Observation of the first 2^+ state in ^{40}Si and trends in collectivity approaching N=28

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- **Experiment: (p,p'+γ)**
  - **Why?**
  - **How?**
- **Results**
  - **New gamma-rays/levels**
  - **Inelastic cross-sections**
  - **Trends in β_2**

Nuclei at the Limits 04

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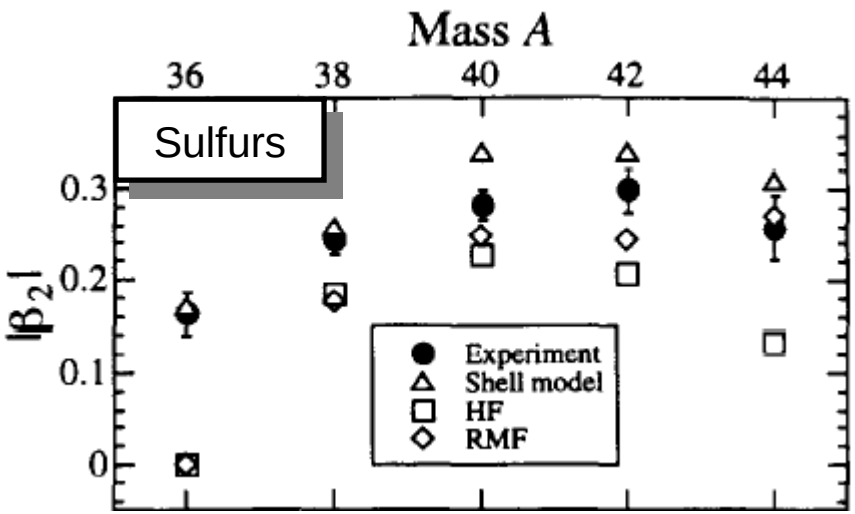
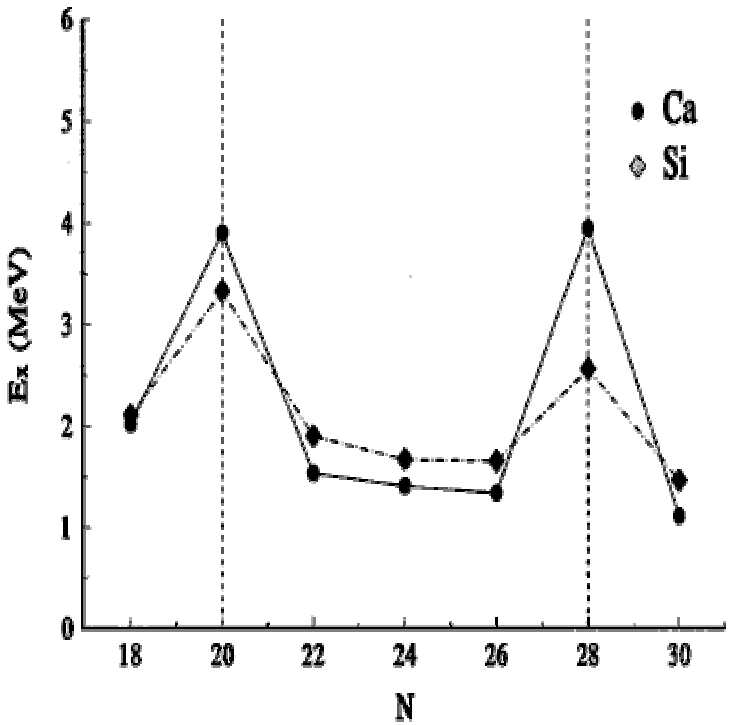
Collectivity in neutron-rich N=28 nuclei

- Beta-decay and Coulex[1-3]
  - Indicates a new region of deformation
- Calculations of ground state deformations [4]
  - Deformed N=28 nuclei
  - Weakened shell closure



- Shell model [5]
  - –N=28 shell may be restored in ^{42}Si
  - –Deformation of sulfurs is local
  - –No larger region of deformation exists



[1] O. Sorlin *et al.*, Nucl. Phys. **A583**, 763 (1995).

[2] H. Scheit *et al.*, Phys. Rev. Lett. **77**, 3967 (1996).

[3] T. Glasmacher *et al.*, Phys. Lett. B **395**, 163 (1997).

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

[5] J. Retamosa *et al.*, Phys. Rev.C **55**, 1266 (1997).

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Inverse-kinematics inelastic proton-scattering with gamma-ray tagging

Why (p,p')?

- Cross-sections give nuclear deformations
- Comparison to Coulex separates neutron and proton contributions
- **Higher probability of excitation for a fixed target energy-loss**

Why look at γ-rays?

- **Thicker targets can be used**
- Better energy resolution
  - States above the first 2^+ state
  - Odd Z,A isotopes

Given a fixed target energy loss (p,p') can give **8x** the number of excitations as Coulex.

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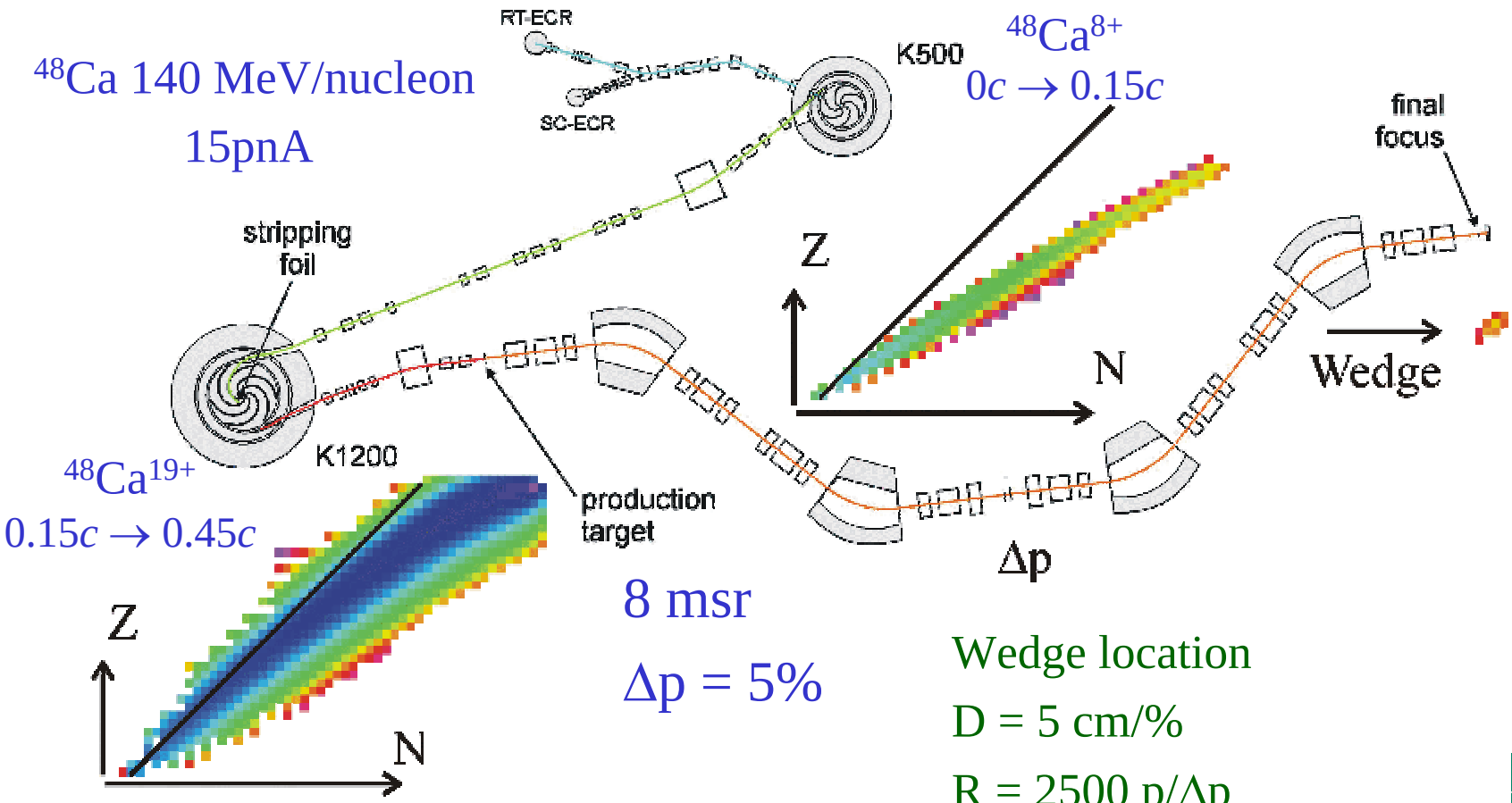
The NSCL Coupled Cyclotron Facility (CCF)



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

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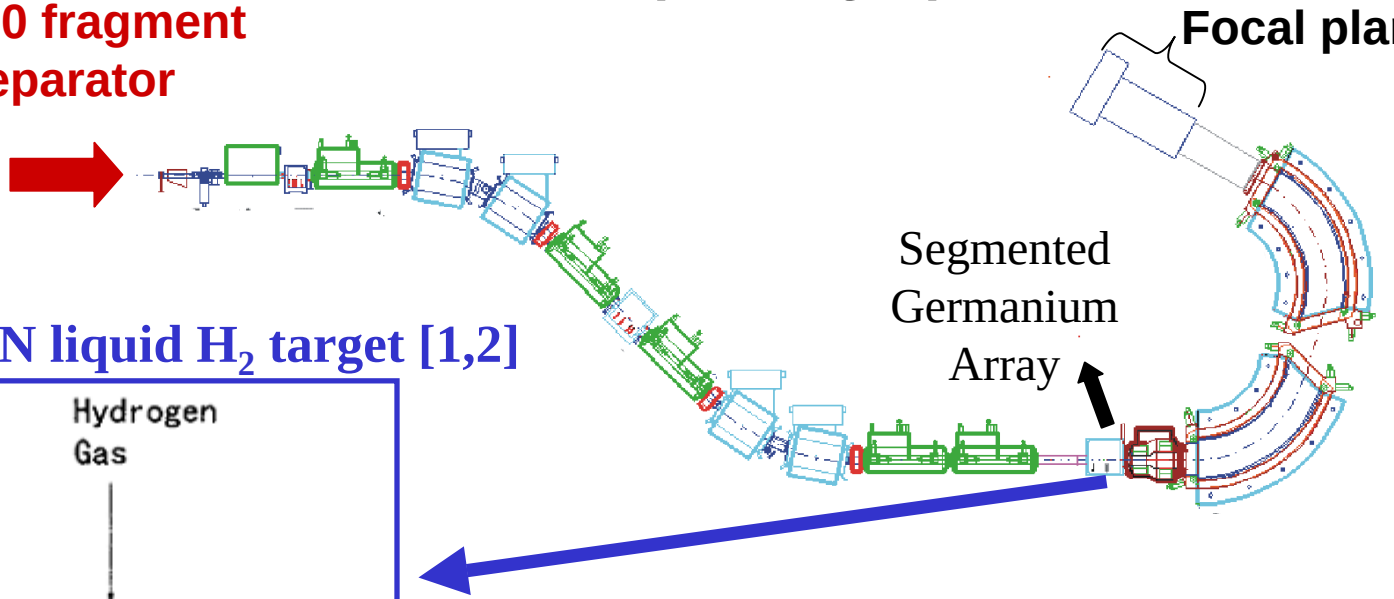
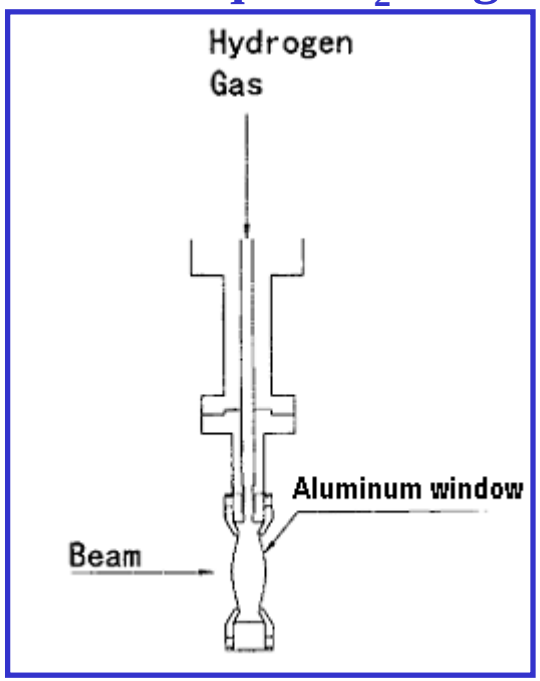
Experimental setup

Exotic beams from A1900 fragment separator

S800 spectrograph



RIKEN liquid H_2 target [1,2]



- Target cell:
  - 30mm diameter
  - 11mm thick
- No carbon atoms, unlike CH2. Aluminum atom fraction < 5%. No background run required.

[1] Provided by H. Sakurai, N. Aoi, *et al.*, (2003)

[2] H. Akiyoshi *et al.*, RIKEN Accel. Prog. Rep. **32**,167 (1999).

[3] J. Yurkon et al., NIM A422, 291 (1999)

[4] D. Bazin et al., NIM B204, 629 (2003)

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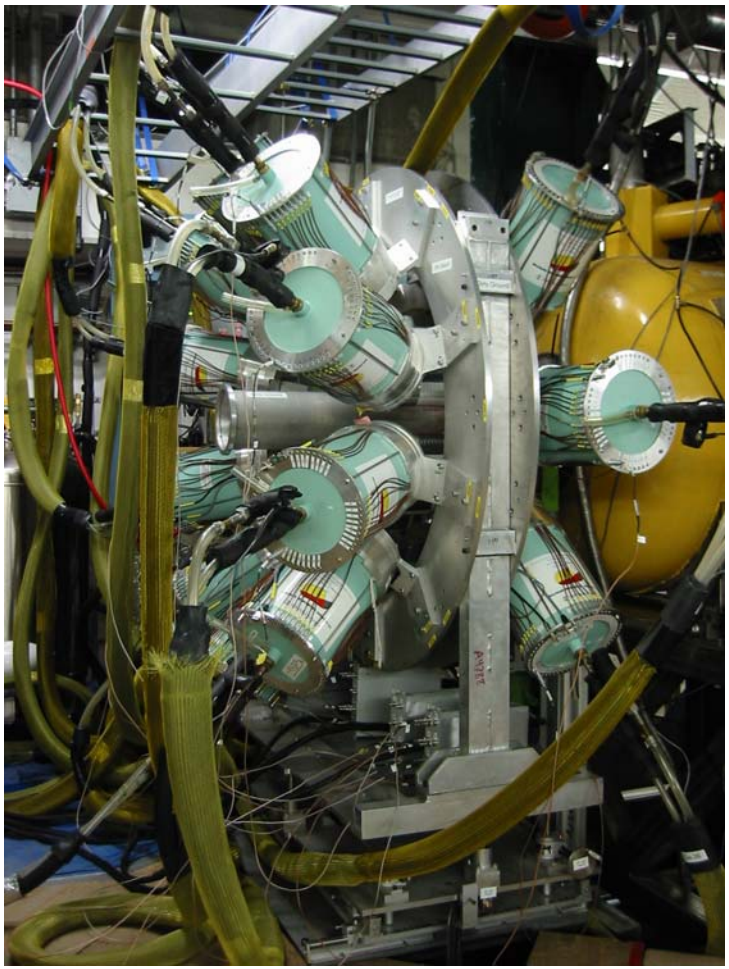


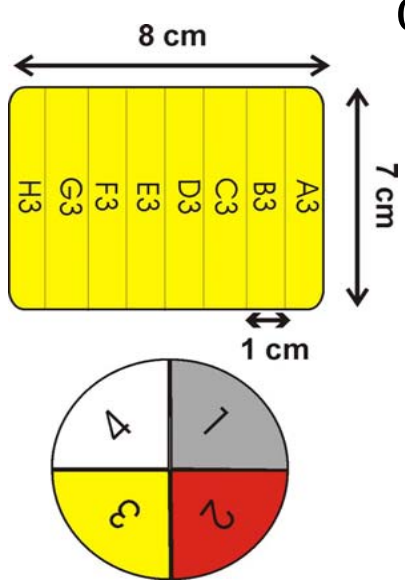
SeGA

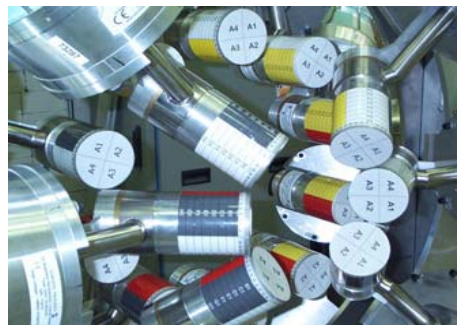
(**Se**gmented **G**ermanium **A**rray)—Eighteen 32-fold segmented HP germanium detectors

Energy resolution (intrinsic): 0.3%
Energy resolution (in-beam): 3%

Roughly equal contributions:

Target thickness ($\Delta\beta$)
Opening angle ($\Delta\theta$)





Two rings: 37° and 90° from beam axis

Efficiency (source): 2% @ 1.3MeV

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

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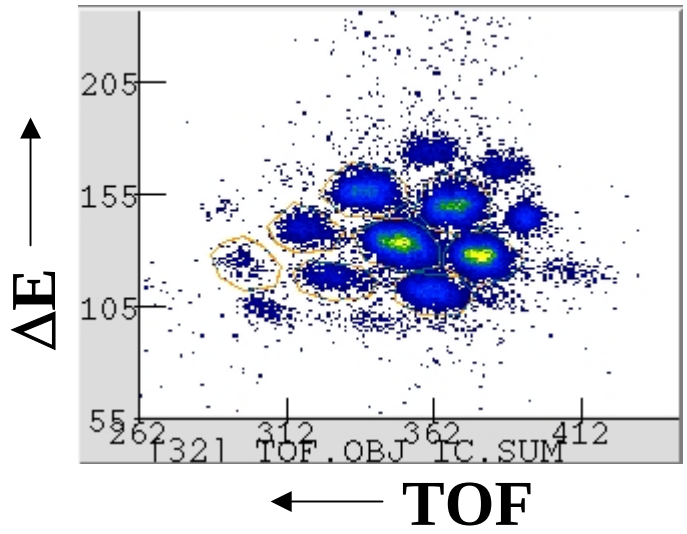
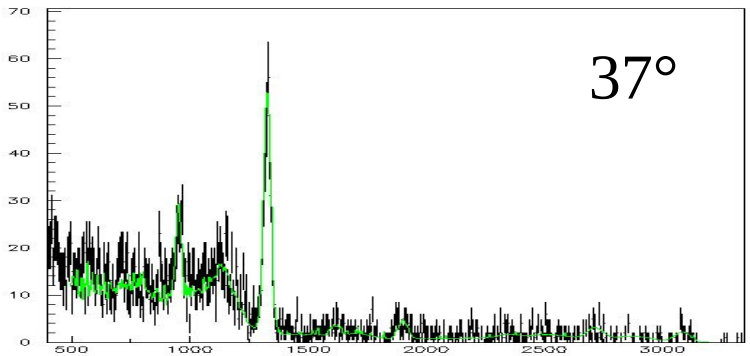
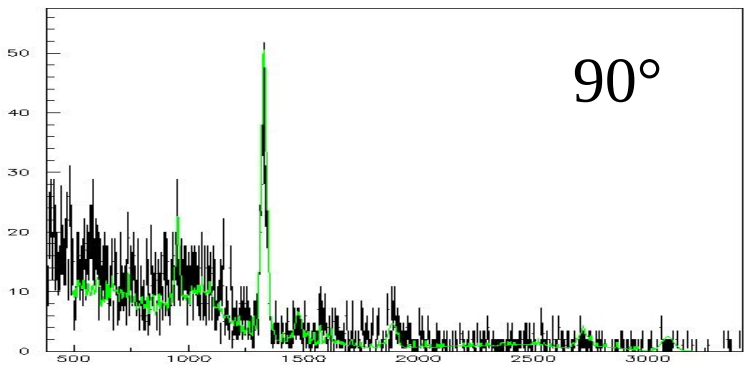
Data reduction

- Select elastic/inelastic events for the nucleus of interest
  - Pre-target PID
  - Post-target PID
  - Momentum change







- Gate gamma-ray spectra by elastic/inelastic AND prompt Ge time

- Fit spectra from 37° and 90° with response spectra generated by GEANT

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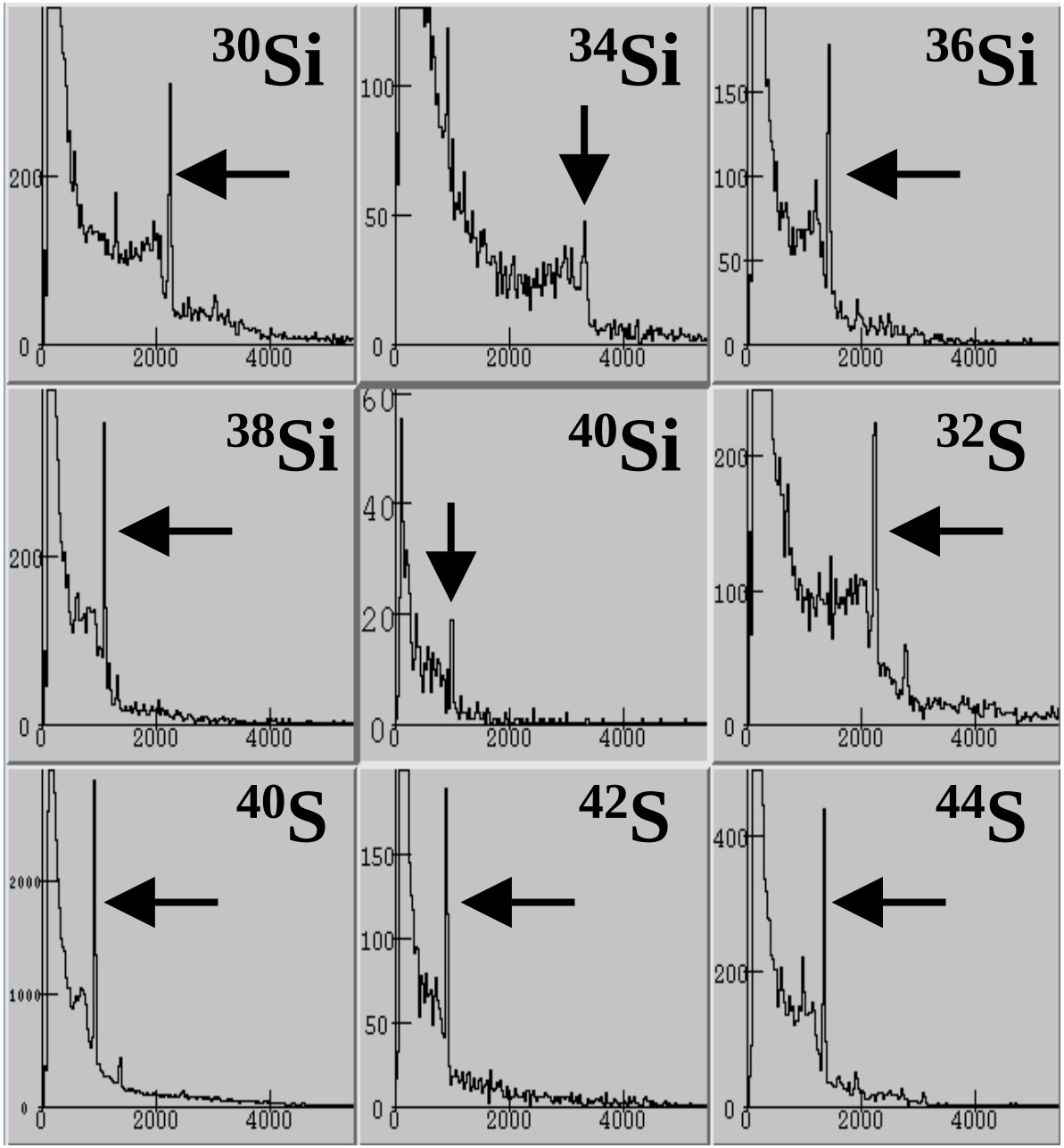

- Three cocktail beams: 80-105 MeV/nucleon
- Nine even-even silicon and sulfur nuclei studied
- Photopeak areas range from about 30 - 3500 counts

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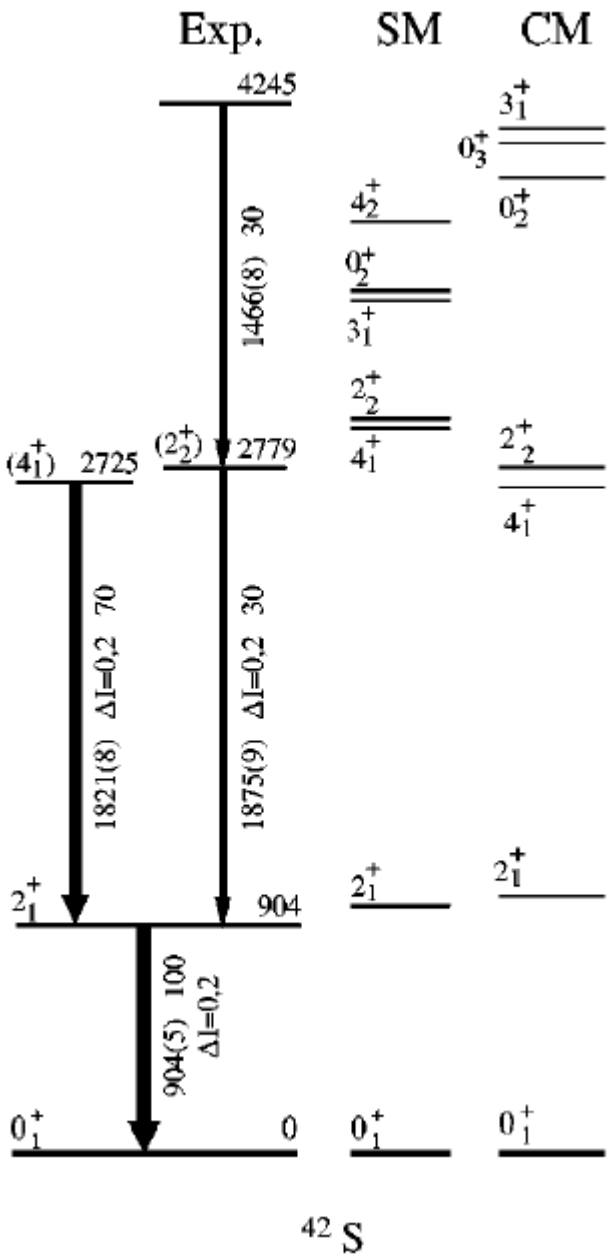
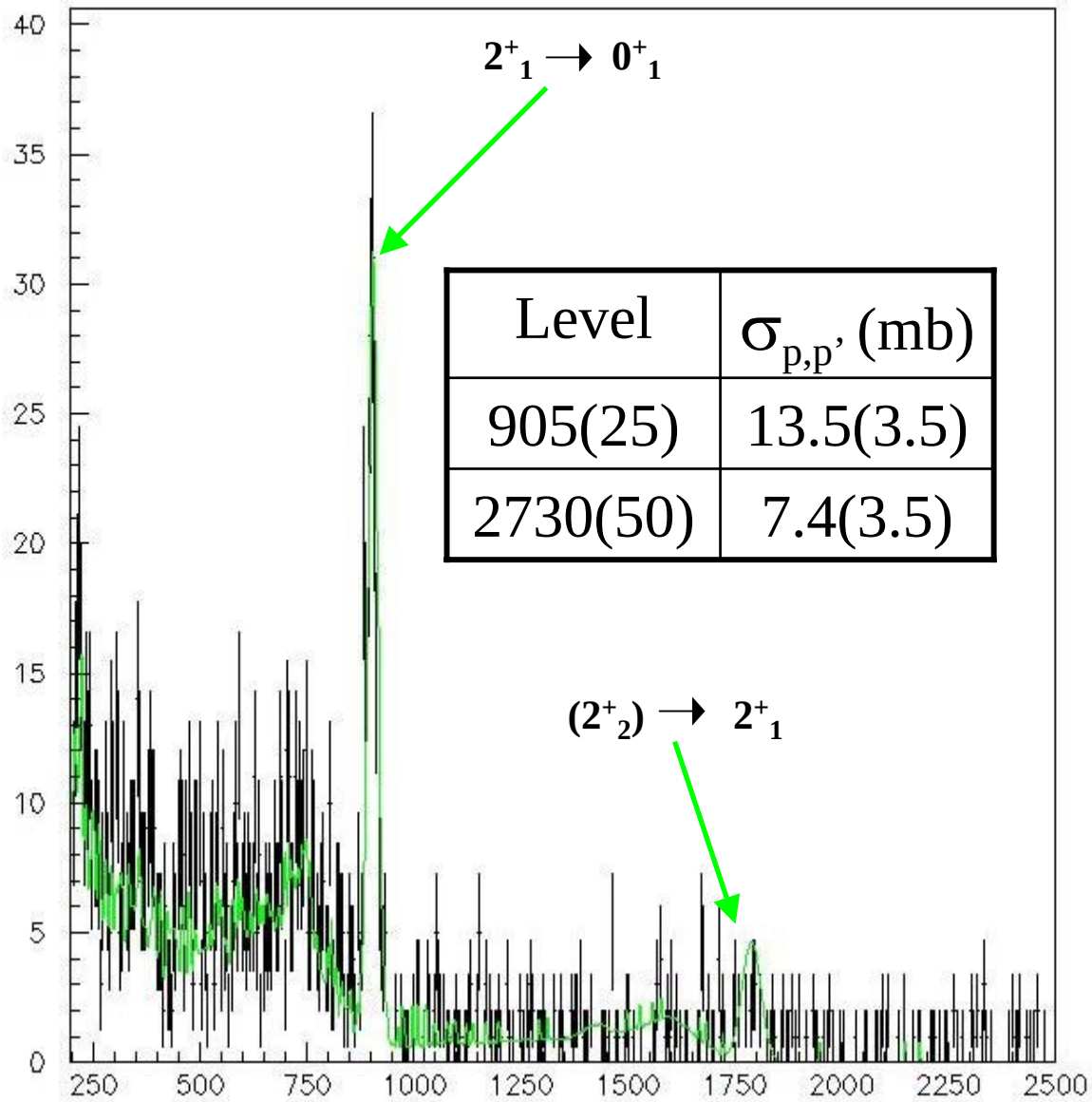
Sample spectrum: ^{42}S



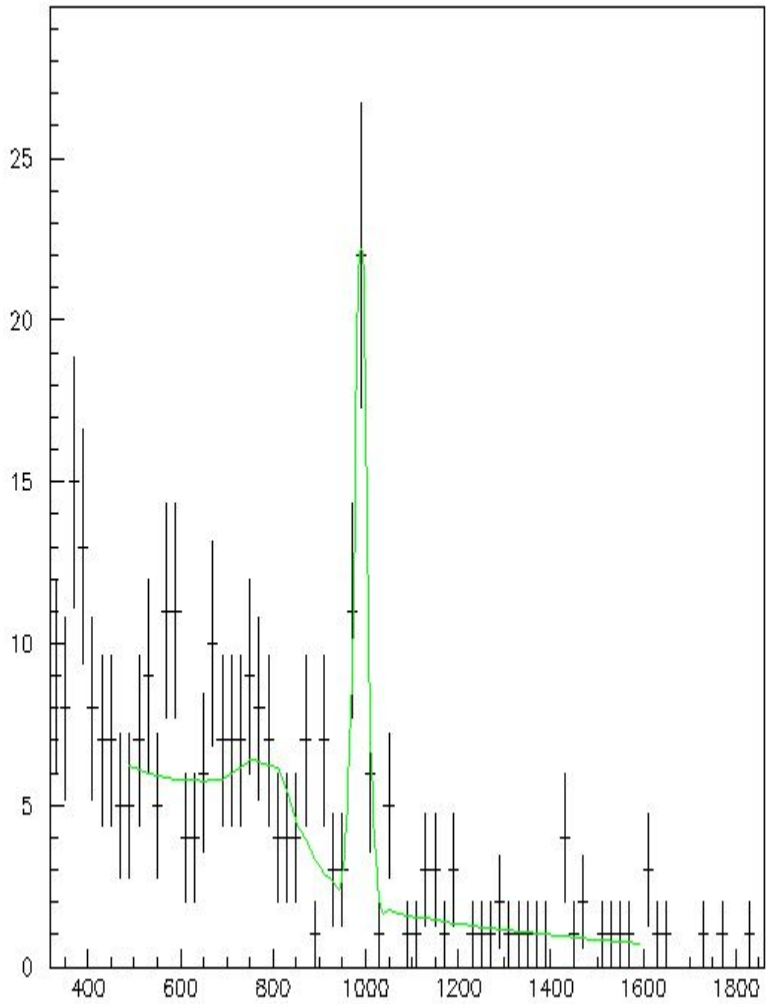


Level	$\sigma_{p,p'}$, (mb)
905(25)	13.5(3.5)
2730(50)	7.4(3.5)

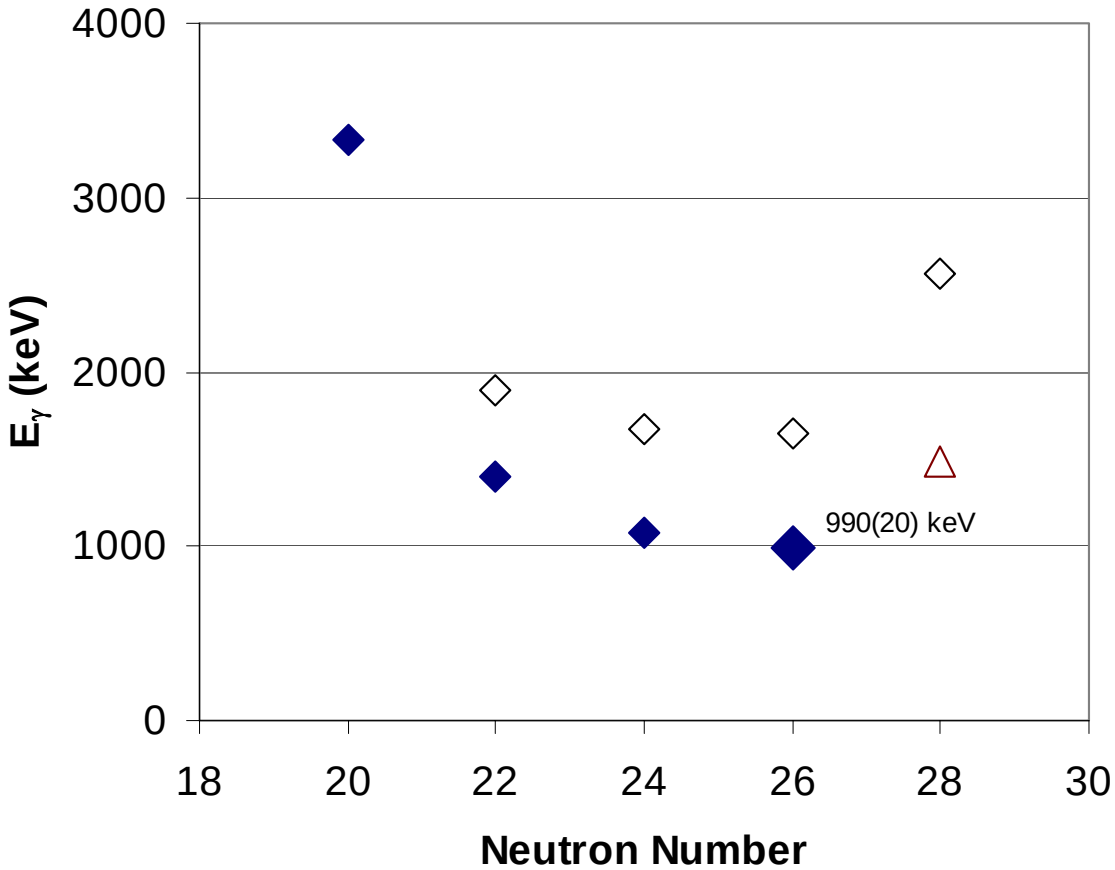
D. Sohler *et al.*, Phys. Rev. C **66**, 054302 (2002).

Observation of the first 2^+ state in ^{40}Si

- 1.5 million ^{40}Si beam particles
- A single gamma-ray was observed at 990(20) keV
- ~30 counts in the photopeak
  - Total array was used in fitting due to limited statistics.
- $\sigma_{p,p'} = 19.5(26)$ mb
- No feeding correction



Evolution of silicon 2^+_1 energies



- Energy of the first 2+ states of ^{34,36,38,40}Si [1].
- Shell model predictions [2].
- Revised shell model prediction for ^{42}Si [3].

[1] R.W. Ibbotson *et al.*, PRL 80,2081 (1998).
[2] J. Retamosa *et al.*, PRC 55,1266 (1997).
[3] S. Nummela *et al.*, PRC 63, 044316 (2001).

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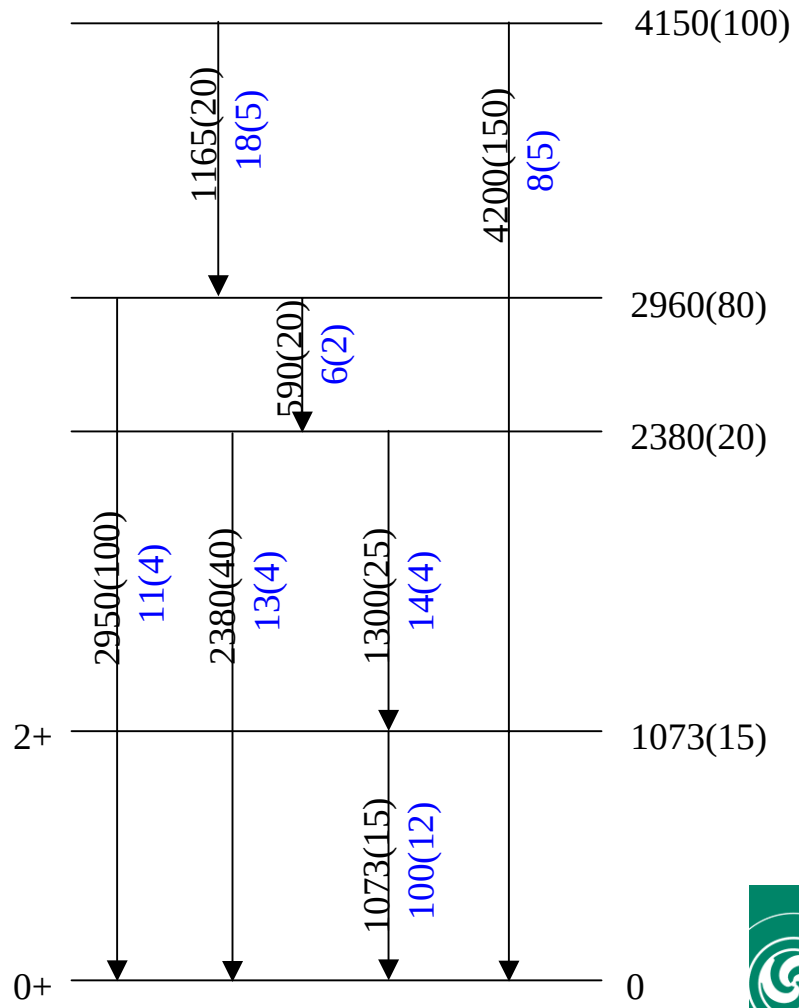
^{38}Si - Preliminary

- 20 million ^{38}Si beam particles

Level	$\sigma_{p,p'}$ (mb)
1073	19(6)
2380	4.9(23)
2960	0(3)
4150	6.0(23)



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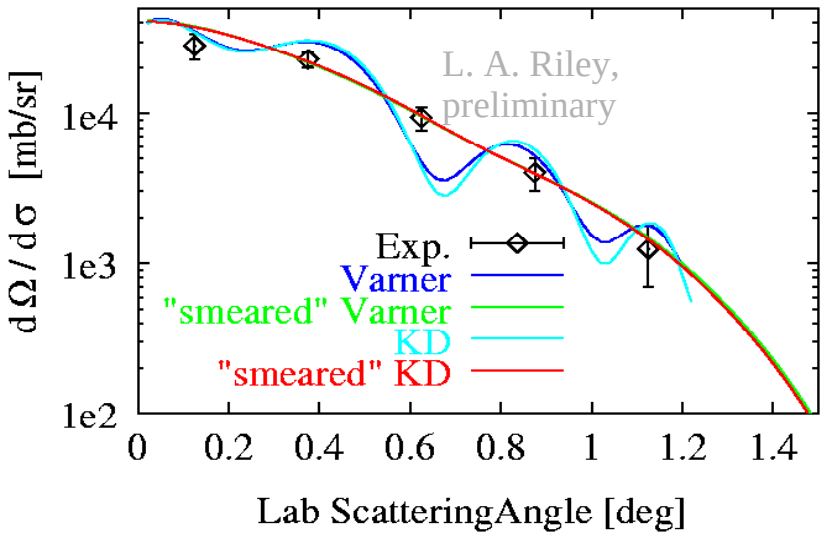
From σ to β_2

- For each nucleus, the total cross section to each excited state was calculated from the gamma ray yield per incoming particle.
- The cross section to the first 2^+ state of each nucleus was corrected for known feeding transitions.
- Feeding from unknown levels was estimated in each case.
- The nuclear deformation (β_{2N}) was deduced from this feeding-corrected cross section for (0^+_1 -> 2^+_1) excitation using ECIS88 and a global nucleon-nucleus potential [1]

- Two global nucleon optical potentials [1,2] checked against data
- Model predictions convolved with detector response
- ^{46}Ar differential inelastic cross-section to the first 2^+ state, measured by a separate experiment, is shown below



[1] A.J. Koning and J.P. Delaroche, Nucl. Phys. **A713**, 231 (2003).
[2] Varner, *et al.*, Phys. Rep. **201**, 57 (1991).

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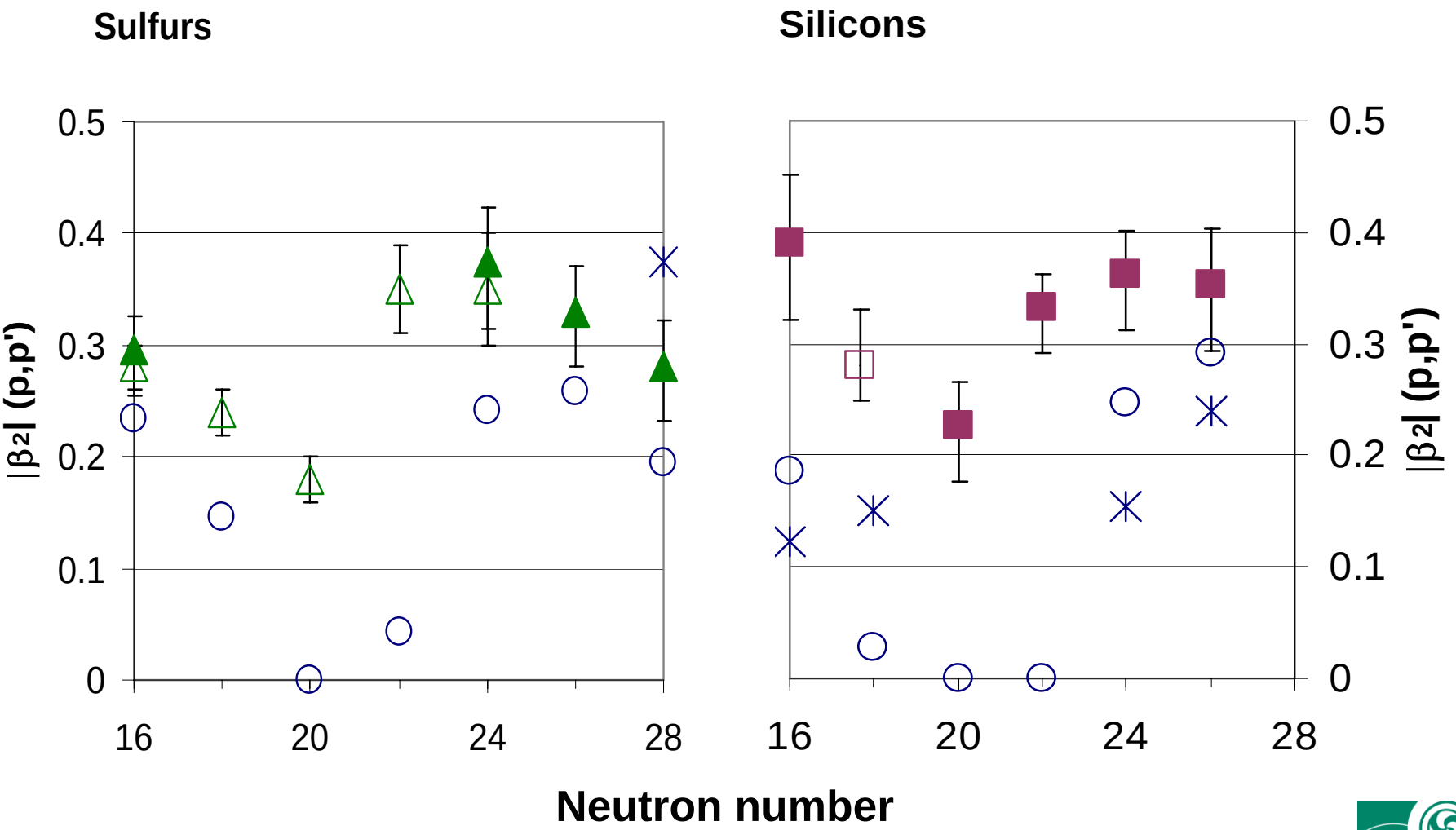
Evolution of β_2



F. Marechal *et al*, PRC **60**, 034615 (1999).
P.D. Cottle *et al*., PRL **88**, 172502 (2002).
G.A. Lalazissis *et al*., NPA **628**, 221 (2002).

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Summary and outlook

- Gamma selected inelastic proton scattering
  - First observation of $E(2^+_1)$ ^{40}Si: 990(20)keV
  - Measured $\beta_{2,(p,p')}$ shows silicon remains deformed at N=26
  - New gamma-rays and a level scheme found
  - ^{36,38,40}Si show similar nuclear deformation to sulfurs
- Future work
  - Continue finding and placing gamma-ray transitions
  - Expand analysis to cover odd nuclei
  - Check (p,p n γ) and other reaction channels
  - Consult shell model predictions to assign J^π values
  - Include higher lying states and couplings in ECIS

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Supported by:

National Science Foundation under Grants No. PHY-00110253,
PHY-9875122, PHY-0244453, INT-0089581
and by the Japan Society for the Promotion of Science.

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