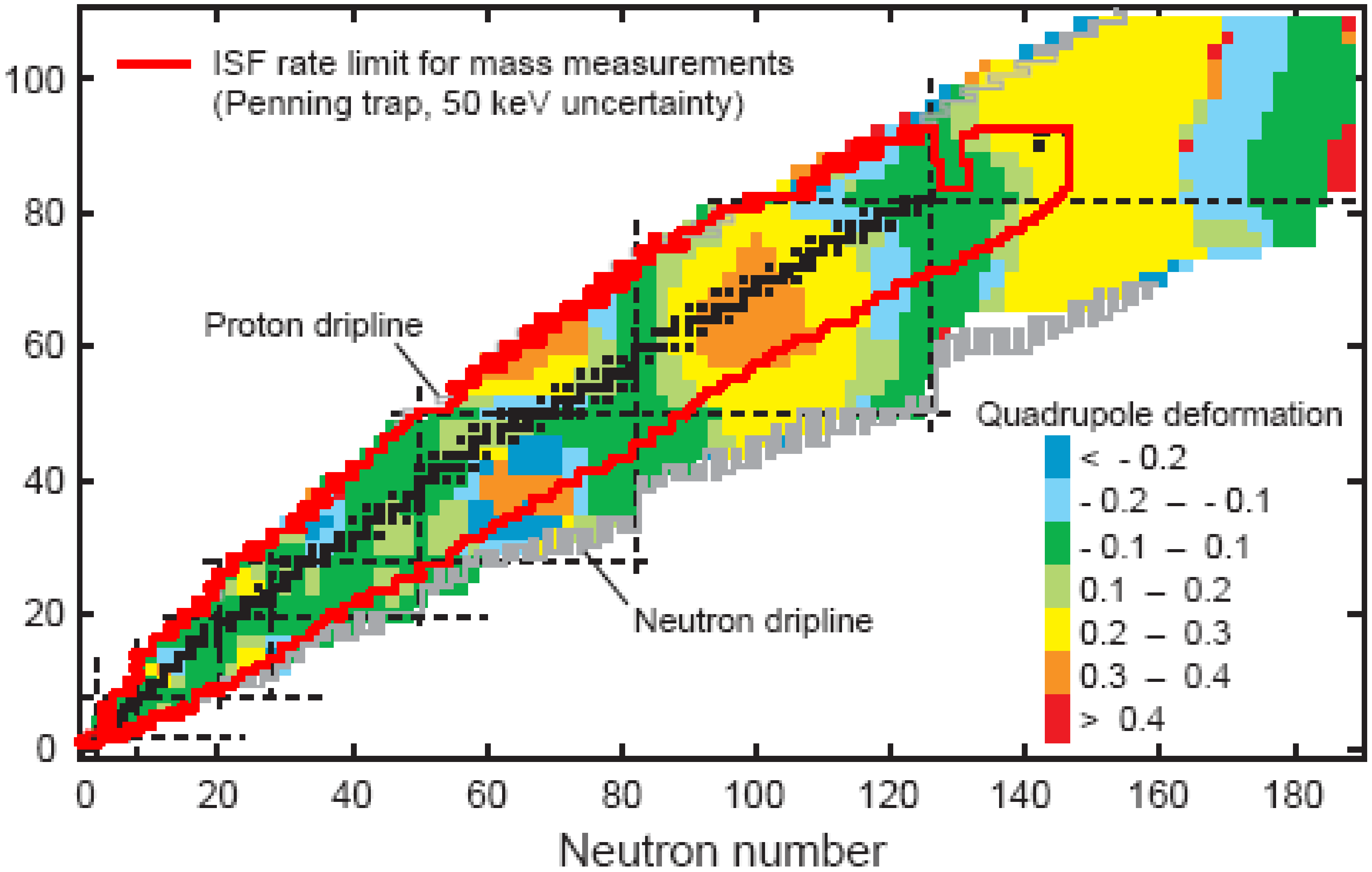
Very neutron-rich nuclei are expected to exhibit diffuse surfaces, which leads to a reduced spin-orbit coupling and "melting" of the shell structure.

Single Particle vs. Collective Pictures



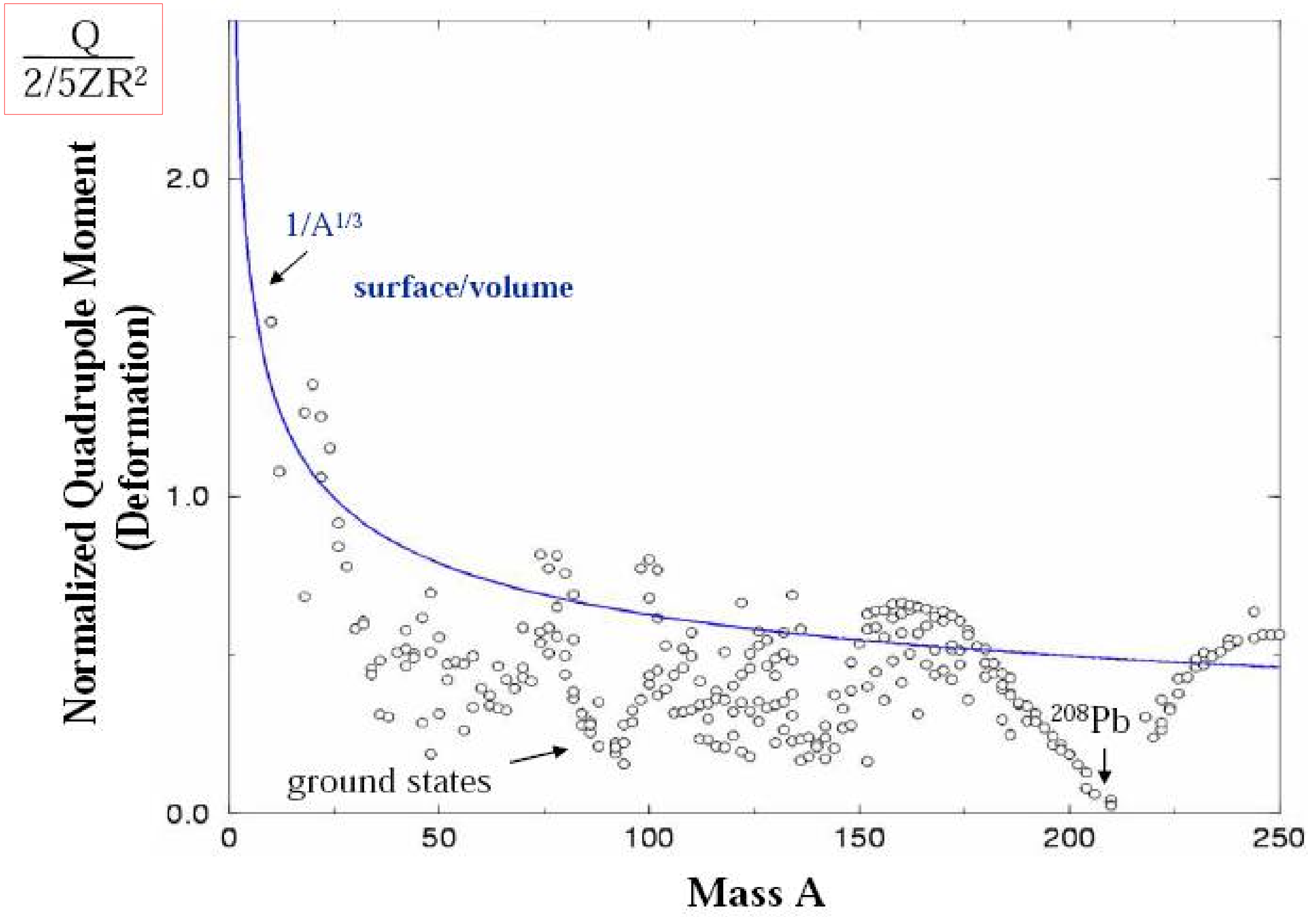
- Nuclei with N,Z near closed shells can be successfully described as many-body systems
- Interactions of valence- protons and neutrons lead to collective correlations, so that
- Nuclei far away from closed shells are also described through a (deformed) mean field

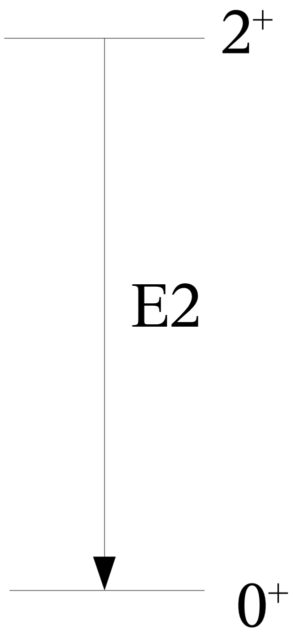
Quadrupole - Deformation



Deformed of Spherical ?

- electric Quadrupole moment leads to electric Quadrupole (E2) transitions.
- Measure E2 transition probability=> B(E2) = measure Quadrupole deformation





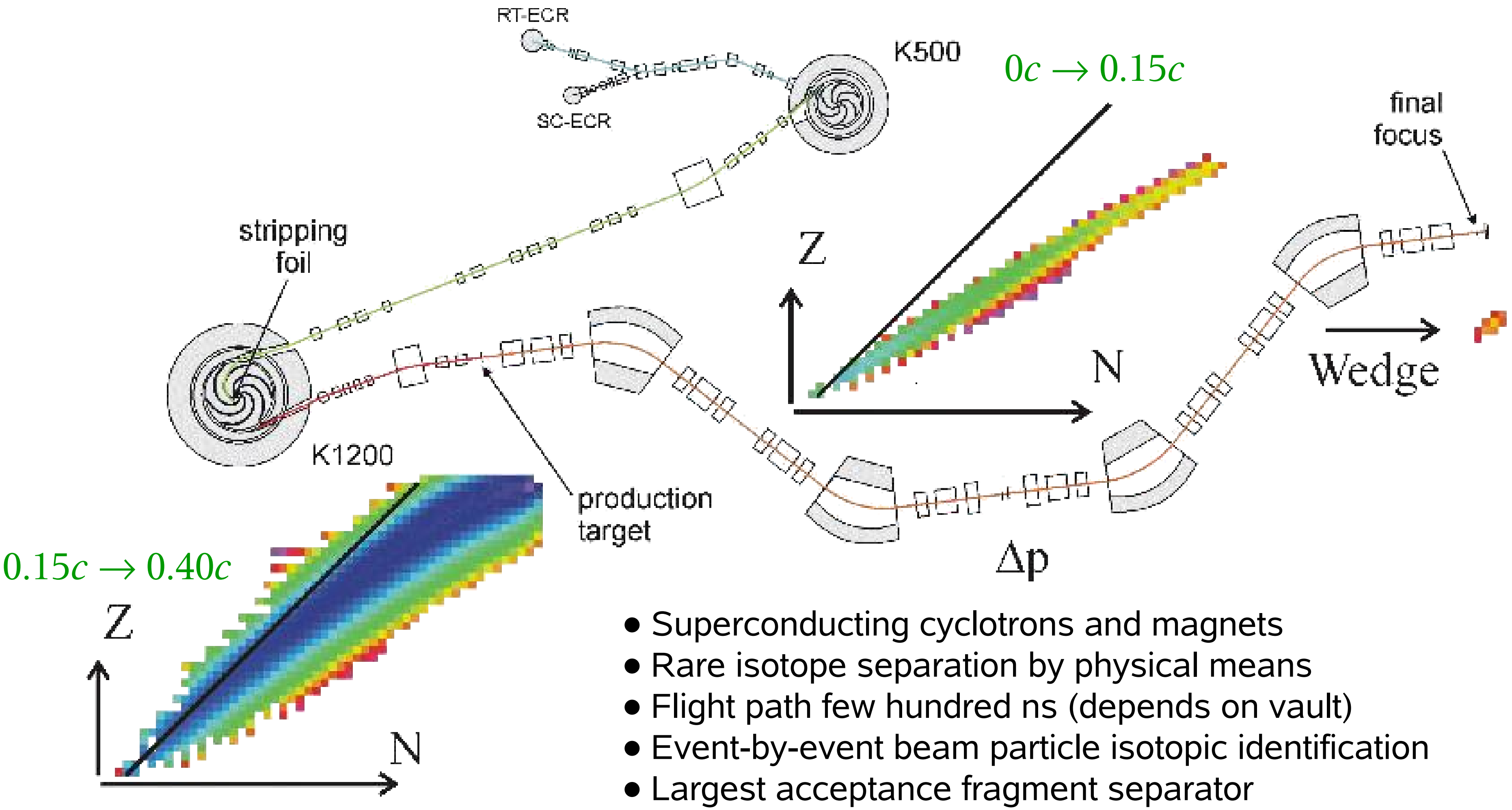
Deformed or spherical 2

- Even simpler : Grodzins Rule:
  Quadrupole transitions
  Quadrupole deformation = lower 2+ energy

$$E(2_1^+) * B(E2)\uparrow = 2.57\, Z^2 A^{-2/3}$$

- If we want to investigate shell structure of exotic nuclei, we need
  - Exotic nuclei
  - Methods to measure excited states
  - Methods to measure Quadrupole transition rates
  - Methods to measure “single-particle” character

NSCL Coupled Cyclotron Facility

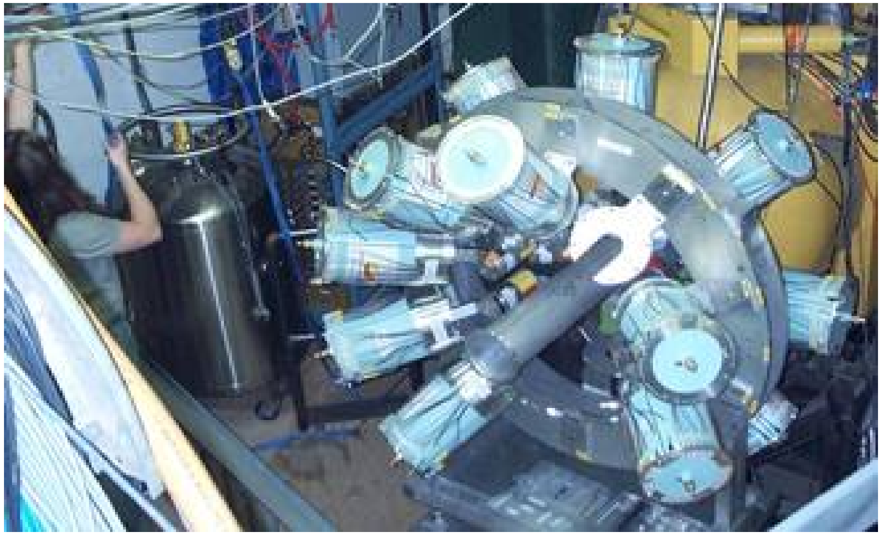


- Superconducting cyclotrons and magnets
- Rare isotope separation by physical means
- Flight path few hundred ns (depends on vault)
- Event-by-event beam particle isotopic identification
- Largest acceptance fragment separator
- Can track beam momentum event-by-event

D.J. Morrissey *et al*, NIM **B 204** (2003) 90

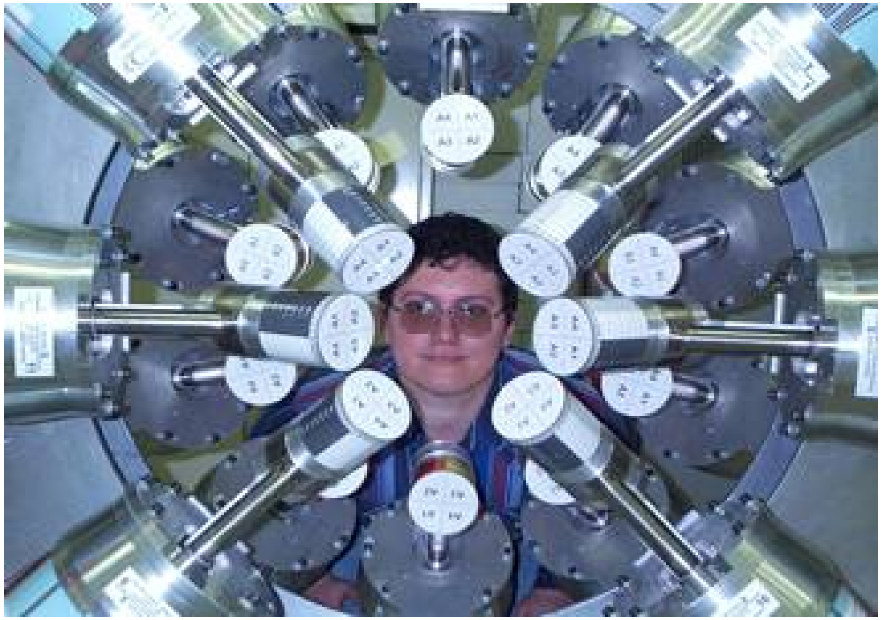
Segmented Germanium Array (SeGA)

Highly-segmented HPGe detectors for fast beams



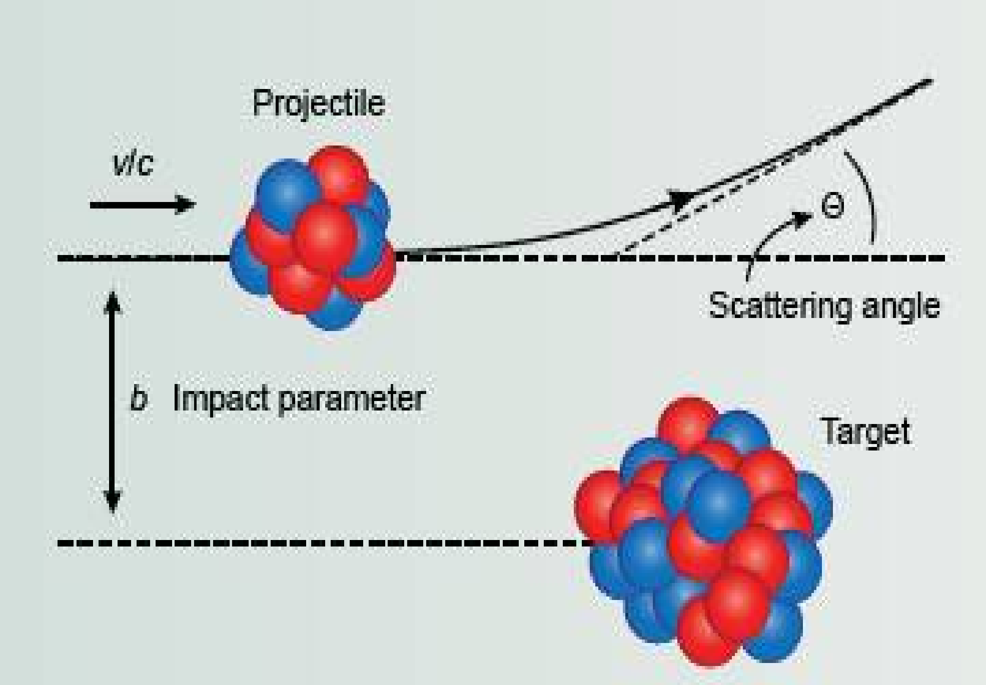
MICHIGAN STATE UNIVERSITY

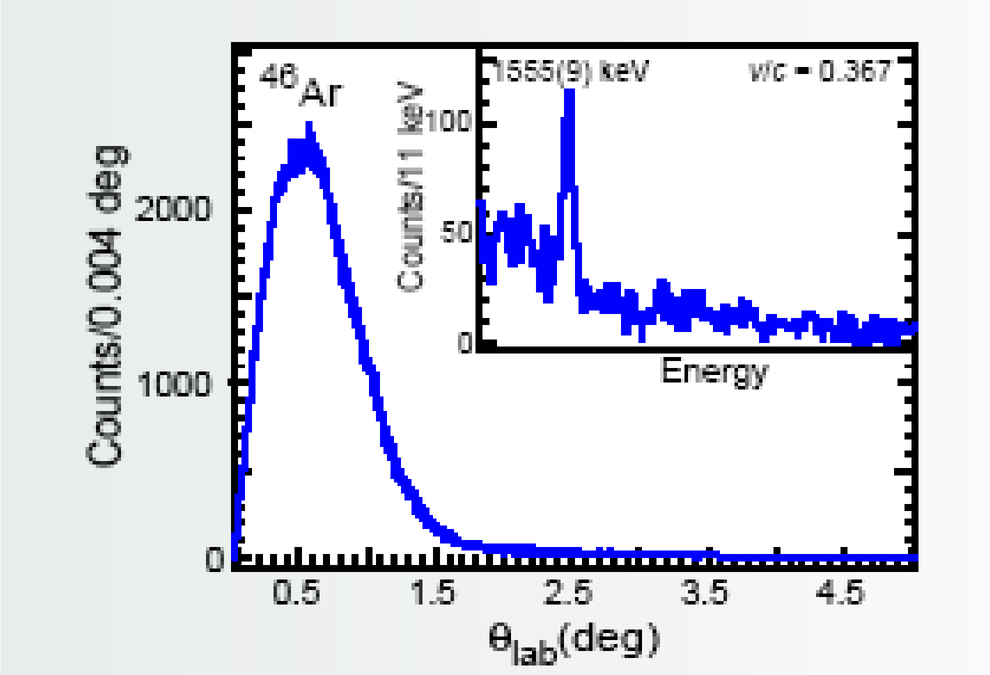
W. Mueller *et al*. Nucl. Instr. Meth. **A 466** (2001) 492.
Z. Hu *et al*. Nucl. Instr. Meth. **A 482** (2002) 715.
K.L. Miller *et al*., Nucl. Instr. Meth. **A 490** (2002) 140.

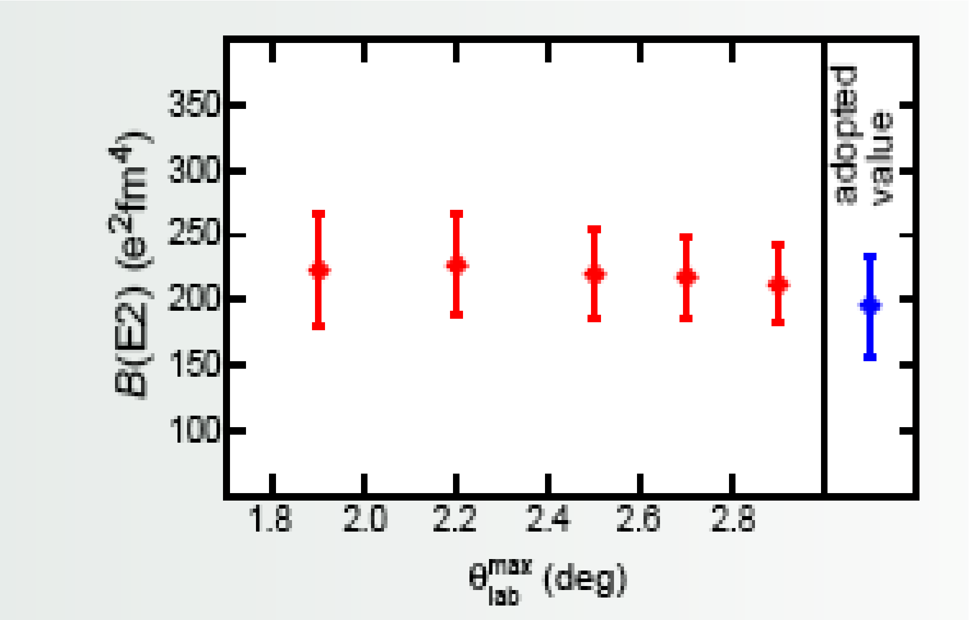


Intermediate Energy Coulomb Excitation

- Only e.m. excitations ?

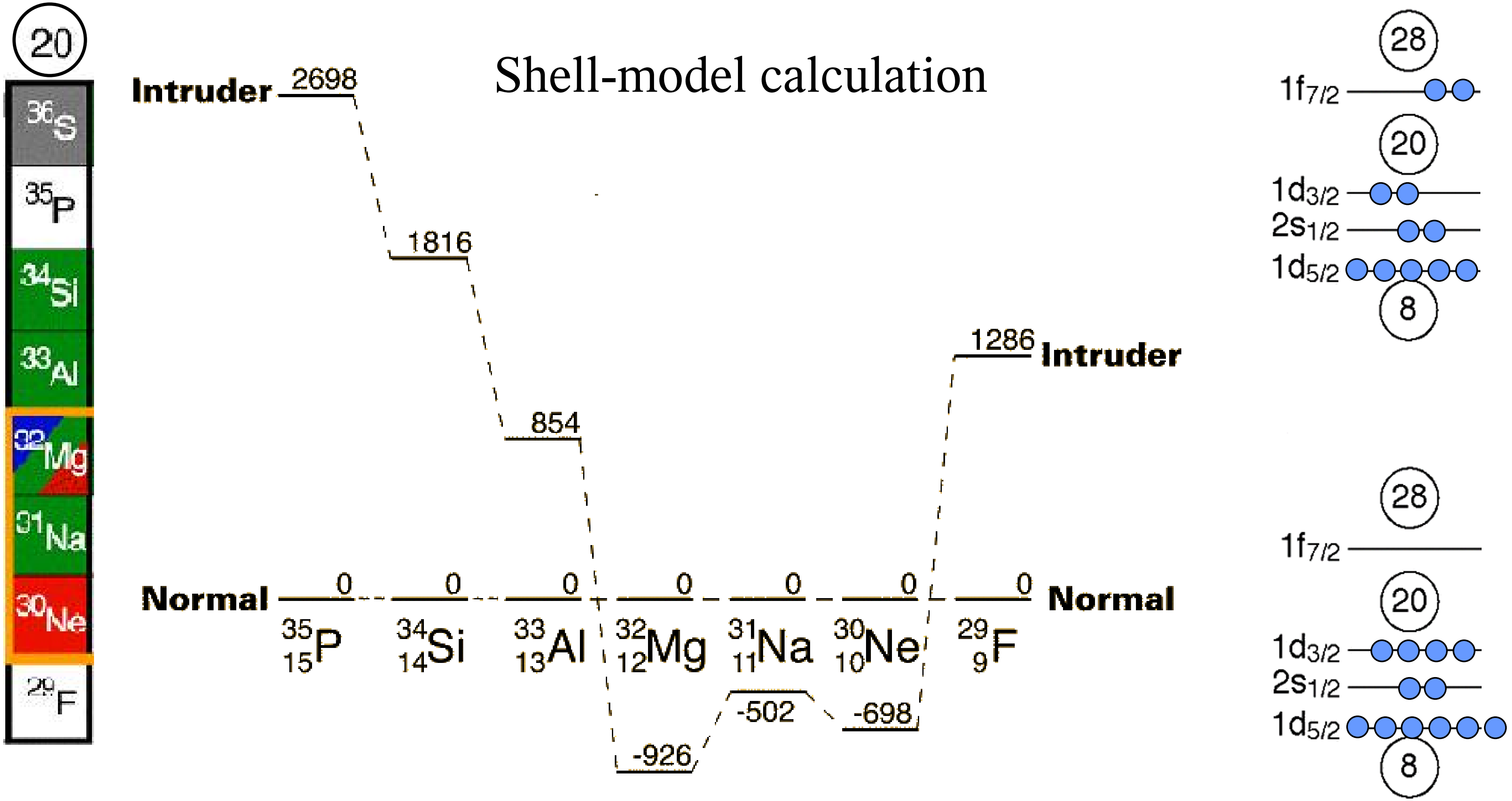






A. Gade *et al.*, Phys. Rev. **C 68** (2003) 014302.

Shape coexistence in the *N*=20 isotones



Mass: C. Thibault *et al.*, Phys. Rev. **C 12** (1975) 644
C. Detraz *et al.*, Nucl. Phys. **A 394** (1983) 378

$f_{7/2}$: X. Campi *et al.* Nucl. Phys. **A 251** (1975) 193

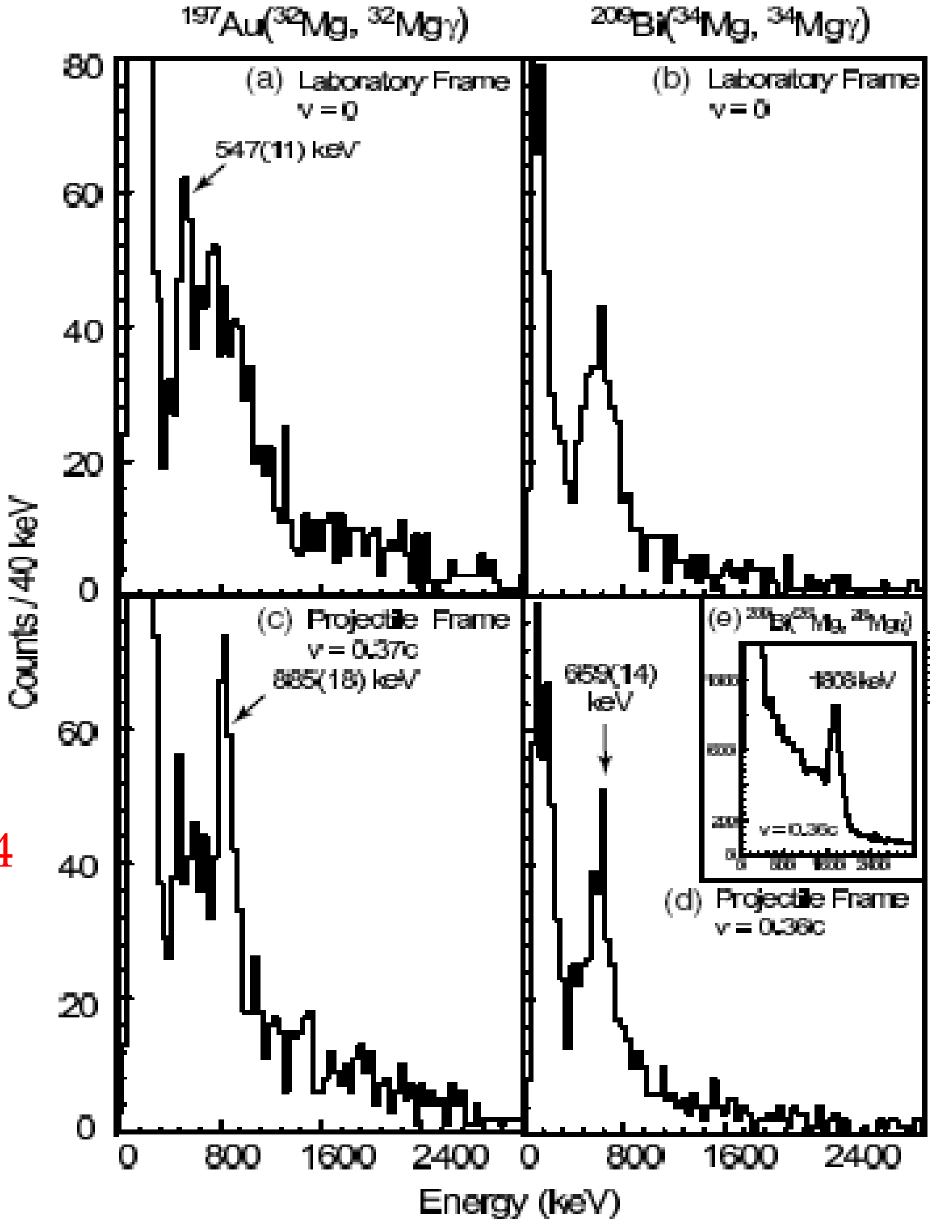
"Island of Inversion": E. Warburton, B.A. Brown, J. Becker, Phys. Rev. **C 41** (1990) 1147

Coulomb Excitation: ^{32}Mg, ^{34}Mg

J.A. Church et al.: PHYS.REV. C 72, 054320 (2005)

^{32}Mg + ^{209}Bi

^{32}Mg:
B(E2↑) =
447(54)e^2 fm^4
(deformed)

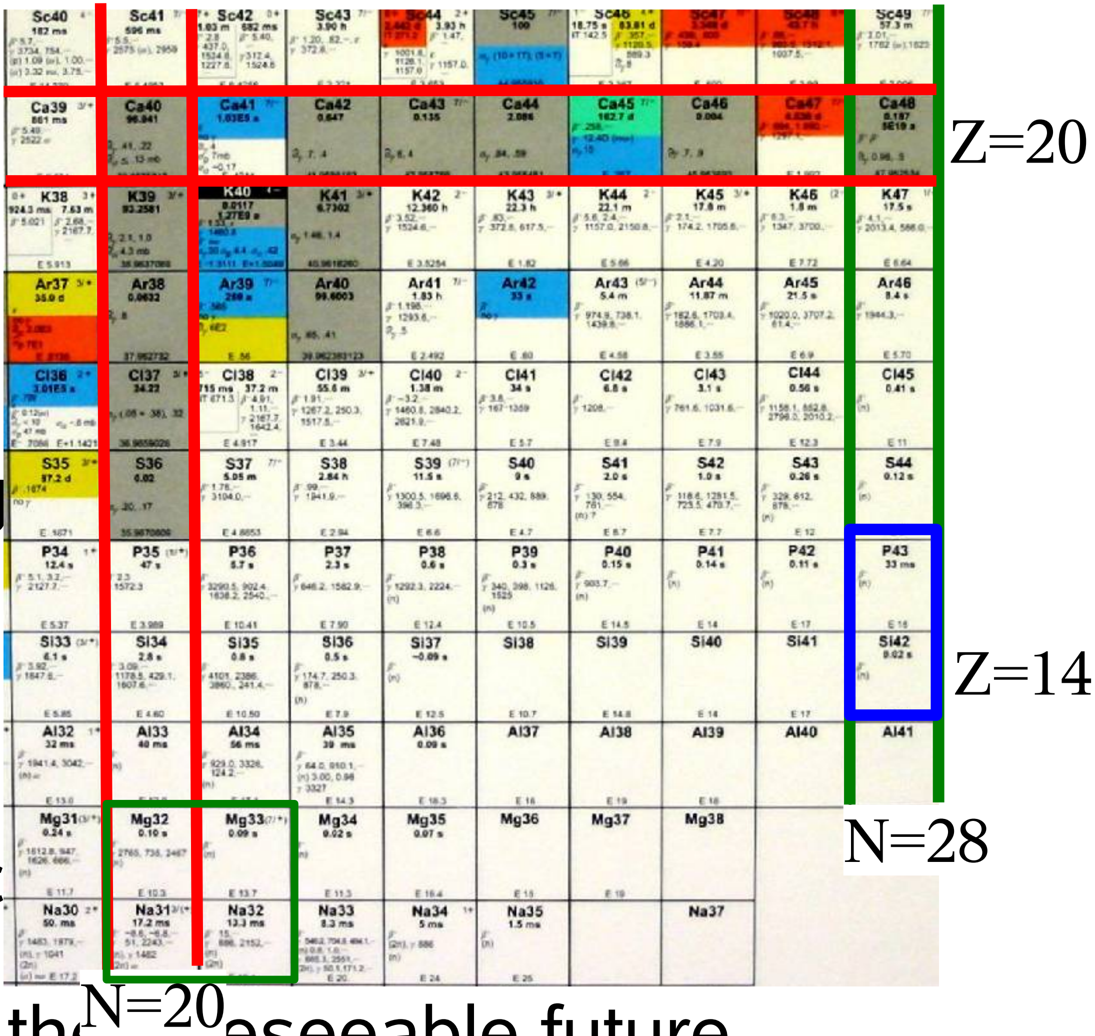


^{34}Mg + ^{209}Bi

^{34}Mg:
B(E2↑) =
541(102)e^{2}fm^4
(deformed)

Investigation of magic numbers close to the drip-line

- Modification of the shell structure may be most easily detected around the neutron magic numbers.
- N=20 is broken in the “island of inversion” at ^{32}Mg
- N=28 is the lightest magic number generated by the spin-orbit coupling
- N=28 is the heaviest magic number, for which the drip-line can be reached in the foreseeable future
- Knockout reactions allow us to measure particle structure



The *N*=28 magic number below Ca

- $T_{1/2}$ (^{44}S) too short to be spherical

M. Lewitowicz *et al.*, Nucl. Phys. **A496**, 477 (1989)

O. Sorlin *et al.*, Phys. Rev. **C 47**, 2941 (1993); Nucl. Phys. **A583**, 763c (1995)

- Microscopic calculations

T. Werner *et al.*, Phys. Lett. **B 335**, 259 (1994); Nucl. Phys. **A597**, 327 (1996)

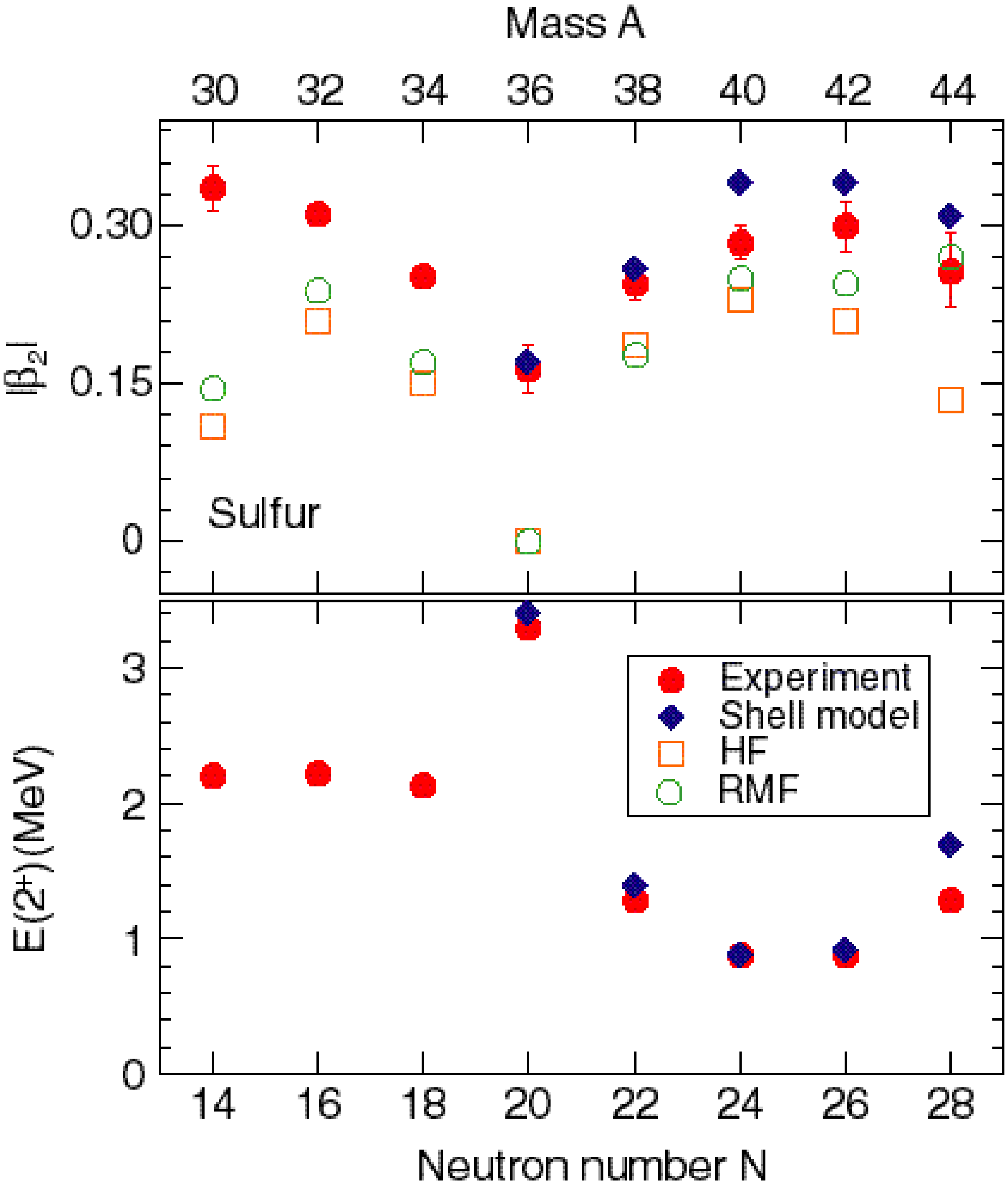
  - strong deformation for N≈28
  - $f_{7/2} \rightarrow$ *fp* core breaking

- Measurement of B(E2), collectivity

H. Scheit *et al.*, Phys. Rev. Lett. **77** (1996), 3967; T. Glasmacher *et al.*, Phys. Lett. **B 395** (1997), 163.

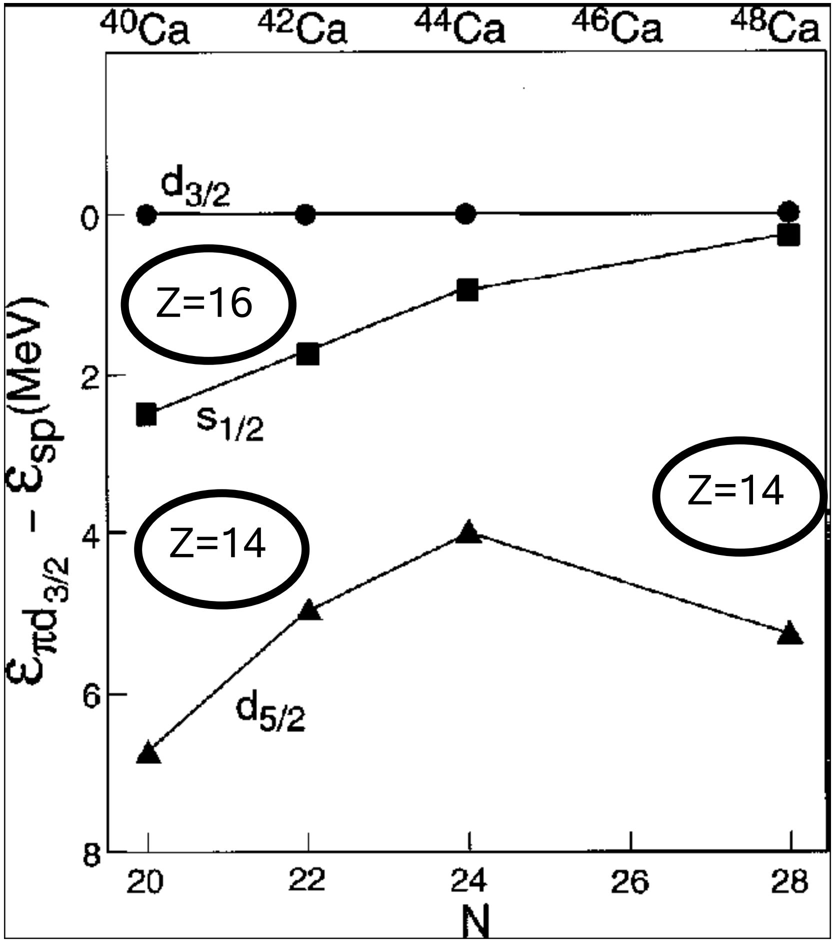
- Mass measurements at GANIL

Sarazin *et al.*, Phys. Rev. Lett. 84, 5062 (2000).



Explanation for collectivity in ^{44}S: Proton Shell Structure

- As the $\nu(f_{7/2})$ fills from 0 to 8, the $E(\pi d_{3/2})$ is depressed due to $\nu f_{7/2}$-$\pi d_{3/2}$ interaction
- Explains difference between ^{36}S and ^{44}S
- Explains ^{34}Si
- Explains ^{38}Ar and ^{46}Ar $(\pi d_{3/2})^2$
- Predicts *Z*=14 shell closure for ^{42}Si



Single proton hole energies from Ca(d,^{3}He) [P. Doll et al, Nucl. Phys. **A 263** (1976) 210]

R.K. Bansal, J.B. French, Phys. Lett. **11** (1964) 145

F. Pellegrini, Phys. Rev. **C 19** (1979) 2412

P.D. Cottle, K.W. Kemper, Phys. Rev. **C 58** (1998) 3761

New magic nucleus ^{42}Si

- I.W. [1], J. Fridmann[1], P. Cottle[1], A. Gade[1], P. Fallon[3], P.G. Hansen[1], L.T.Baby[1], D. Bazin[1], B.A. Brown[1], C.M. Campbell[1], J.M. Cook[2], E. Diffenderfer[1], D.-C. Dinca[2], T. Glasmacher[2], K. Kemper[1], J.L. Lecouey[2], W.F. Mueller[2], H. Olliver[2], E. Rodriquez-Vieitez[3], J.R. Terry[2], J. Tostevin[2] , A. Volya[1], K. Yoneda[2].

[1] Florida State University
[2] NSCL, Michigan State University
[3] Lawrence Berkeley National Lab

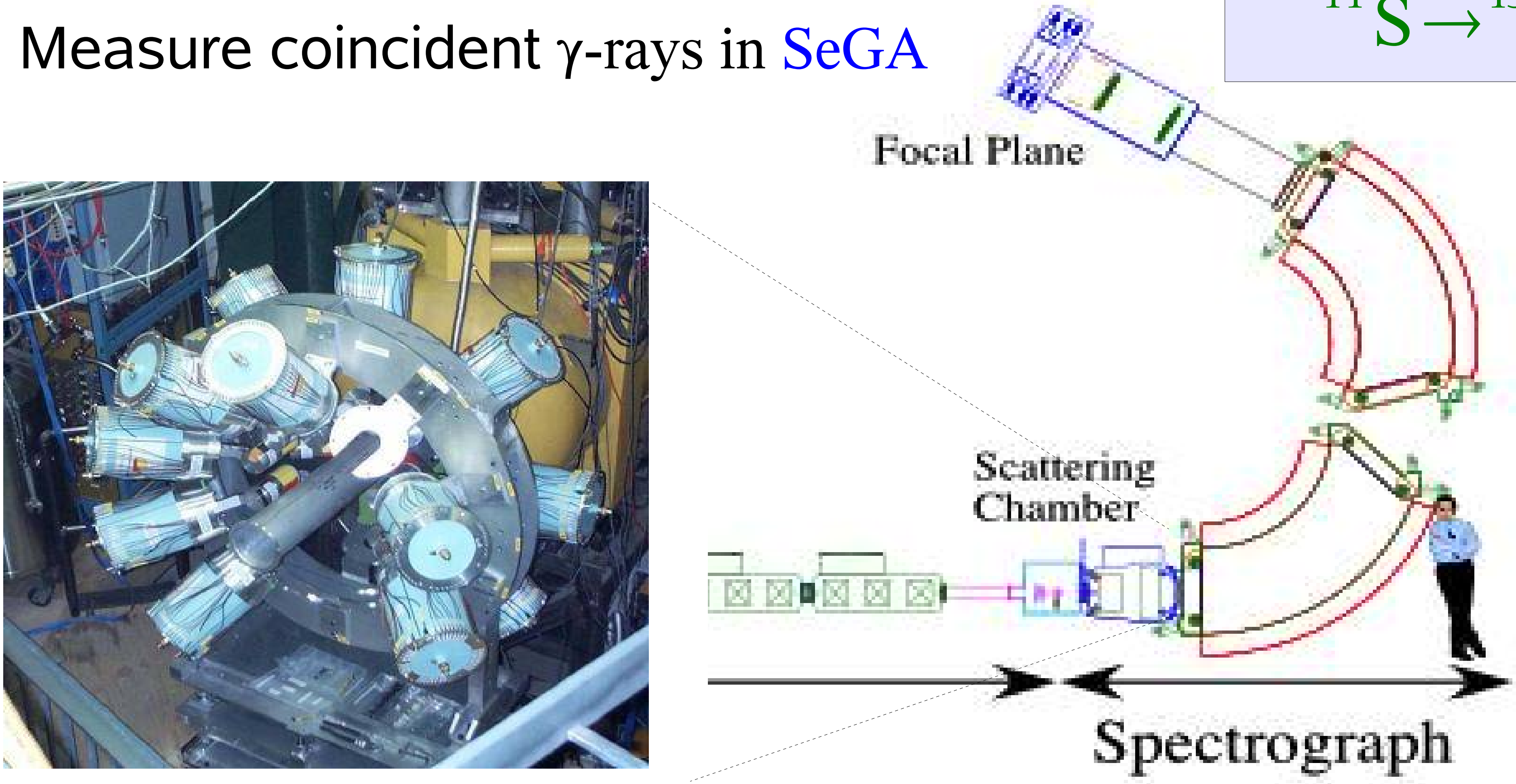
Nature 435, 922 (2005)

- Two experiments at the Coupled Cyclotron Facility.
- Primary beam:
  ^{48}Ca, 140 MeV/u
- Secondary beams:
  ^{44}S, 98.7 MeV/u 300 s^{-1}
  ^{46}Ar (setup and test)
  delivered by A1900 fragment separator

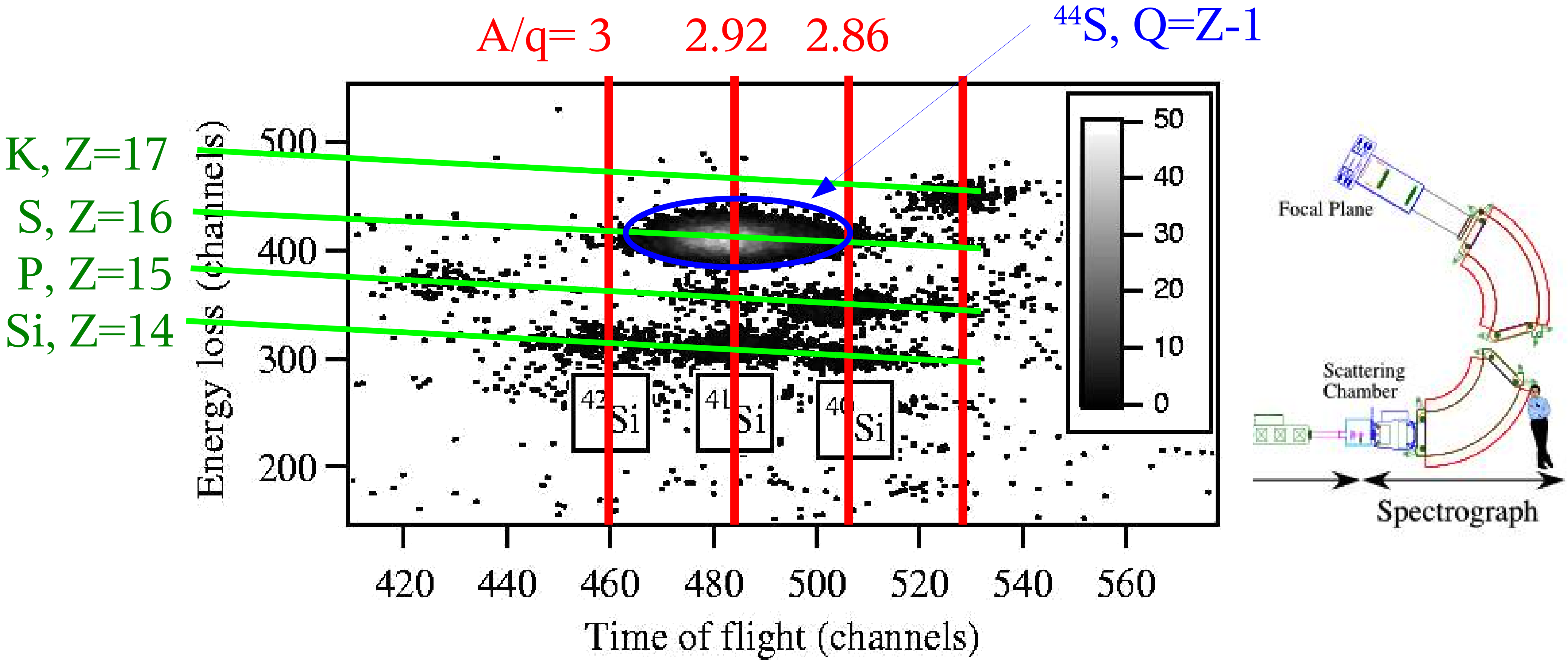
Experiments

- Two and one proton-knockout on exotic beams:
- Identify secondary reaction products in S800
- Measure coincident γ-rays in SeGA

$$^{46}\mathrm{Ar} \rightarrow {}^{44}\mathrm{S}$$
$$^{44}\mathrm{S} \rightarrow {}^{42}\mathrm{Si}$$
$$^{44}\mathrm{S} \rightarrow {}^{43}\mathrm{P}$$

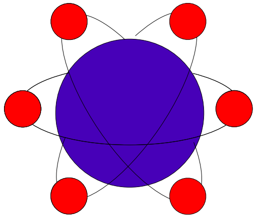


Particle Identification: "In and Out"

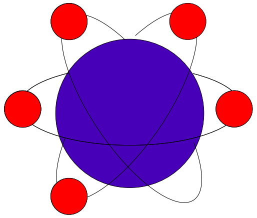


- Spectrograph selects rigidity $B\rho \approx v\, A/q$
- Reaction product's Z are identified by energy loss .
- Mass number A is identified by path-corrected tof.

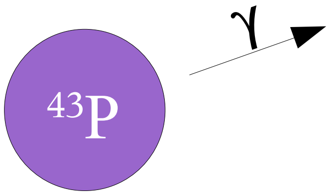
Single-Proton Knockout $^{44}S \rightarrow {}^{43}P$



$${}^{44}S:\pi\left(\alpha(d_{3/2})^2+\beta(s_{1/2})^2+\gamma(d_{5/2})^2\right)\otimes\nu\left(xyz\right)$$



$$\sigma_{sp}(j,S_p)$$

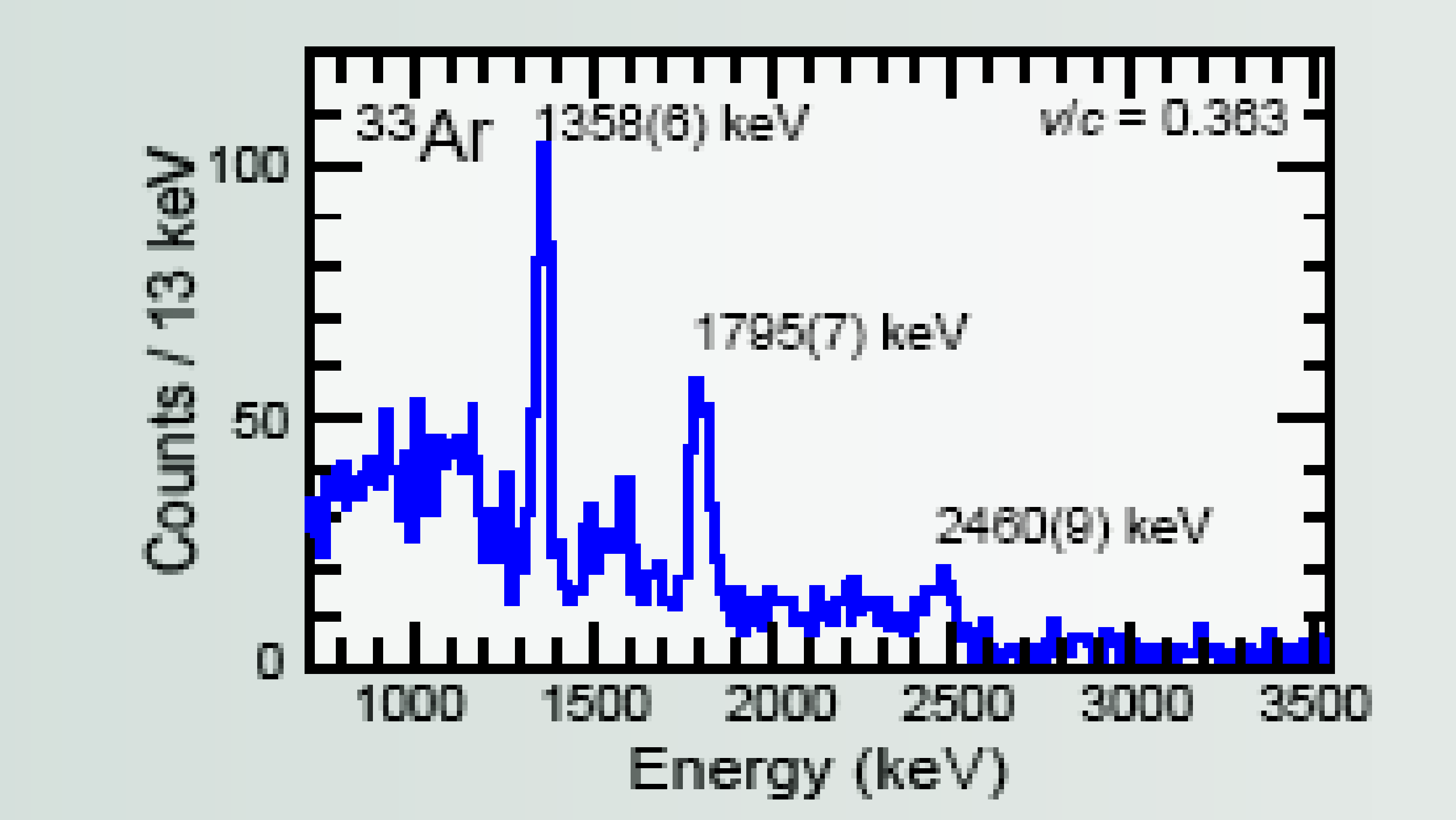


$$\sigma(I^\pi)=\sum c^{2S}(j,I^\pi)\,\sigma_{sp}(j,S_p)$$

- Calculate eikonal-approach cross section (J. Tostevin) to knock-out either (here) $d_{5/2}$, $d_{3/2}$, $s_{1/2}$ proton
- Measured cross section allows determination of spectroscopic factors
- Large cross sections mean single particle wave functions

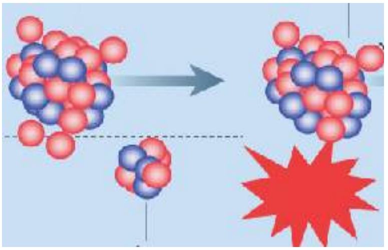
Example: Neutron-knockout

- Example: ^{34}Ar -n => ^{33}Ar+ γ
- Multiple final states populated



A. Gade et al.: Phys.Rev.Lett. 93,042501 (2004)

N-rich nuclei : Occupation of Single-Particle Orbits



Counting nucleons in single-particle orbits in exotic nuclei: **1-nucleon removal reactions**

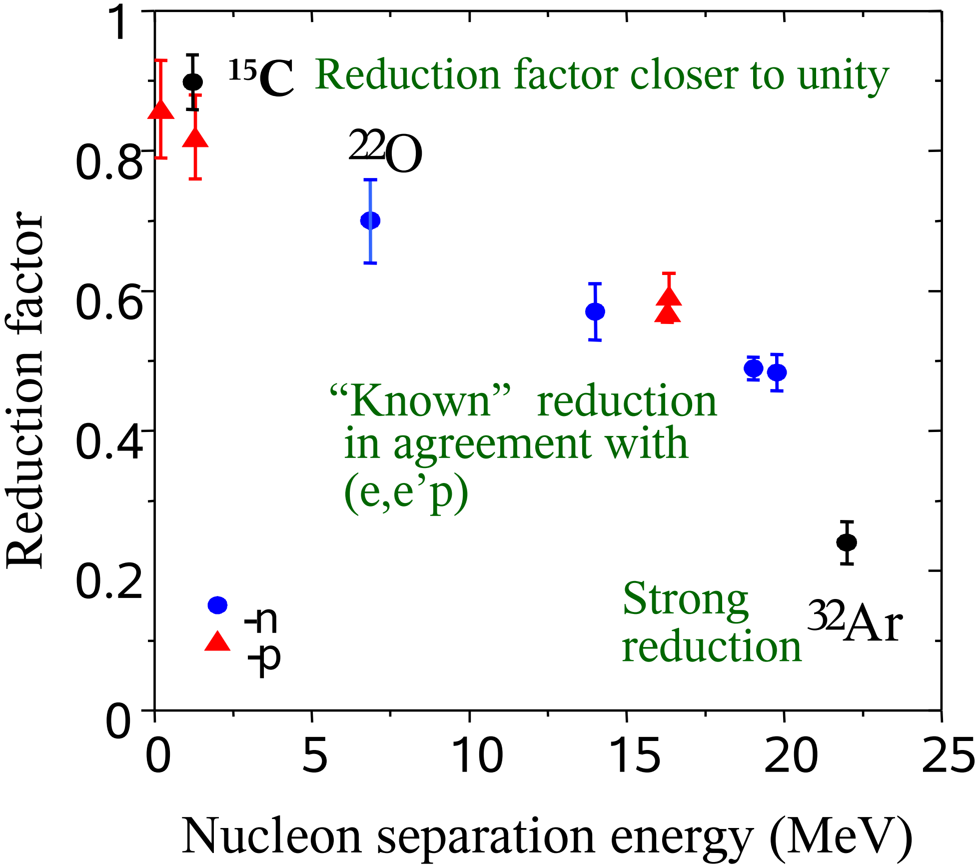
Measured spectroscopic factor C^2S relates to the occupation number of the orbit involved

Reduction factor with respect to the shell model $R_s = C^2S_{exp} / C^2S_{th}$

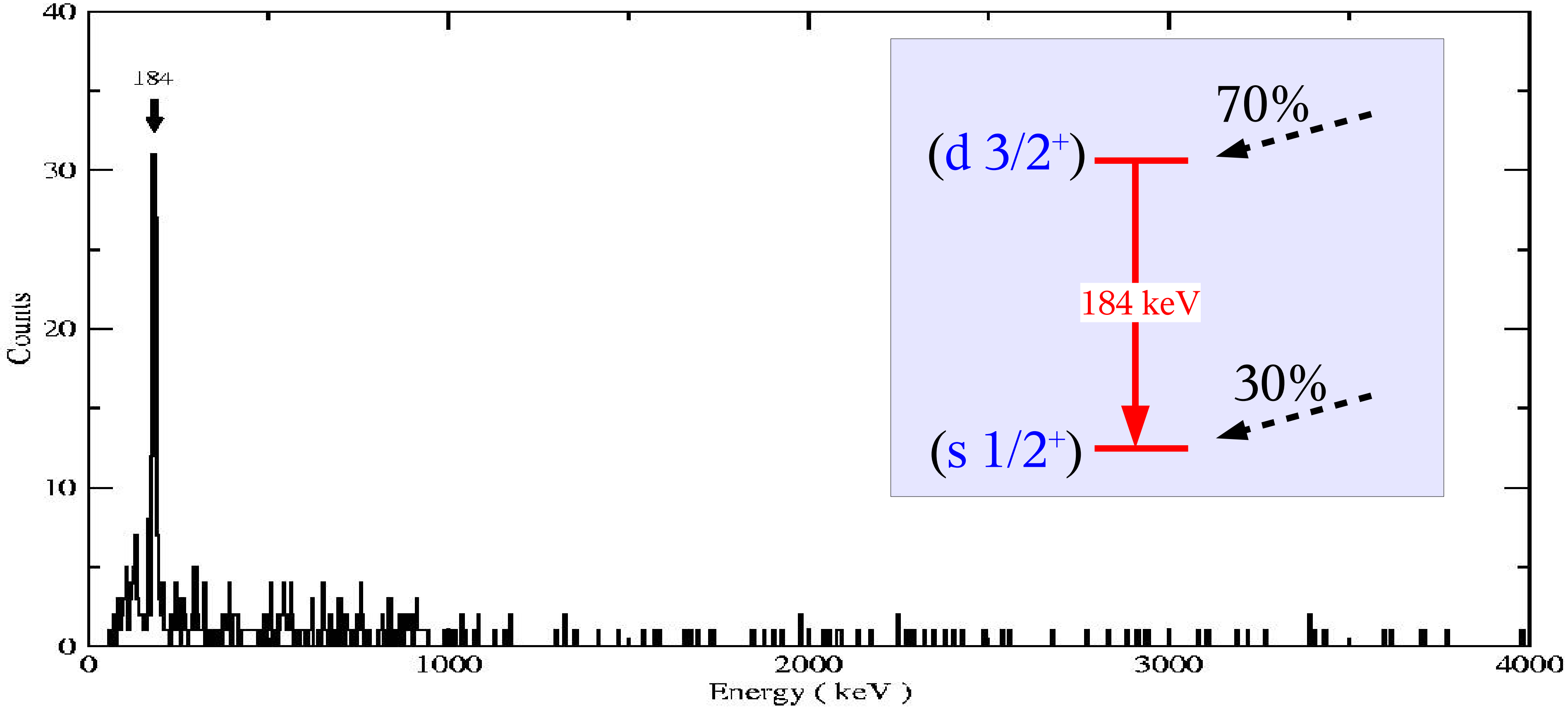
- **Determination of the occupancies probes the foundations of the nuclear shell model and provides information on the presence of correlation effects beyond effective-interaction theory**

- **Reduction has strong dependence on binding energy**

^{32}Ar and ^{22}O have the same neutron configuration but the reduction R_s is very different



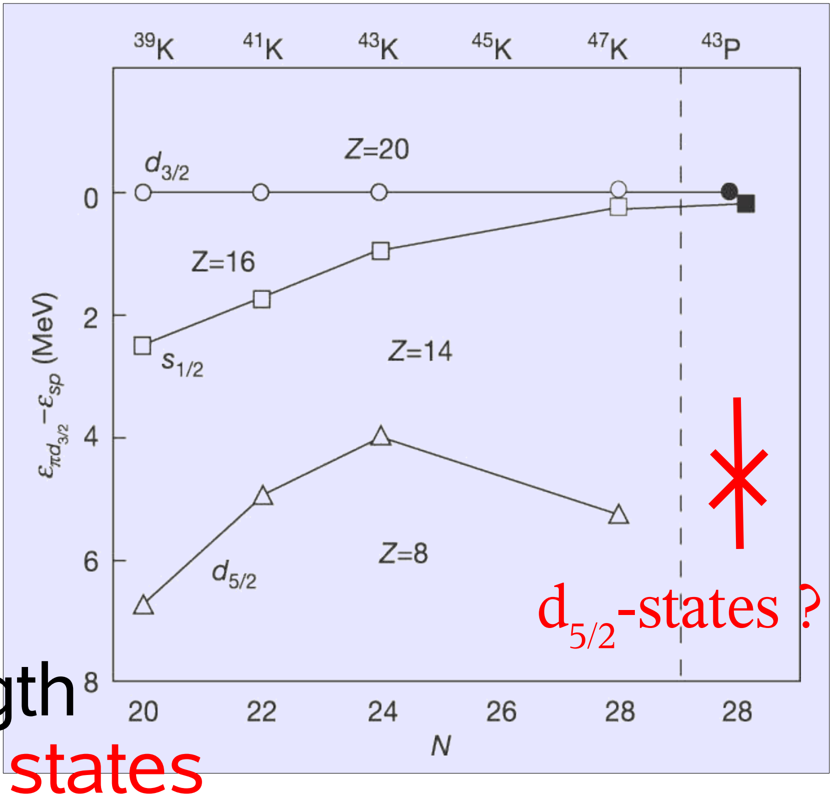
Single-p knockout: $^{44}S \rightarrow {}^{43}P$



- Total production cross section: 7.6(11) mb,
- Only two final states are populated at large cross sections
- Exp. upper limit on $d_{5/2}$ strength up to 4 MeV: <2 mb
- SM: expect $5/2^+$-strength 2.2 mb at 1.5 MeV, 7.2 mb at 2.2 MeV

Proton shell structure at N=28

- Calculation of pure single particle ko cross-section (J. Tostevin) :
  - $d_{3/2}$: 7.7 mb
  - $s_{1/2}$: 6.1 mb
  - total:13.8 mb
- Experiment:
  - total: 7.6(11) mb
- 55% of the “single particle” strength
  “single proton” character for both states
- Degenerate $d_{3/2}$ and $s_{1/2}$ states.
- no significant $d_{5/2}$-strength observed below 4 MeV
- Z=14 is a magic number at N=28



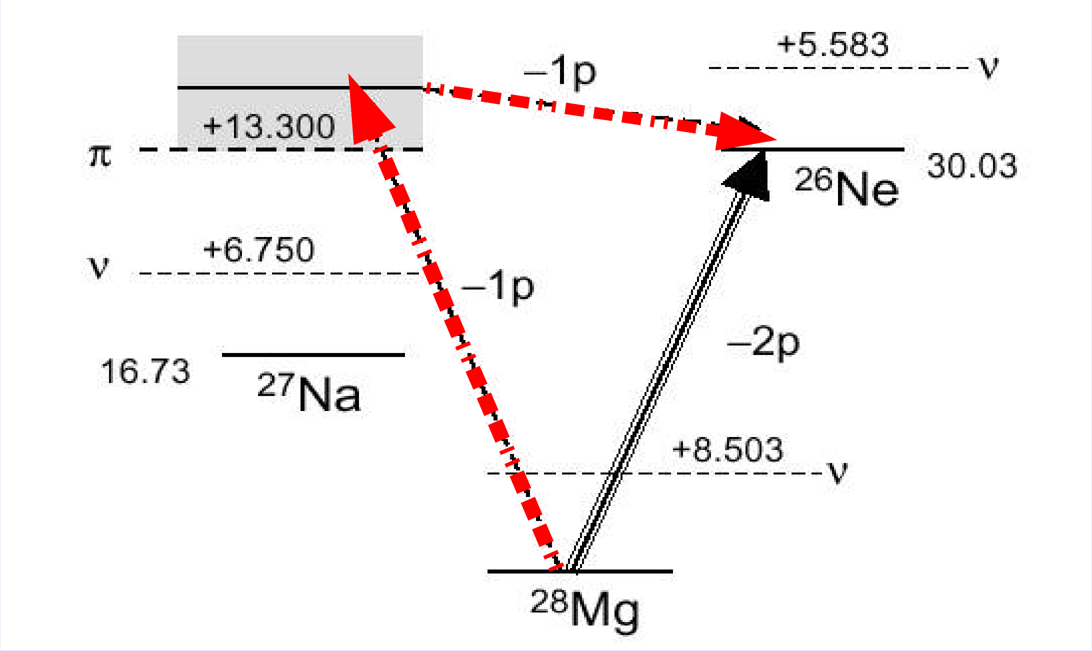
$d_{5/2}$-states ?

2p -Knockout as direct reaction

D. Bazin et al., PRL 91,1 (2003)

Indirect 2p-removal would go through neutron-unbound region

=> would rather evaporate a neutron and not produce the product in question



- Characteristics of “direct” reactions: excitation of few degrees of freedom in nuclei
- Knowledge of initial and final wavefunction allows quantitative characterization of the reaction
- Relatively strong reaction leading to exotic nuclei

2p-Knockout

- Cross sections in previous examples:

  Bazin et al PRL 91,1 (2003):

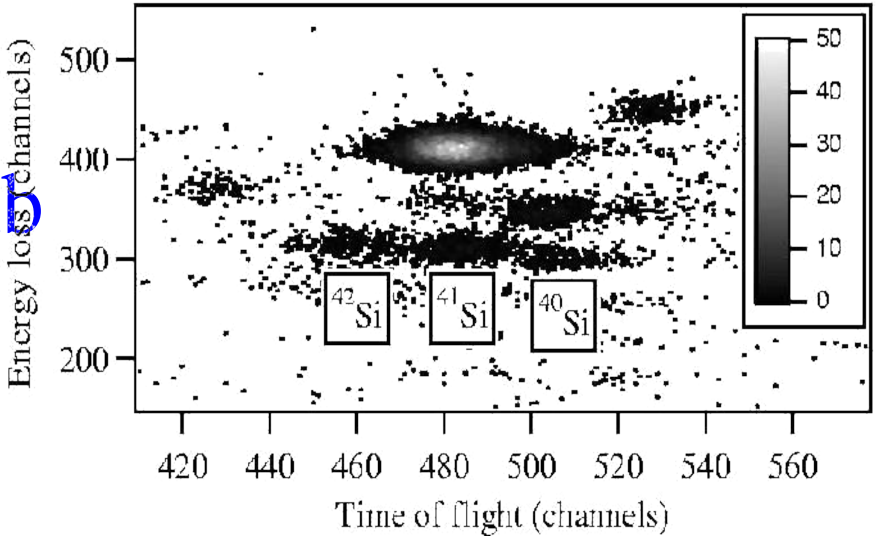
  $^{28}\mathrm{Mg} \rightarrow {}^{26}\mathrm{Si}, \sigma = 1.5\ \mathrm{mb}$

  $^{34}\mathrm{Si} \rightarrow {}^{32}\mathrm{Mg}, \sigma = 0.76(10)\ \mathrm{mb}$

- Our experiments:

  $^{46}\mathrm{Ar} \rightarrow {}^{44}\mathrm{S}, \sigma = 0.23(2)\ \mathrm{mb}$

  $^{44}\mathrm{S} \rightarrow {}^{42}\mathrm{Si}, \sigma = 0.12(2)\ \mathrm{mb}$



- Calculations: (Brown / Tostevin)

  $^{46}\mathrm{Ar} \rightarrow {}^{44}\mathrm{S}, \sigma = 0.36\ \mathrm{mb}$

  $^{44}\mathrm{S} \rightarrow {}^{42}\mathrm{Si}, \sigma = 0.17\ \mathrm{mb}$

Strawman-calculation: without Z=14-gap

$^{46}\mathrm{Ar} \rightarrow {}^{44}\mathrm{S}, \sigma = 2.9\ \mathrm{mb}$

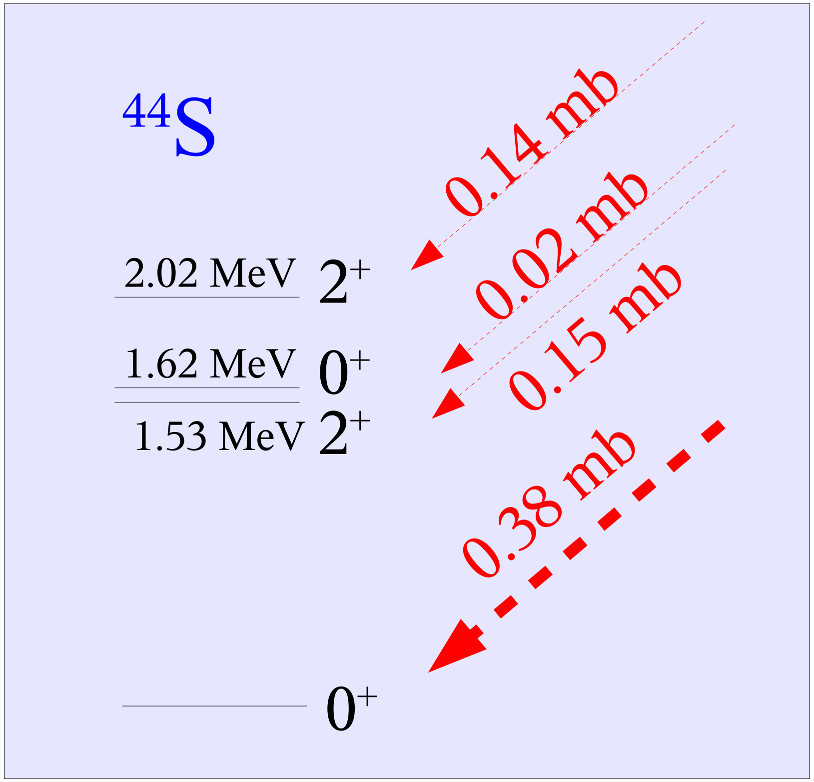
$^{44}\mathrm{S} \rightarrow {}^{42}\mathrm{Si}, \sigma = 1.7\ \mathrm{mb}$

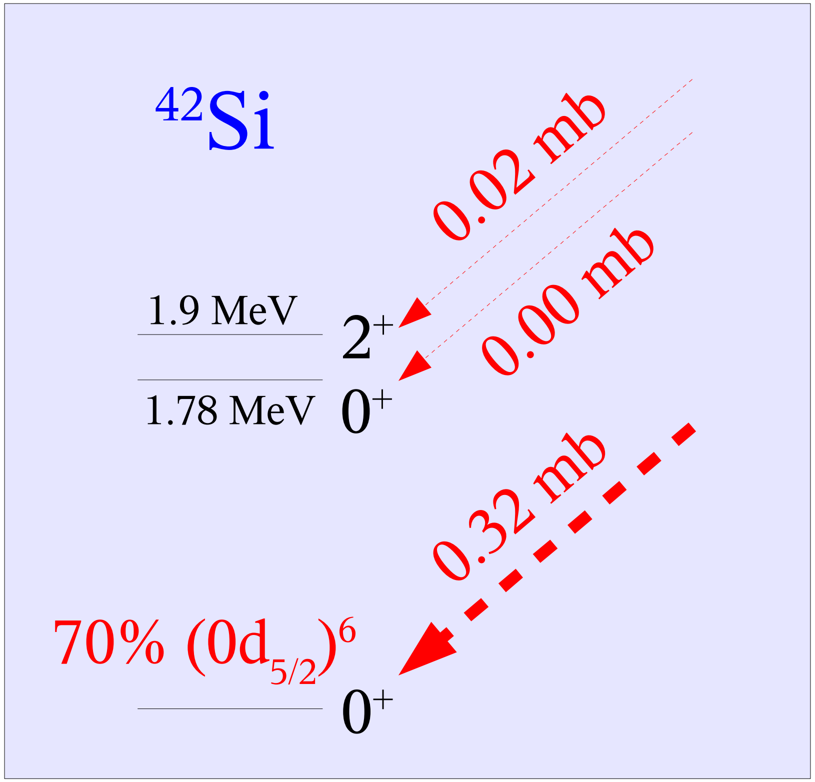
- Reduced cross sections are result of Z=14 shell closure:

  Few valence nucleons available for reaction.

Shell-model + Eikonal theory

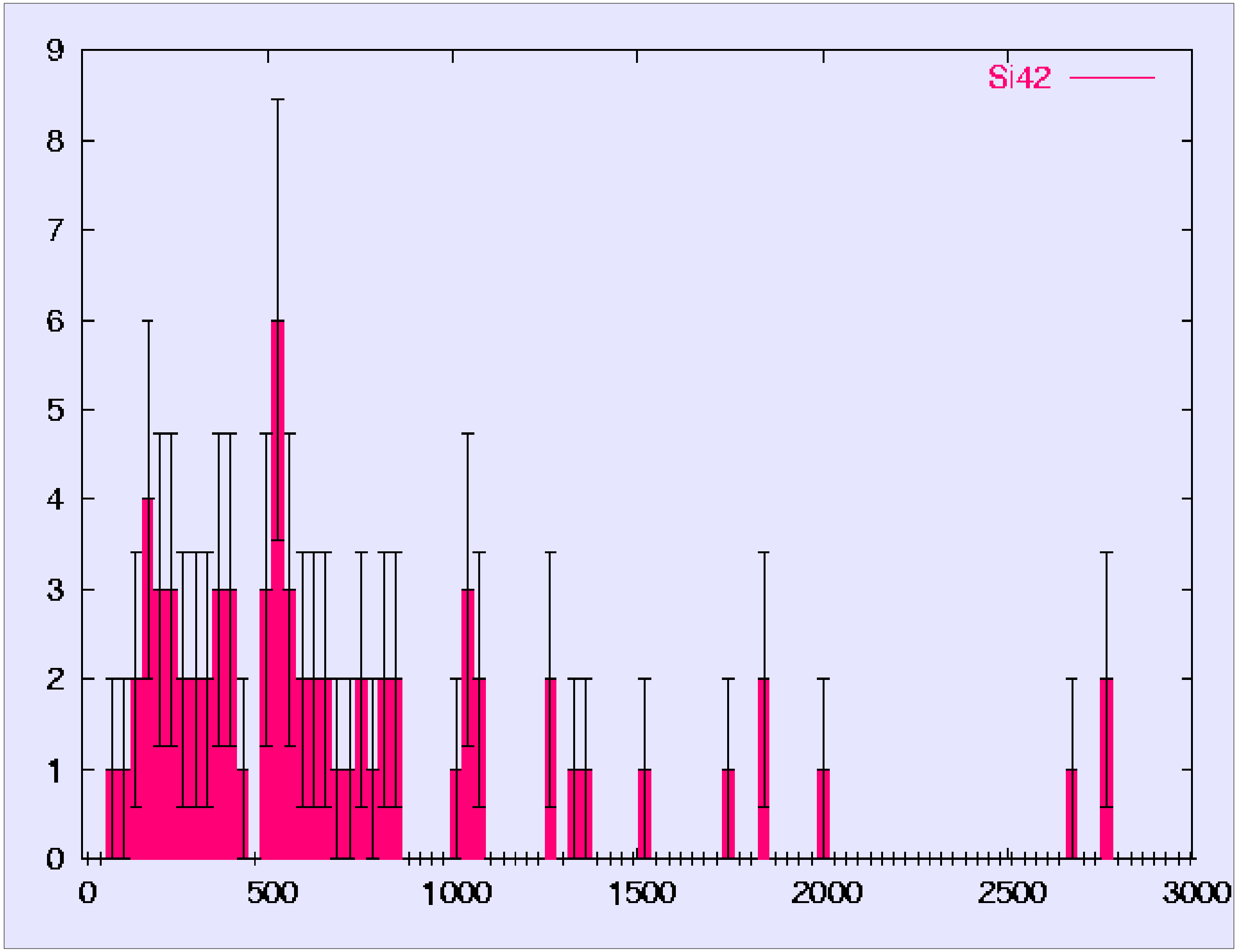
- Calculation using parameters derived from Nowacki PRC63, 44316, (2001)
- Model space $\nu:(0f_{7/2},1p_{3/2})$ $\pi(0d_{3/2},1s_{1/2},0d_{5/2})$
- Calculate both $^{46}Ar \rightarrow {}^{44}S$ and $^{44}S \rightarrow {}^{42}Si$ 2p-knockout





2p-Knockout: ^{42}Si γ-spectrum

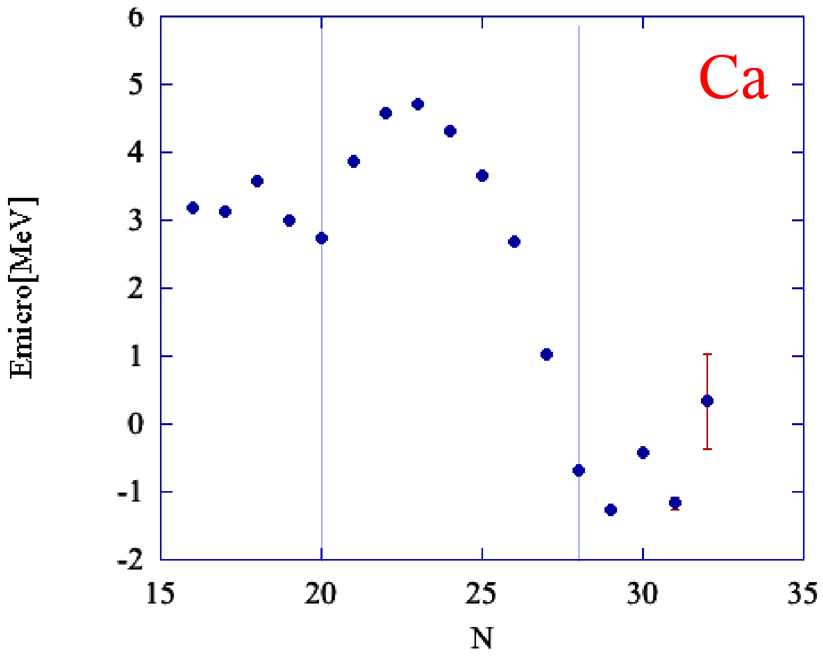
- Data from ~500 ^{42}Si nuclei
- Number of gammas counted $N(\gamma) / N(^{42}Si) = 0.25(3)$
- γ-spectrum is consistent with no peaks observed

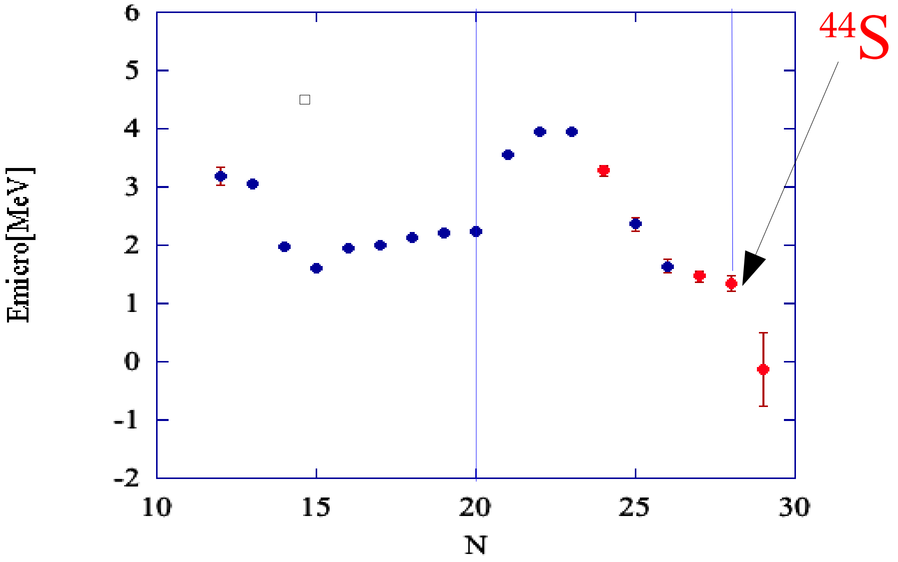


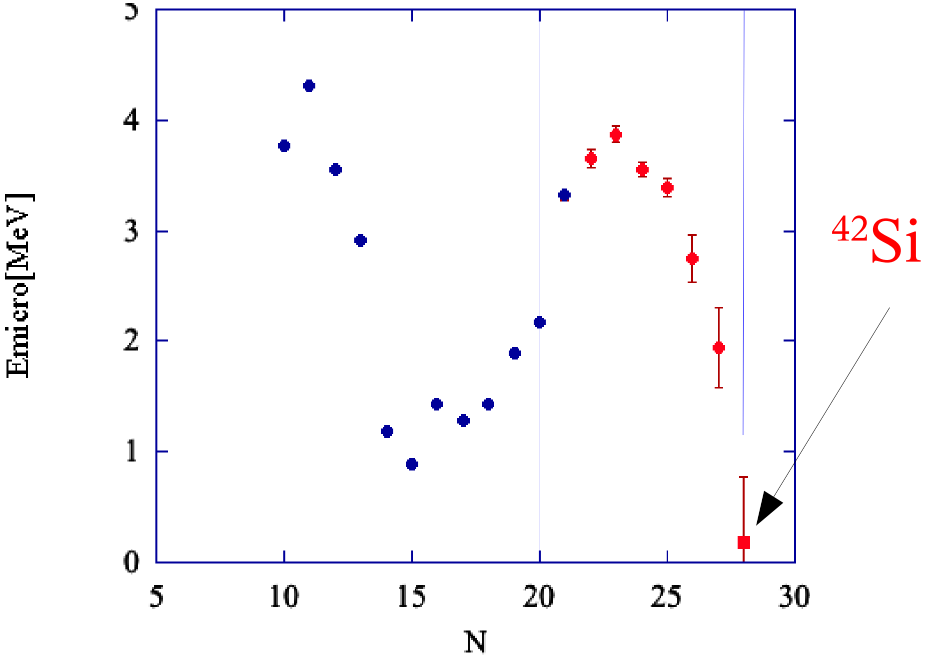
Masses- measured at GANIL

"Microscopic correction" - energy

$m_{micro} = m_{exp} - m_{FRLDM}$





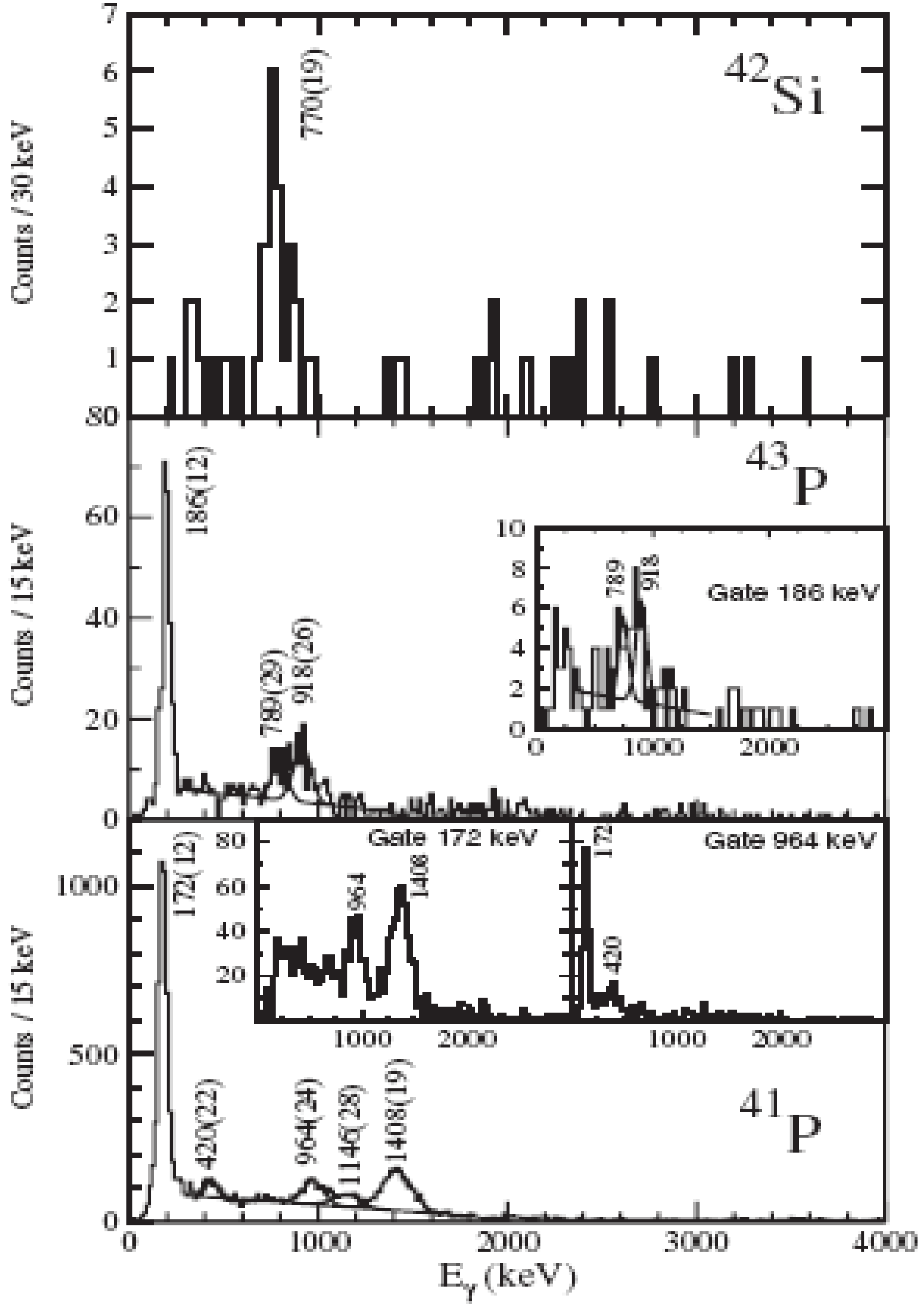


-
- N=28 shell closure washed out in ^{44}S
- N=28 shell closure clearly visible in ^{42}Si
- S_N in ^{42}Si: 5.9(7) MeV

B.Jurado,W. Mittig et al., to be published

GANIL: ^{42}Si: low energy gamma-ray

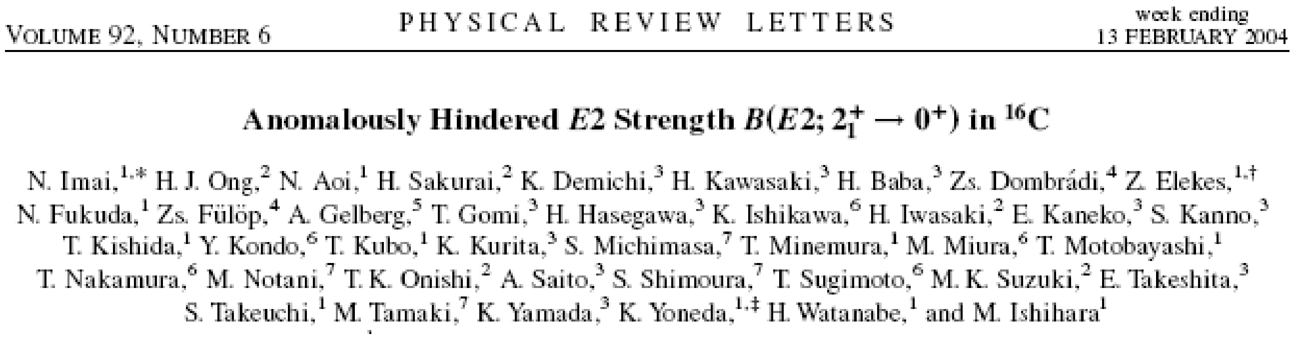
- Bastin, Grevy et al.: PRL 99, 022503 (2007)
- Two-proton knockout identifies low-energy 770 keV gamma-ray in ^{42}Si.
- Breakdown of N=28 shell closure ?
- or new mode of collective excitation ?



What's “exotic” about neutron-rich nuclei

- Many (?) examples for modification of shell structure in neutron-rich nuclei are known (N,Z<50)
- What may be the more interesting question: What are the collective excitations of neutron matter ?

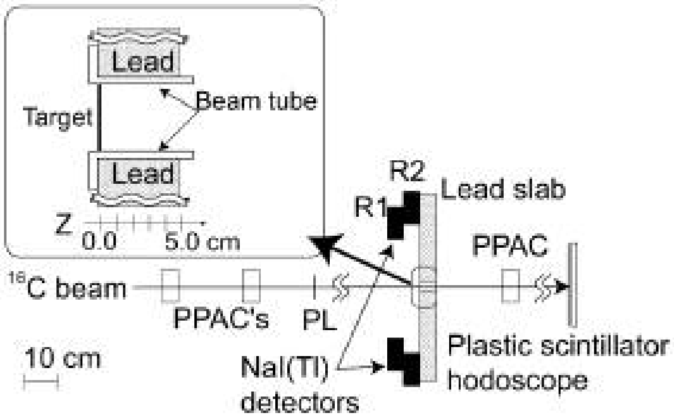
Riken: Long lifetime of the low 2^+ in ^{16}C

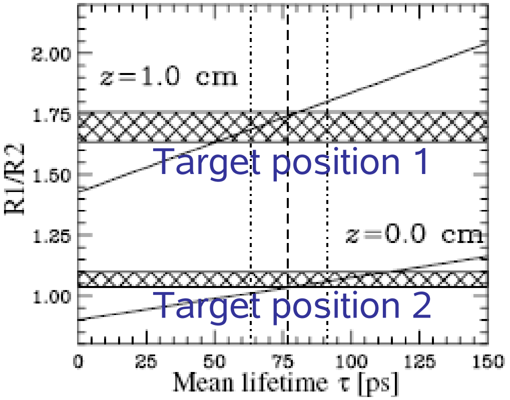


VOLUME 92, NUMBER 6 PHYSICAL REVIEW LETTERS week ending 13 FEBRUARY 2004

Anomalously Hindered $E2$ Strength $B(E2; 2_1^+ \to 0^+)$ in ^{16}C

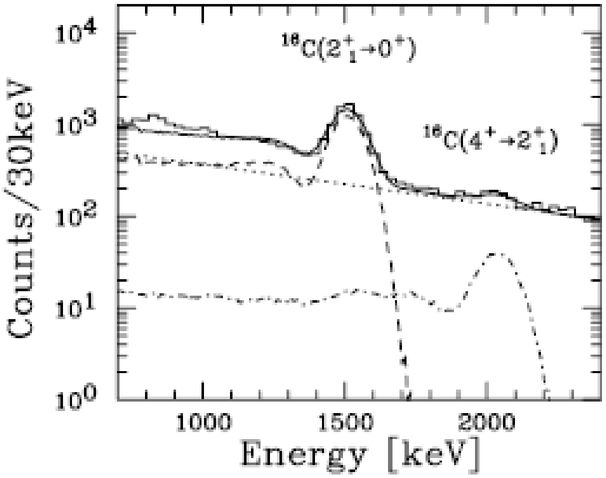
N. Imai,[1,*] H. J. Ong,[2] N. Aoi,[1] H. Sakurai,[2] K. Demichi,[3] H. Kawasaki,[3] H. Baba,[3] Zs. Dombrádi,[4] Z. Elekes,[1,†] N. Fukuda,[1] Zs. Fülöp,[4] A. Gelberg,[5] T. Gomi,[3] H. Hasegawa,[3] K. Ishikawa,[6] H. Iwasaki,[2] E. Kaneko,[3] S. Kanno,[3] T. Kishida,[1] Y. Kondo,[6] T. Kubo,[1] K. Kurita,[3] S. Michimasa,[7] T. Minemura,[1] M. Miura,[6] T. Motobayashi,[1] T. Nakamura,[6] M. Notani,[7] T. K. Onishi,[2] A. Saito,[3] S. Shimoura,[7] T. Sugimoto,[6] M. K. Suzuki,[2] E. Takeshita,[3] S. Takeuchi,[1] M. Tamaki,[7] K. Yamada,[3] K. Yoneda,[1,‡] H. Watanabe,[1] and M. Ishihara[1]

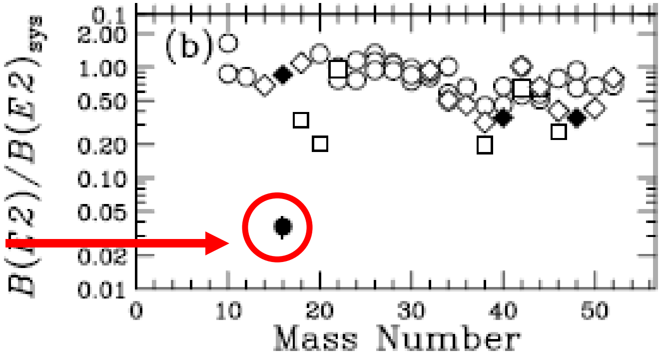




Target position 1

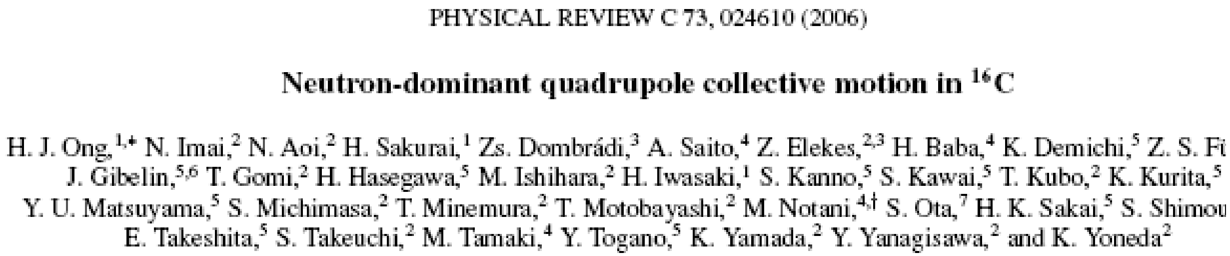
Target position 2





- Inelastic excitation of ^{16}C
- extremely low B(E2) = 0.26(W.u.)
- Far off systematics of E(2+) vs B(E2)

Riken: Neutron – Structure of ^{16}C



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Neutron-dominant quadrupole collective motion in ^{16}C

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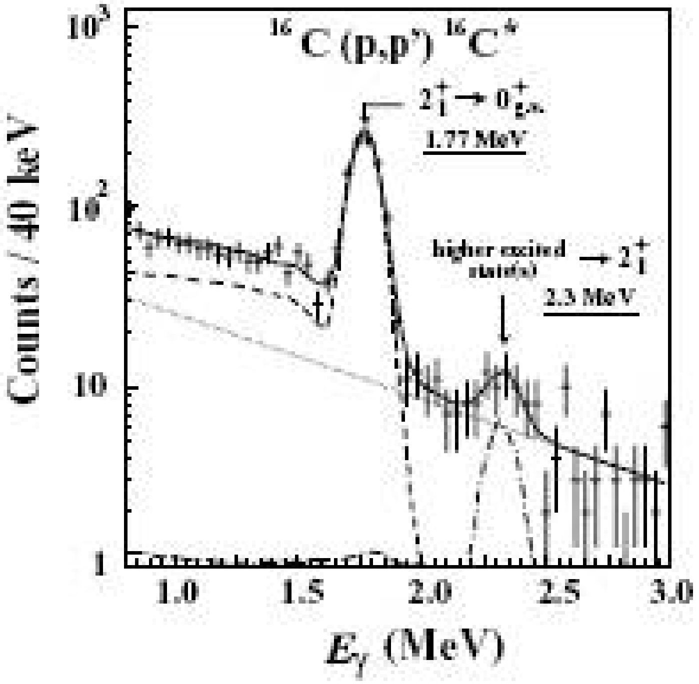
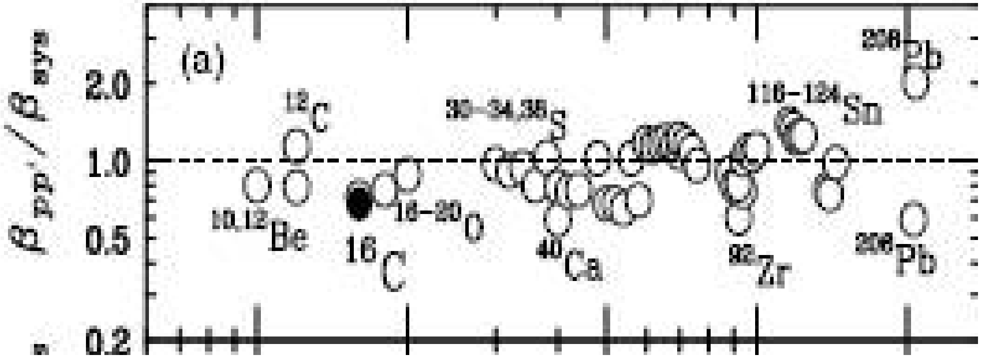
J. Gibelin,[5,6] T. Gomi,[2] H. Hasegawa,[5] M. Ishihara,[2] H. Iwasaki,[1] S. Kanno,[5] S. Kawai,[5] T. Kubo,[2] K. Kurita,[5]
Y. U. Matsuyama,[5] S. Michimasa,[2] T. Minemura,[2] T. Motobayashi,[2] M. Notani,[4,†] S. Ota,[7] H. K. Sakai,[5] S. Shimou
E. Takeshita,[5] S. Takeuchi,[2] M. Tamaki,[4] Y. Togano,[5] K. Yamada,[2] Y. Yanagisawa,[2] and K. Yoneda[2]

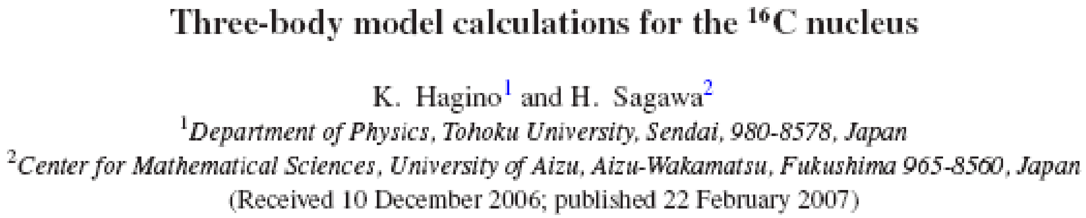


- Inelastic proton-scattering selectively populates neutron-states
- Cross section corresponds to neutron deformation $\beta_{pp'}$=0.47(5)
- 2+ energy expected from Neutron deformation



C16 – Neutron collectivity ?

- 2N+core cluster m



Three-body model calculations for the ^{16}C nucleus

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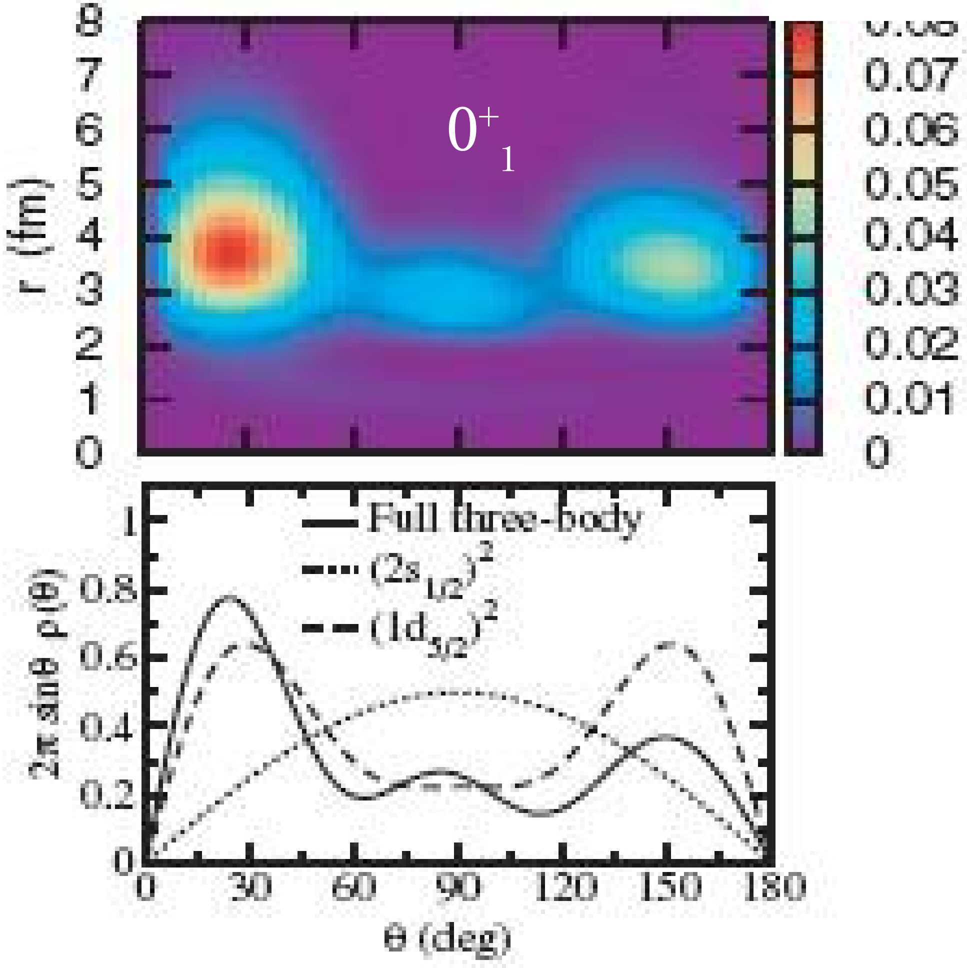
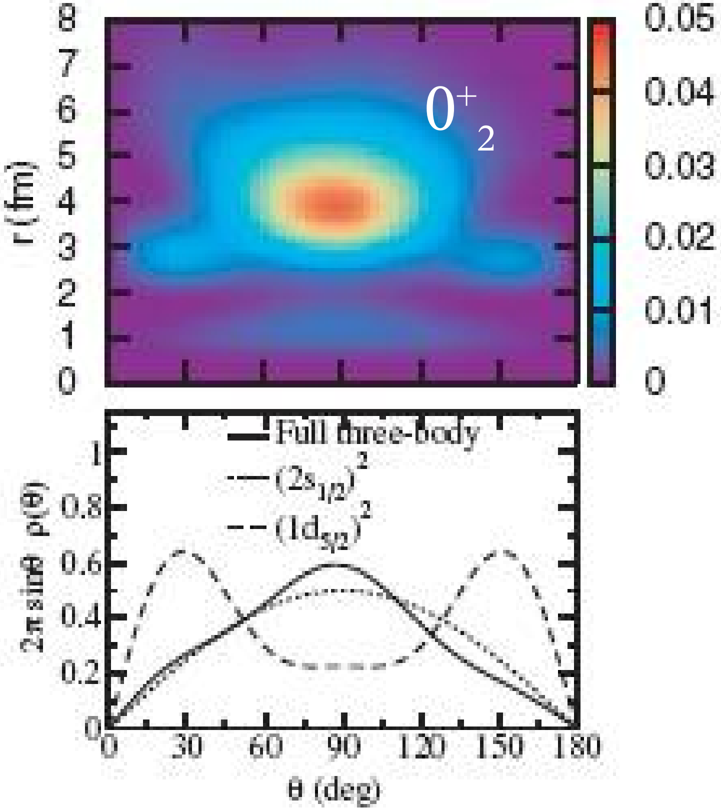
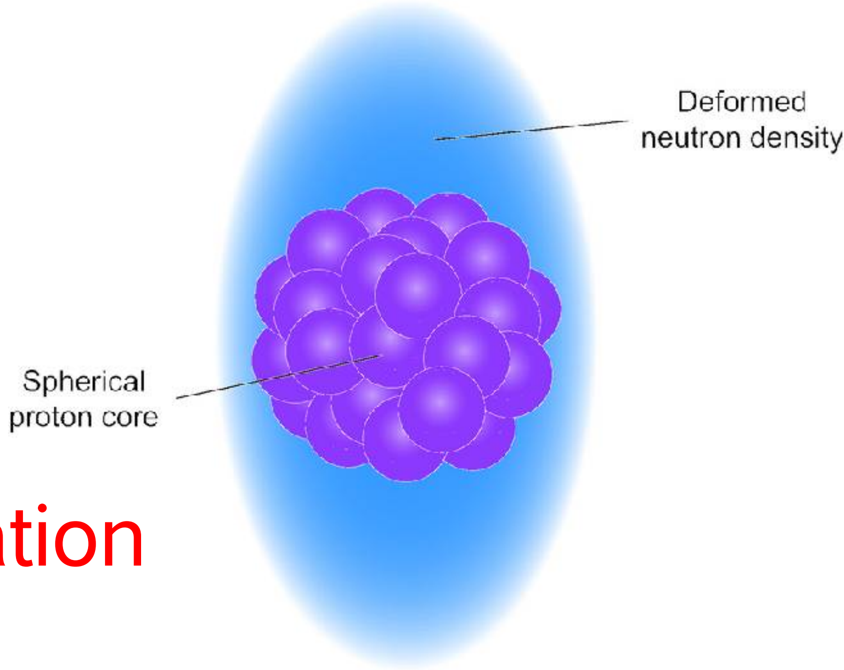




A new type of collectivity ?



- How to explain small B(E2) :
  “Decoupling” of neutrons
  or “Destructive Interference” ?
- The B(E2) strength has to be somewhere !
  Barrier energy Coulomb excitation
- Do protons contribute at all ?
  Proton-knockout study: ^{17}N → ^{16}C (+γ ?) (NSCL)
- What is the neutron-wavefunction ?
  Pair transfer ^{16}C(p,t)^{14}C (+γ ?)
- Are there more, heavier nuclei with this behaviour ?
- Is this what we have to expect at the dripline ?

Exotic Nuclei: Made to thrill

- Neutron-rich nuclei have shell structure different from their “stable” siblings and their proton-rich mirrors !
- New collective excitations have to be expected: Neutron-only collectivity ?
- We need more detailed experiments than the $E(2^+)$ $B(E2)$ of the first excited state !