The lowest 4^+ state in ^{44}S: a shape- / structure- / K-isomer

Or: One exotic nuclear structure in an exotic nucleus

J.J. Parker IV, I.W., L.T. Baby, J. Baker, P. Cottle, M.A. Riley
Florida State University

A. Gade, D. Weisshaar, H. Iwasaki, D. Bazin, B.A. Brown, N.N.
NSCL, Michigan State University

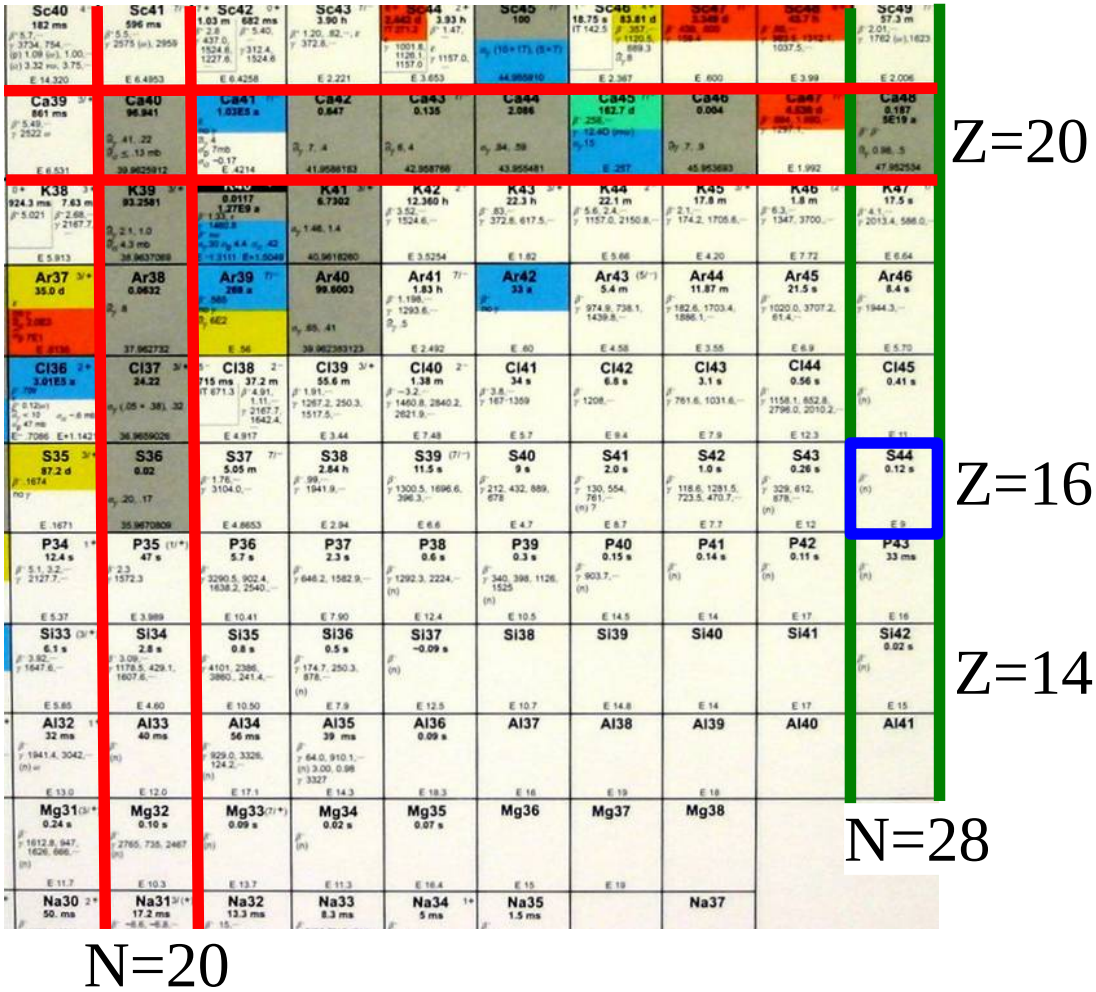
K. Wimmer, Central Michigan University

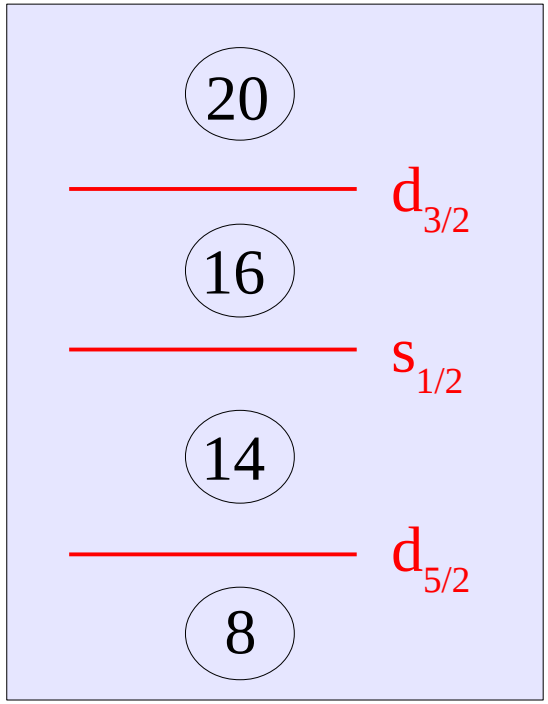
D. Santiago-Gonzalez, Louisiana State University

H. Crawford, A.O. Macchiavelli, P. Fallon, N.N.
Lawrence Berkeley National Laboratory

J. Tostevin, University of Surrey

Shell Structure around N=28 Z=16



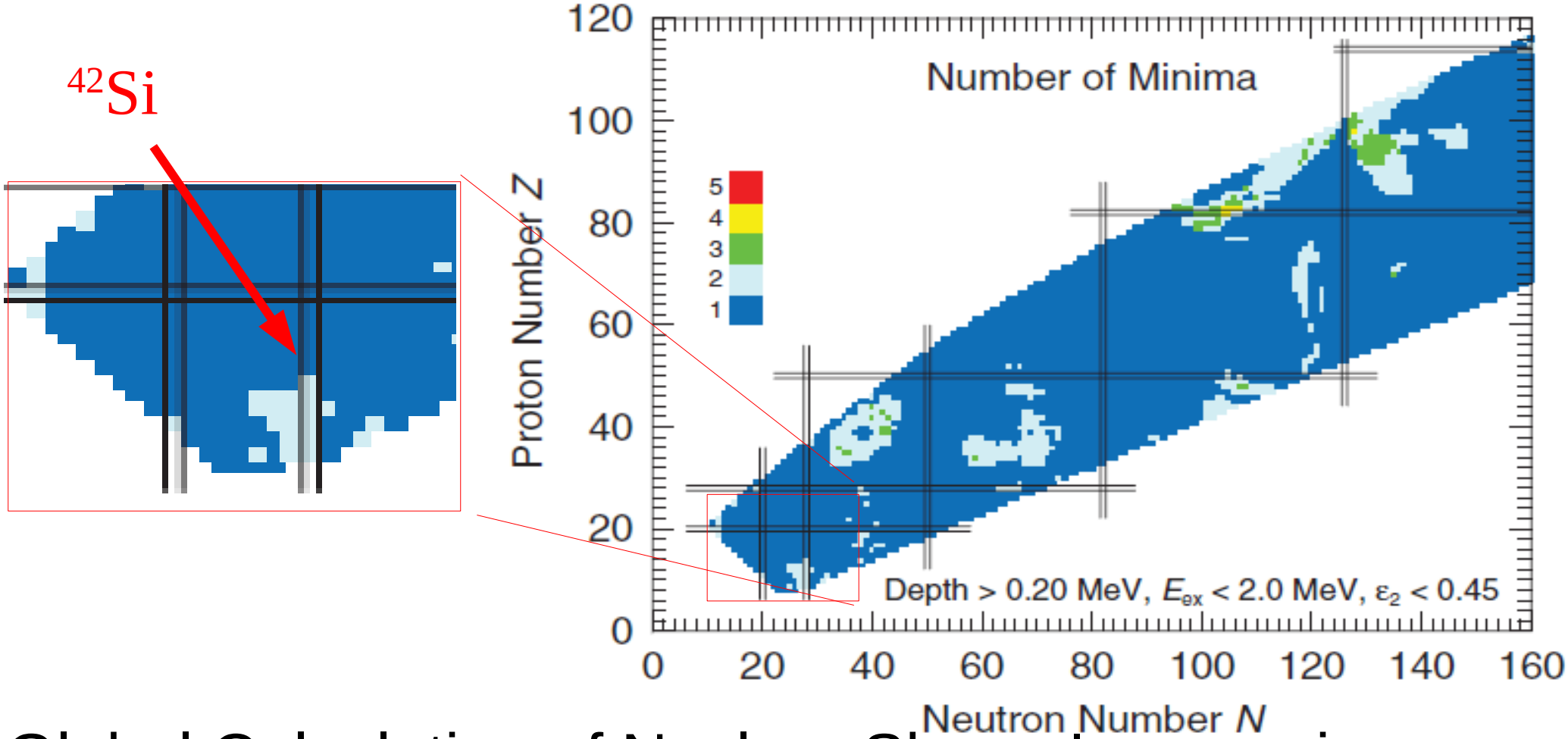


- Investigate N=28 magic number

Investigate Proton-shell structure

Global Calculation of Shape coexistence

P.Möller,A.J. Sierk, R.Bengtsson, H. Sagawa, T. Ichikawa: PRL 103, 212501 (2009)



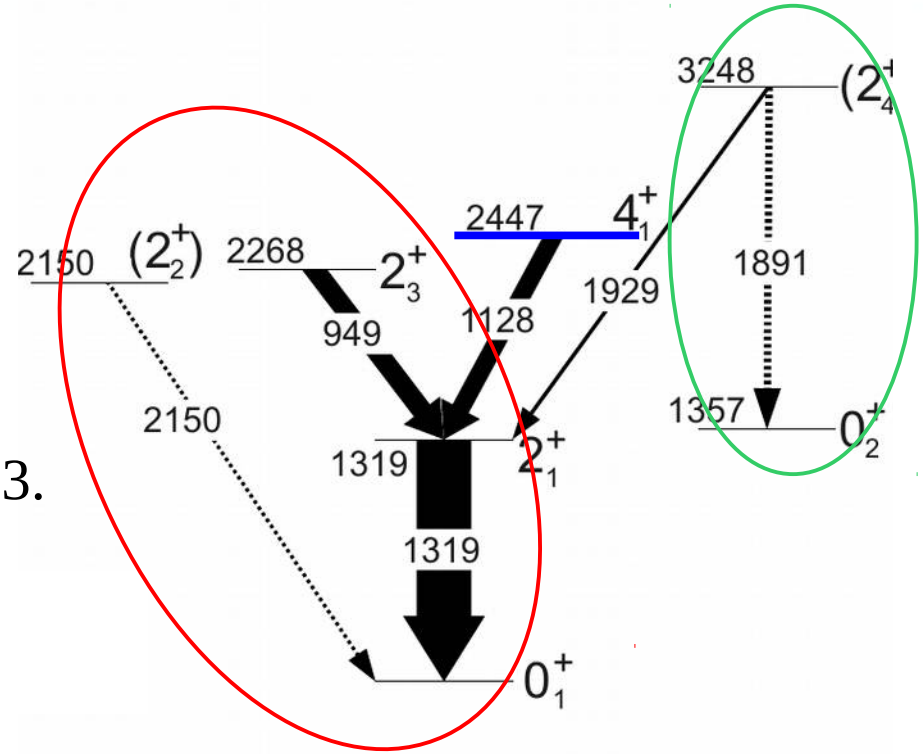
Global Calculation of Nuclear Shape Isomers in macroscopic-microscopic model predicts shape coexistence for ^{42}Si.

Triple Configuration -Coexistence in N=28 ^{44}S

D. Santiago-Gonzalez *et al.* PRC 83, 061305 R (2012)

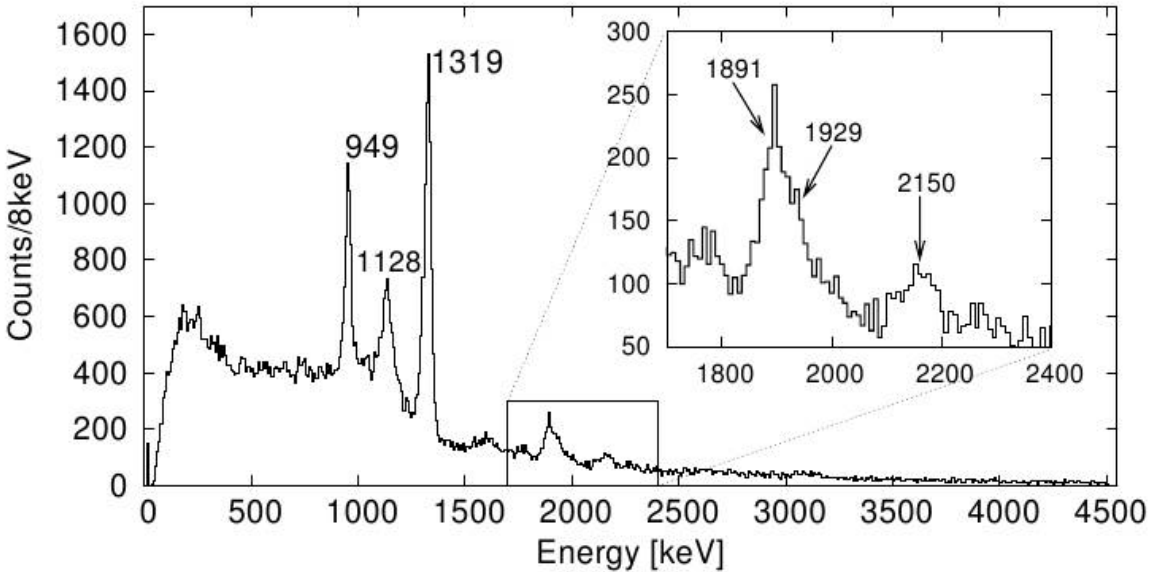
- In ^{44}S, the N=28 shell is broken through Neutron (2p-2h), coexisting with magic (0p-0h) config.

  T. Glasmacher *et al.*, PLB 395 (1997), 163.
  C. Force et al, PRL 105, 102501 (2010)

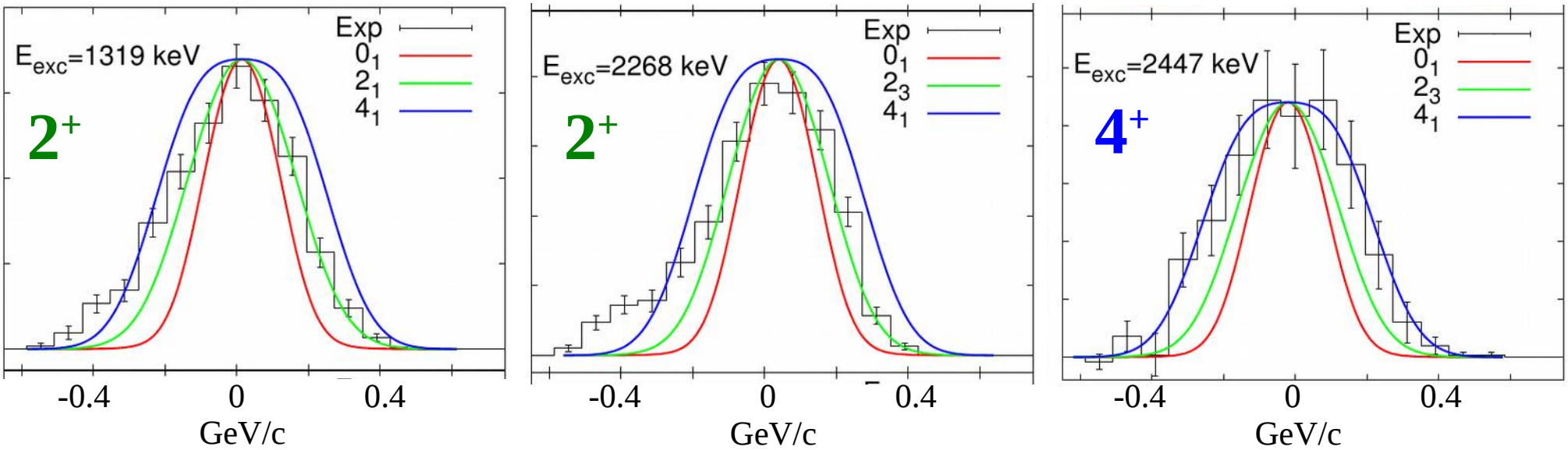


- SeGA-experiment and Shell model suggests third configuration: (1p,1h), characterized by isomeric K=4 band-head

- 2447 keV state life-time is the "fingerprint"



Longitudinal Momentum Distributions

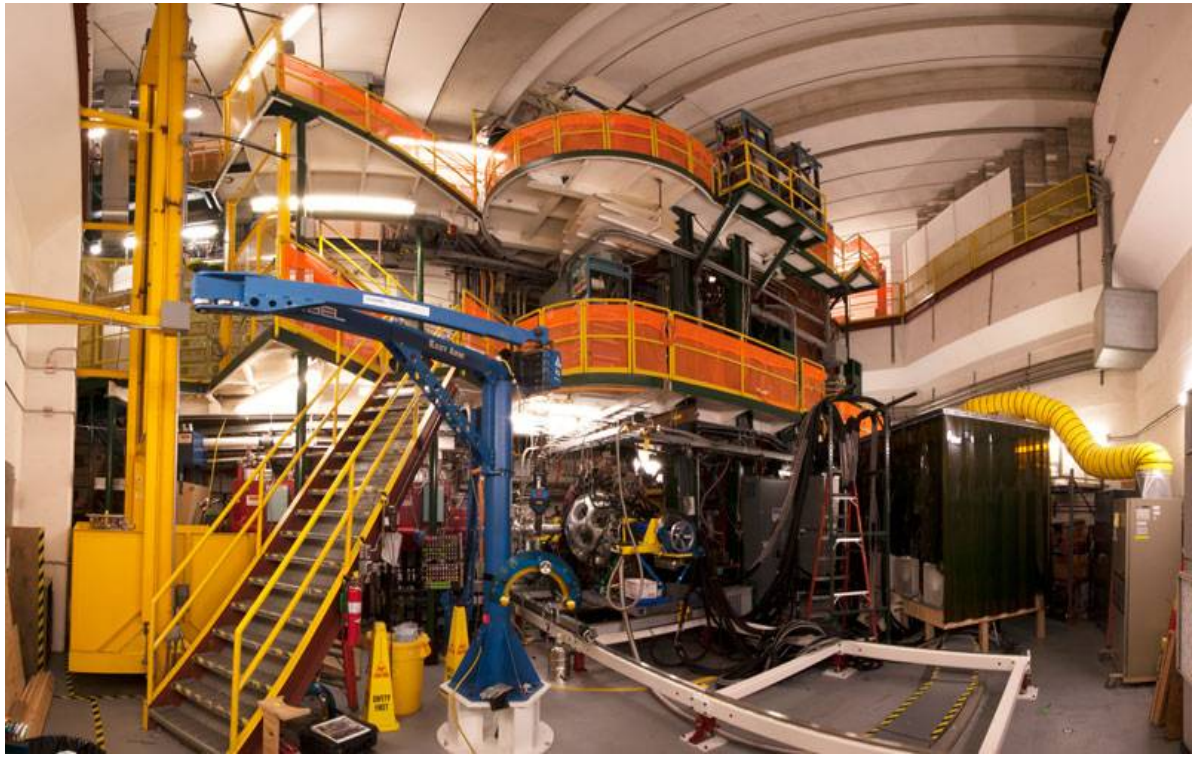


- Residue momentum measured in S800 spectrograph, gated on excited levels
- Compare experiment to calculated distribution from Eikonal theory + SM wave functions
- Generally: Higher angular momentum => wider distribution

Our RDM Experiment

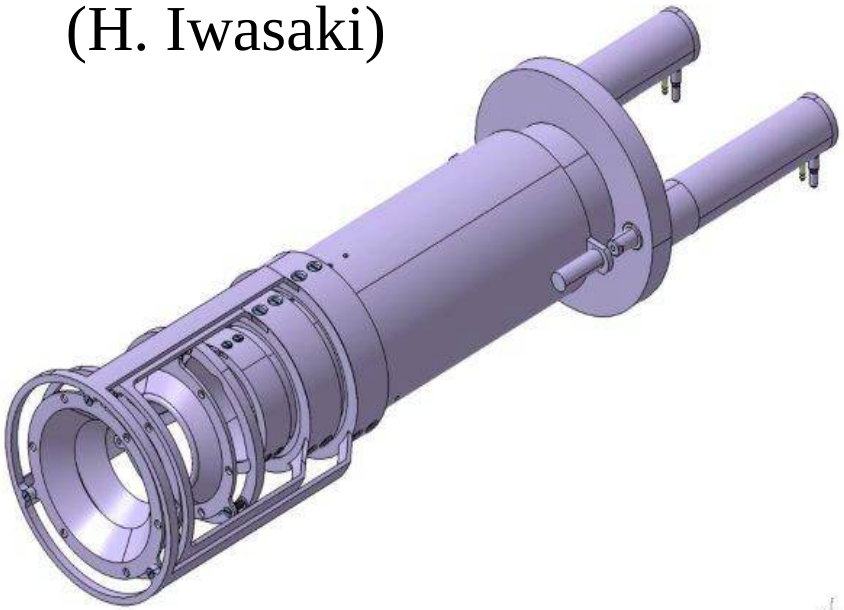
- Two proton-knockout on ^{46}Ar
- Identify secondary reaction products in S800
- Measure Plunger – RDM γ-rays in Gretina

$$^{46}\mathrm{Ar} \rightarrow {}^{44}\mathrm{S}$$



Picture Credit: S. Noji

NSCL triplex plunger
(H. Iwasaki)



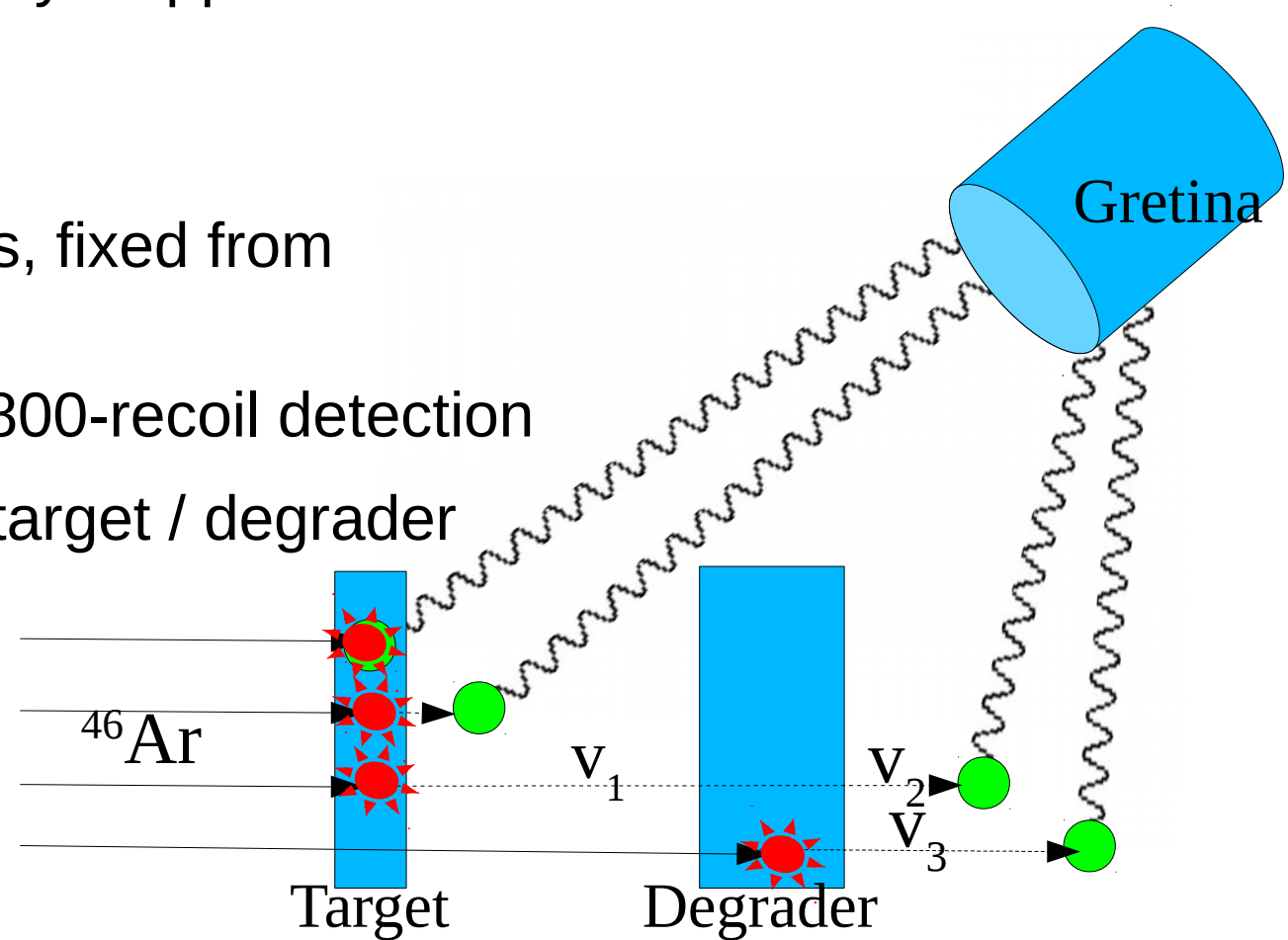
RDM-method at the NSCL

Analysis through "Few Parameter" Monte-Carlo simulation of spectra

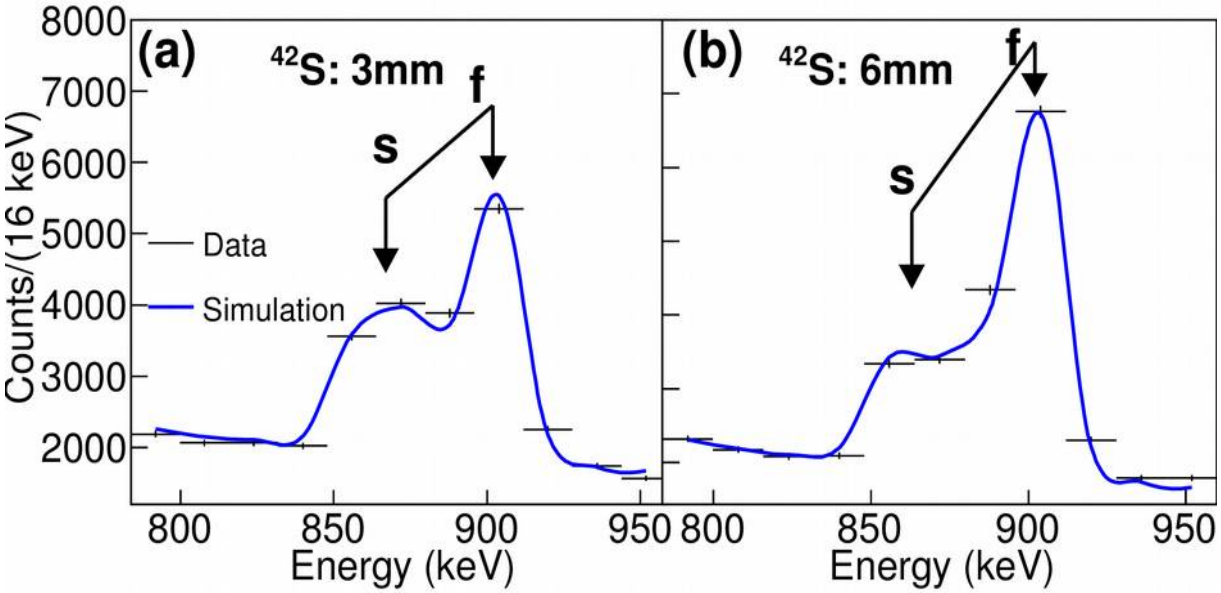
- Compare to all data from Target only, 3 mm, 6 mm, 25 mm dist.
- Simulate Energy losses in target / degrader
- Simulate Geometry, γ-ray Doppler-shifts & Detector interactions

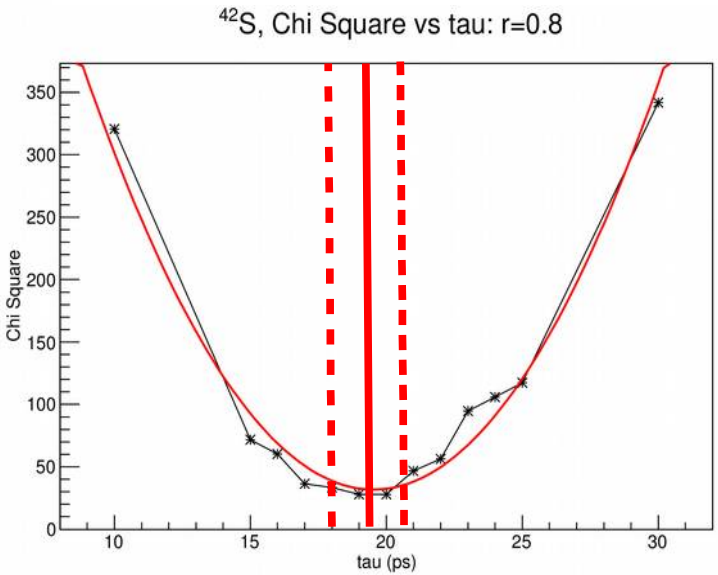
"Global" parameters:

1) State populations yields, fixed from "target only" spectrum
2) Normalize runs from S800-recoil detection
3) Relative reaction yield target / degrader fixed from 25mm- data
4) addtl. spectra Background: exponential, but consistent b/w runs



Test case: ^{42}S





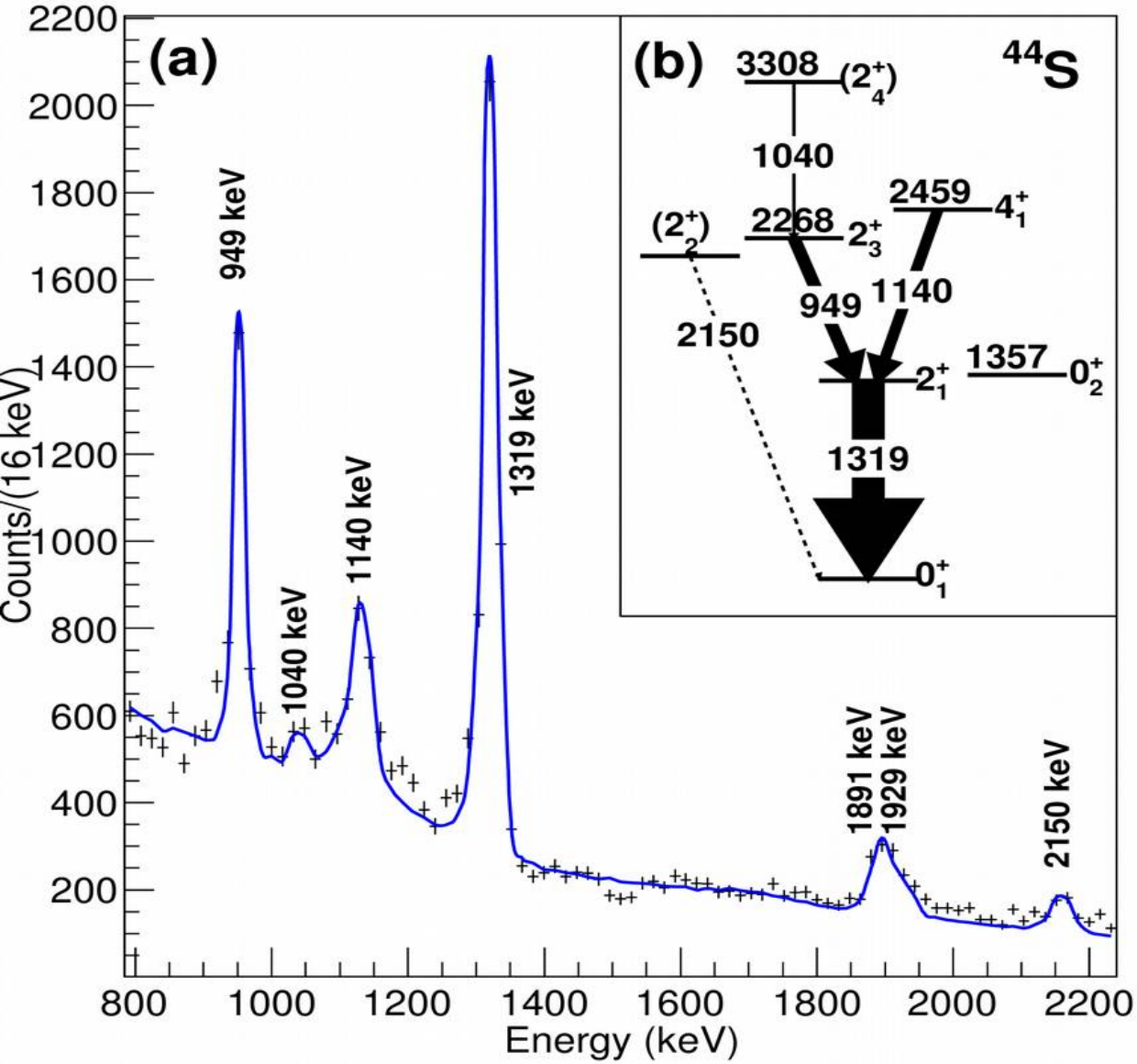
Known Lifetime: 18.5(33) ps from Coulex

H. Scheit et al. Phys.Rev.Lett. 77, 3967 (1996)

our result: τ=19.5(15) ps

Analysis seems to be under control.

The Spectrum "Gretina"

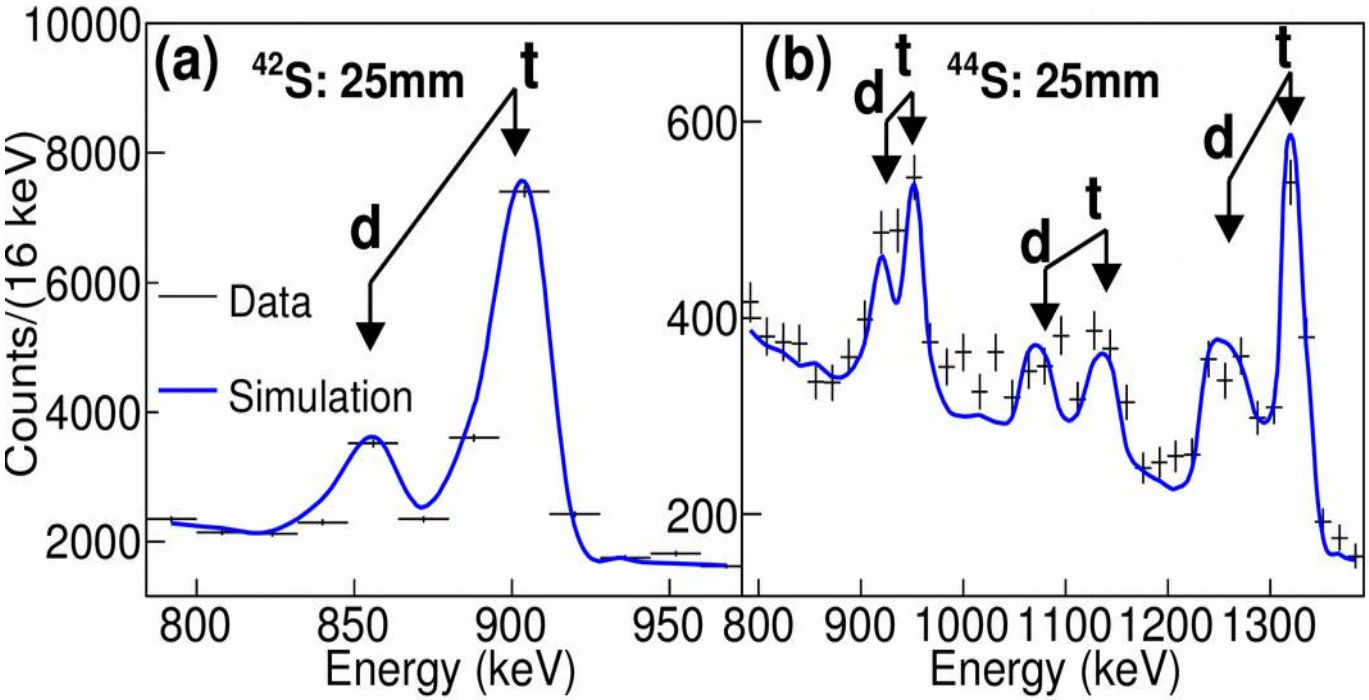


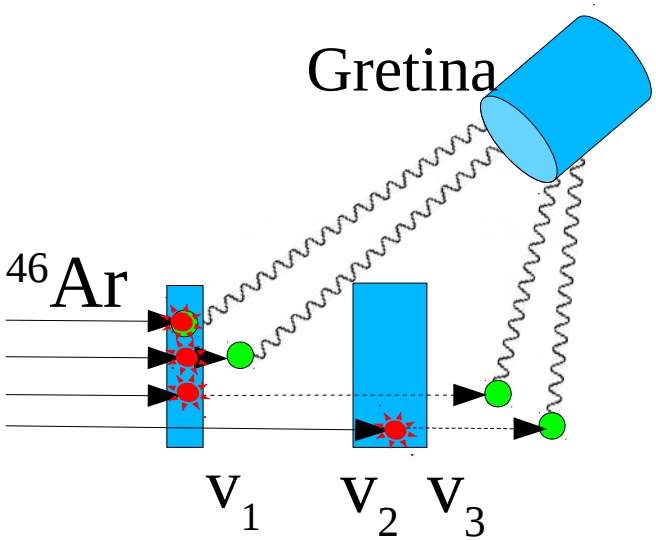
Spectrum and coincidence analysis

Results consistent with Santiago-Gonzalez and L.A.Riley (SeGA)

Investigate life time of lowest 4+ state

Long Distance: Determine Degrader-Reactions

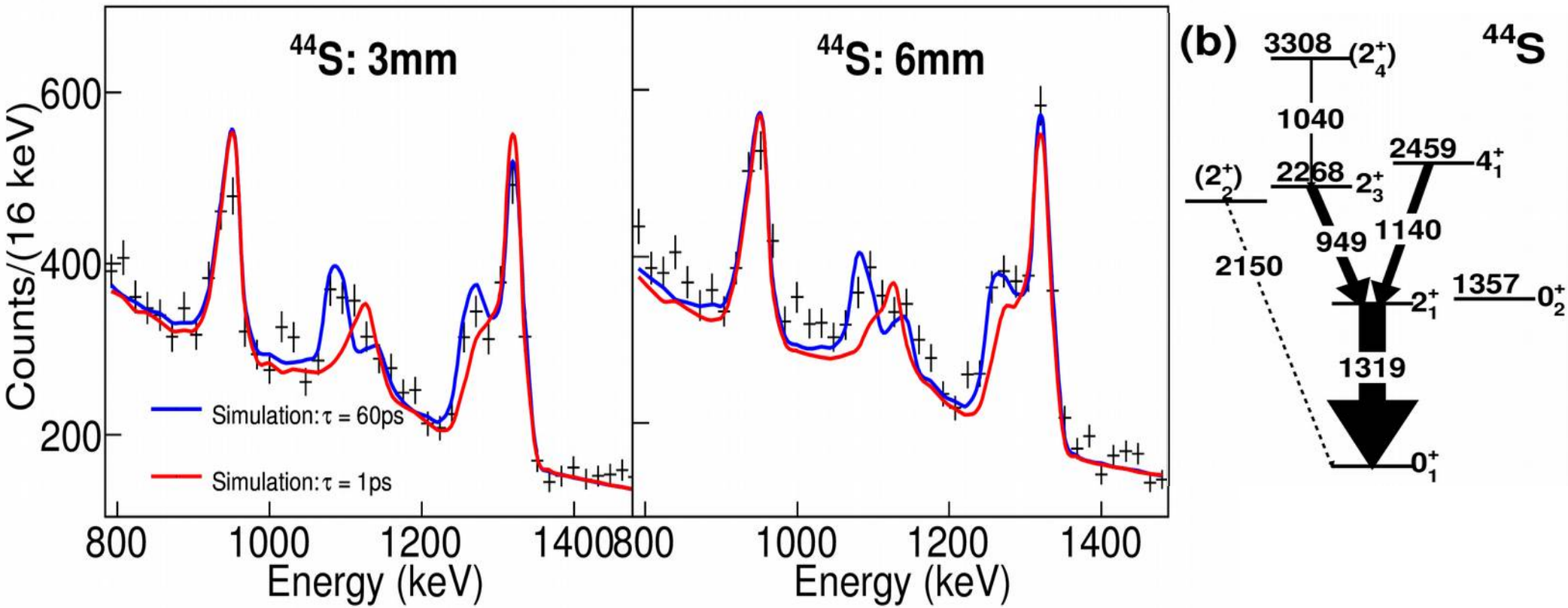




Separate Reactions from degrader “d” and target “t”

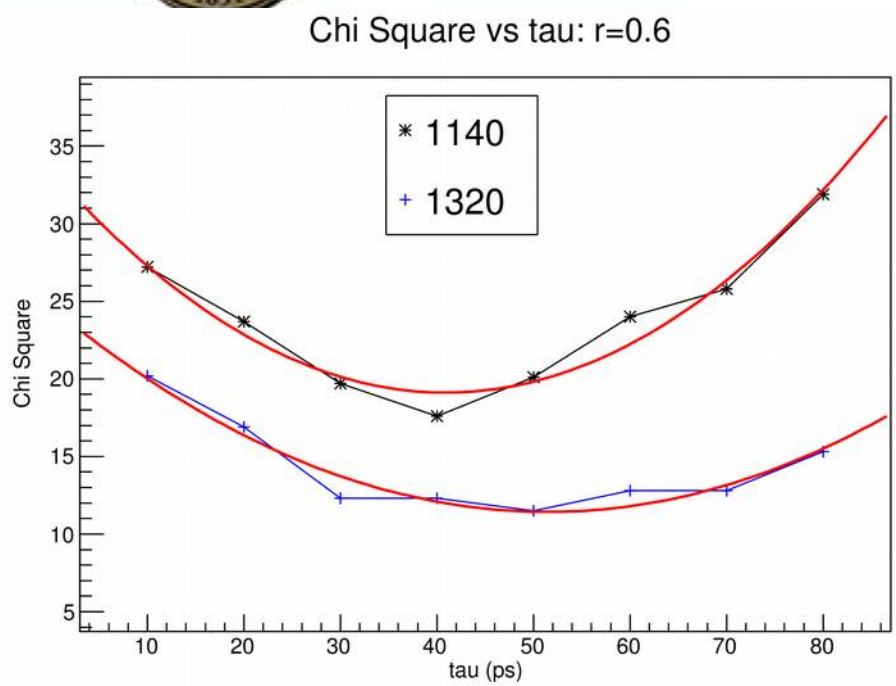
- Ratio for ^{42}S (left) r = N(T)/N(D) = 0.8
- Ratio for ^{44}S (right) r = 0.6 (0.1)
- Effect of S800 focal plane acceptance
- target and degrader reactions - the same spectrum ?

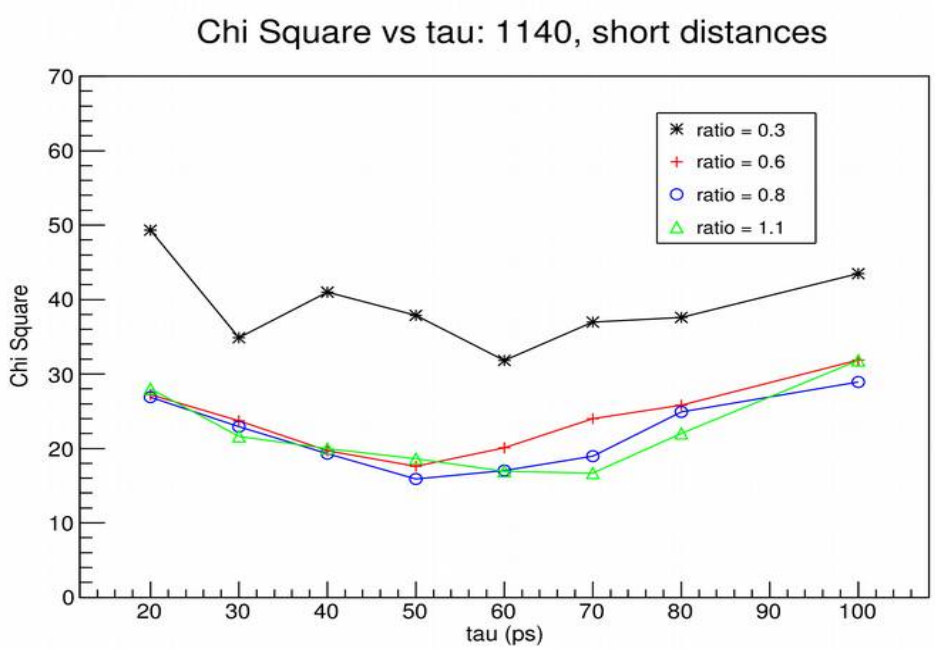
Results: 3mm and 6 mm distance



- Here: comparison of "short" lifetime and 60 ps
- life-time effect visible in 1140 keV and 1320 keV transitions, expected from cascade-emission

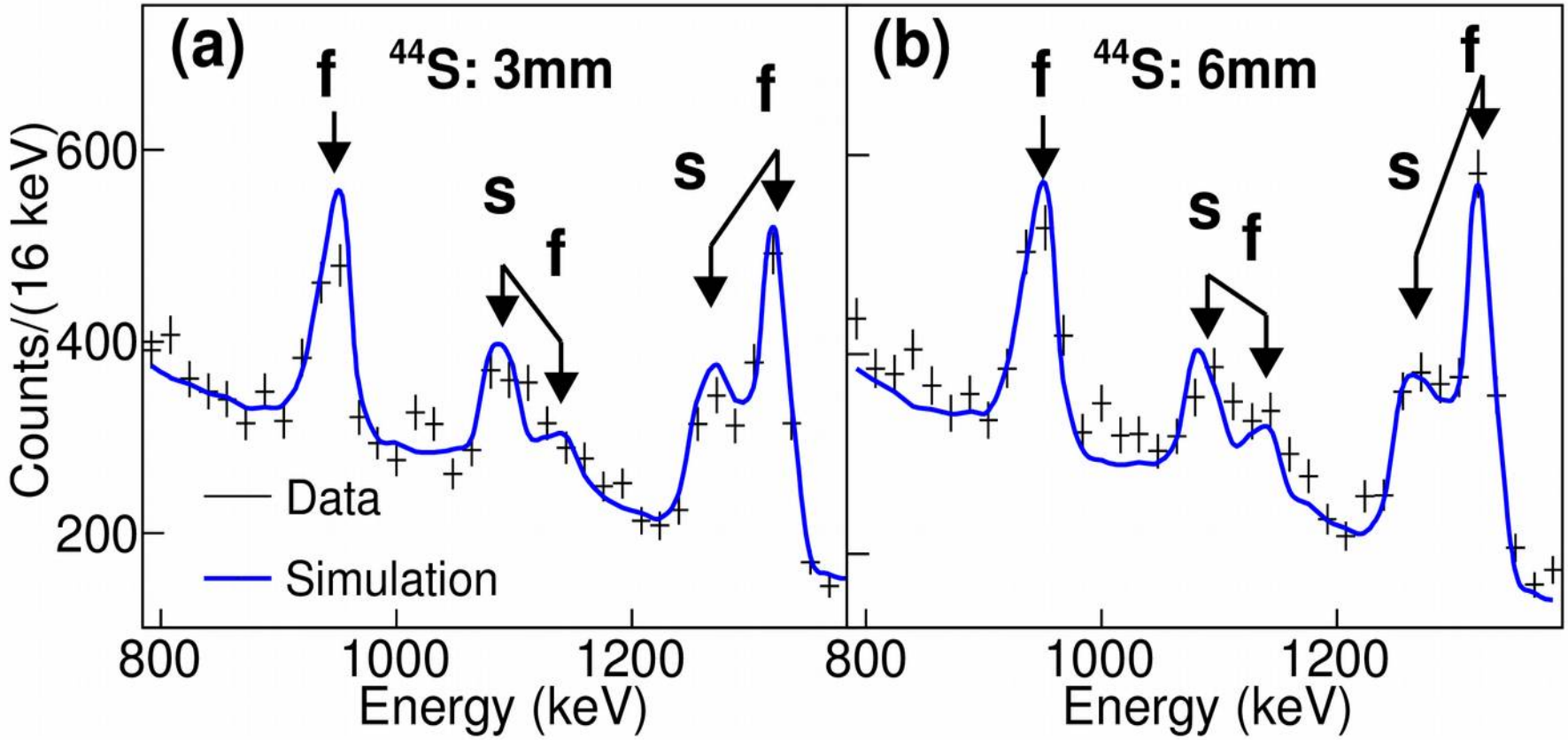
Uncertainties





- Statistical uncertainty: x^2-analysis of 1140 keV,1320 keV, consistent minima,
- combined minimum τ=60(15) ps
- Systematic uncertainty: "Degrader-ratio" between 0.3 and 1.1
- Result between τ=50 ps and τ=70 ps
- Systematic uncertainty +/- 15 ps

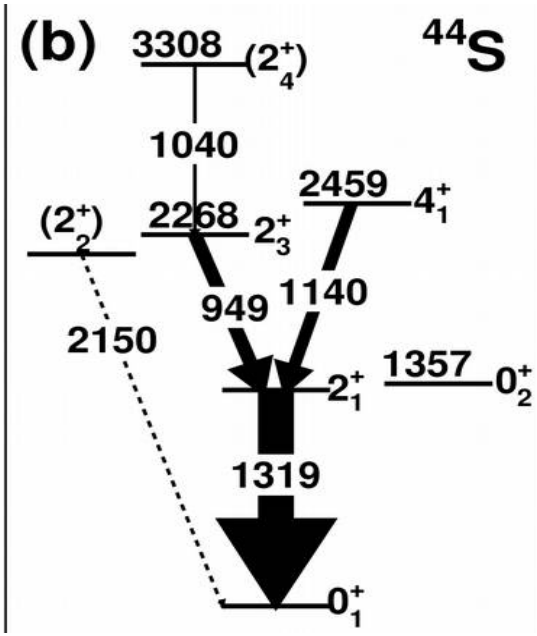
Results: 3mm and 6 mm distance



- 950 keV transition is fast (DSAM-shape)
- 1140 and 1320 have lineshape consistent with 4^+ lifetime of 60(15) ps.

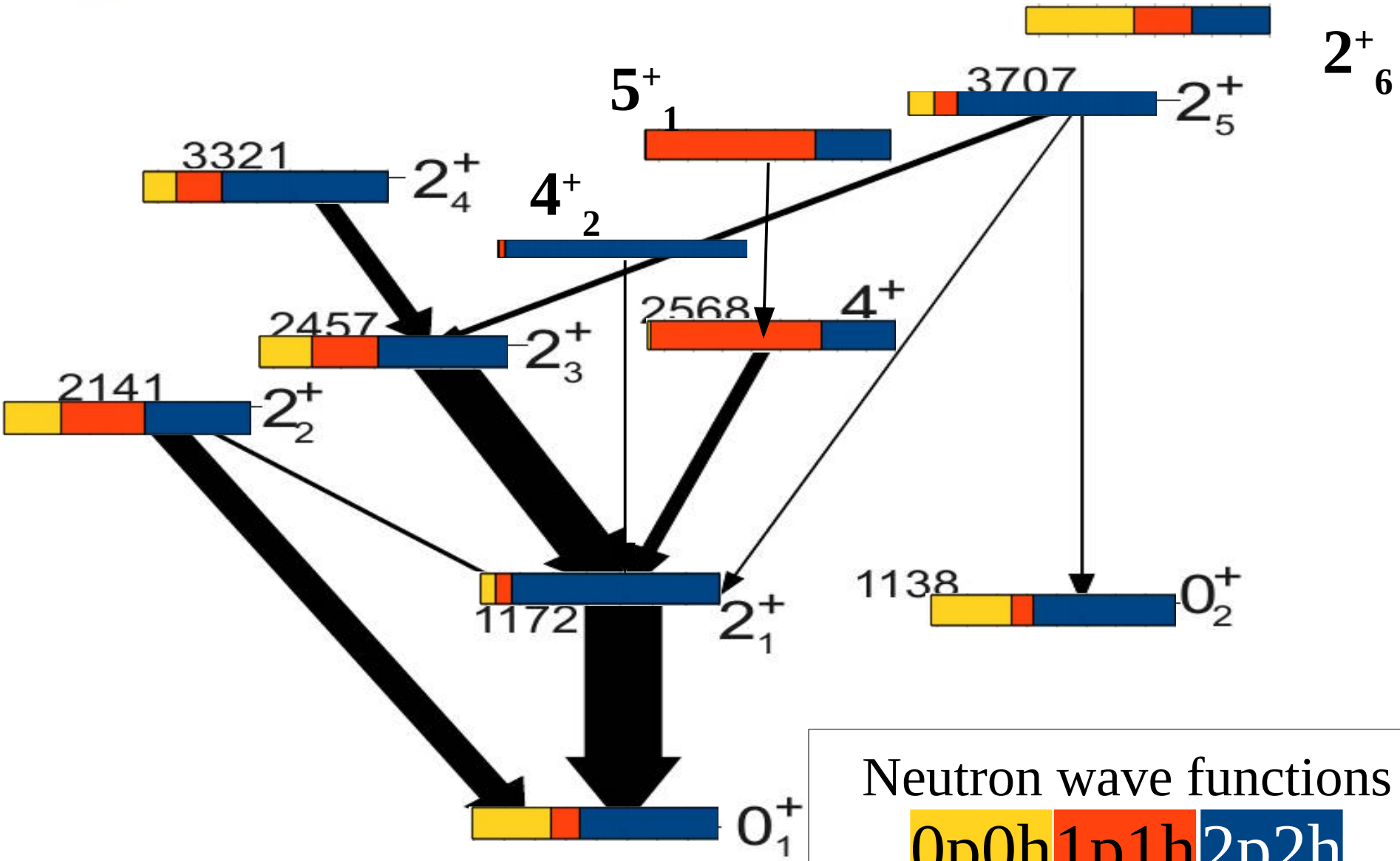
Collectivity – Matrix elements

- Complete set of “distances”: target-only, 3mm, 6mm, 25mm fit with <u>one hypothesis</u>
- Dominant life-time effect: cascade of 1140-1330 keV $4^+ \rightarrow 2^+ \rightarrow 0^+$ delayed



- Lifetime of 4^+ state: τ=60 $(15)_{stat}(15)_{sys}$ ps
- $B(E2,4^+ \rightarrow 2^+) = 7.1(21)\ e^2fm^4 = 0.76(23)$ W.u.
- $B(E2,2^+ \rightarrow 0^+) = 63(18)\ e^2fm^4 = 7(2)$ W.u.
- The 4^+ is not a rotational excitation of the 2^+ !
- Expected rotational $B(E2,4^+ \rightarrow 2^+) = 9 .. 14$ W.u.

Interpretation of ^{44}S spectrum SDPF-U Shell-model Configurations



Neutron wave functions

0p0h 1p1h 2p2h

See also:

R. Chevrier and L. Gaudefroy, Phys.Rev. C 89, 051301 (2014).

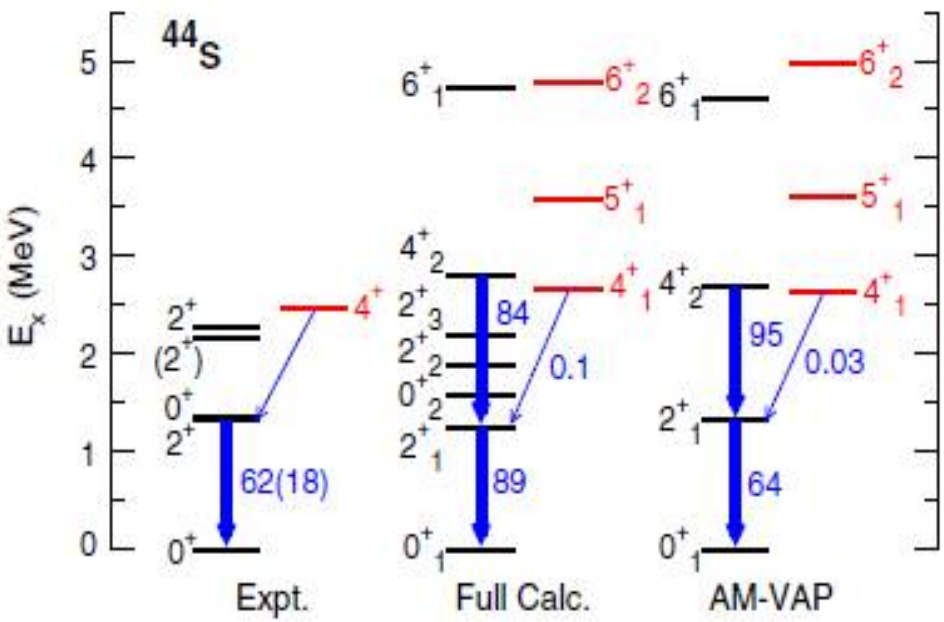
SM-Properties of the 4^+_1 structure

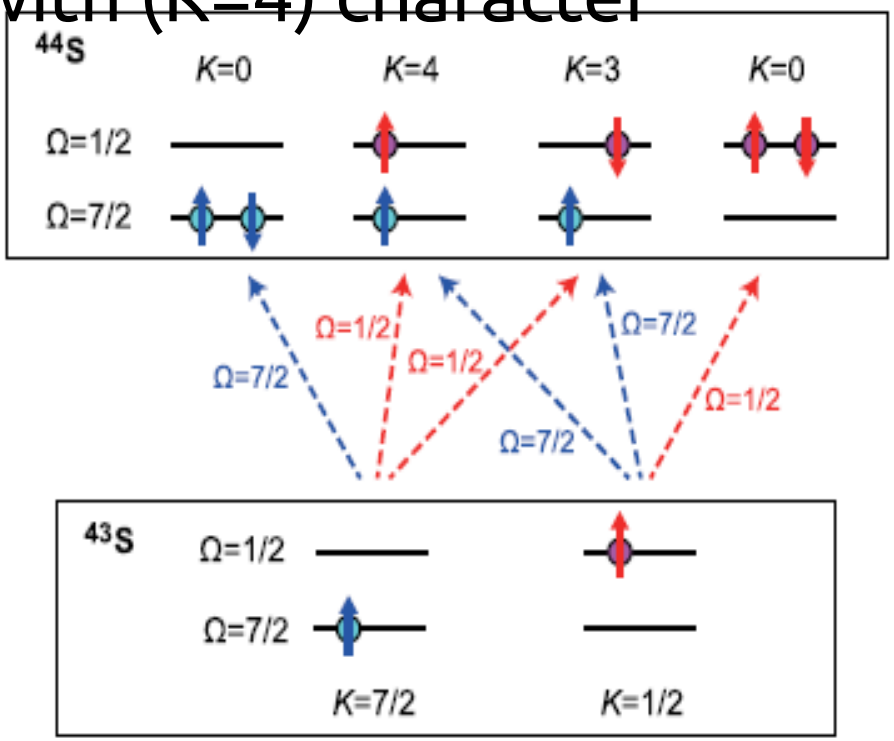
- The 4^+_1 state (and the 5^+_1 above it) show a clearly distinct (and very little mixed) configuration;

  neutron 1 hole 1 neutron-particle across N=28 $(f_{7/2})^{-1}\ p_{3/2}$ dominant
- The 2^+_1 and 4^+_2 have neutron 2 hole-2 particle character
- Both 4^+ states are very little mixed, only 164 keV apart
- The 4^+_1 is calculated to have a large quadrupole moment, but a long life-time, 42 ps consistent with the experimental 60(15) ps

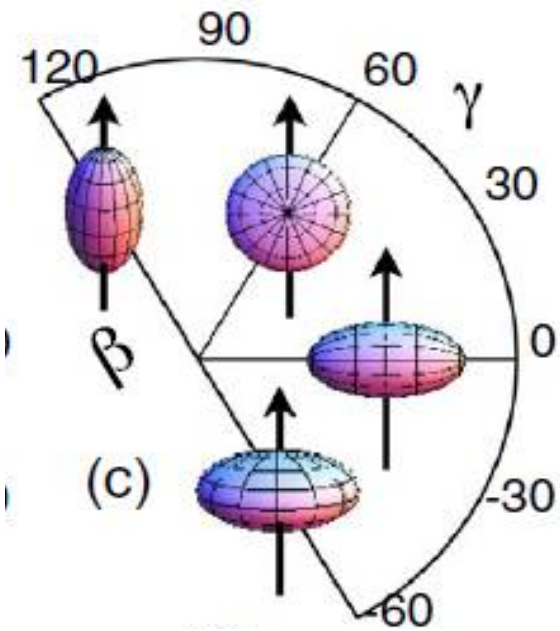
Utsuno et al. PRL 114, 032501 (2015)

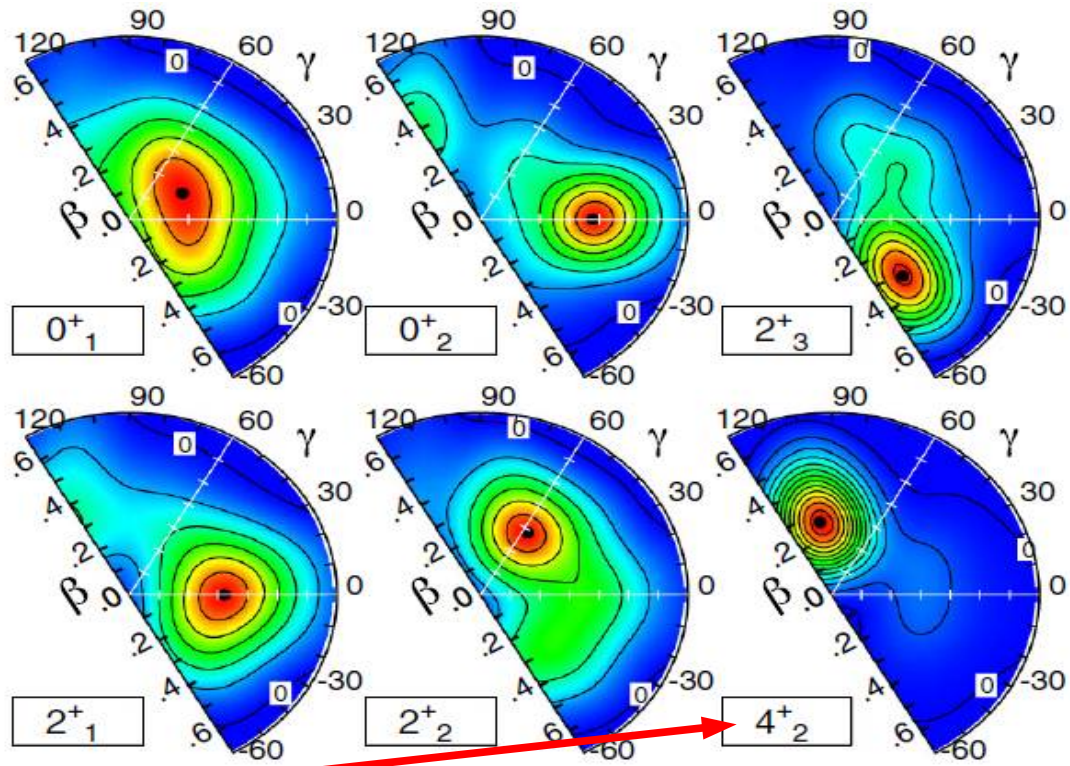
- Interpretation of SDPF-MU shell-model
- performed AM-VAP analysis of wave functions
- 4^+: extracted $\beta = 0.23$ $\gamma = 28°$, 93% (K=4), 7% (K=3)
- $B(E2, 4^+ \rightarrow 2^+) = 0.1\ e^2fm^4$ (<< exp. $7.1(21)\ e^2fm^4$)
- 4^+_1 is almost maximally triaxial, but has good ! angular momentum projection with (K=4) character
- A "new type of K-isomerism" !





- Novel density-functional method





- Here, the 4^+_2 is isomeric, triaxial with "K_X=4"
  β_2= 0:28 – 0:36, B(E2, $4^+ \rightarrow 2^+$) = 1.4 e^2fm^4
- 0^+_1spherical, 0^+_2 2^+_1 4^+_1 prolate, 2^+_2 oblate, 4^+_2 triaxial

Summary

- Observed a complex level structure in the exotic N=28 nucleus ^{44}S
- Measured the life-time of the 4^+_1 state using a RDM experiment with Gretina
- The hindered E2-decay is a fingerprint of an extremely low-lying "K=4" band head, which suggested to be based on a neutron 1 particle 1 hole structure, a third, coexisting configuration
- Calculations indicate near-maximum triaxiality and a "quasi-K" = 4 configuration
- A new type of K-isomerism
- Next step: find the rotational 4^+ !

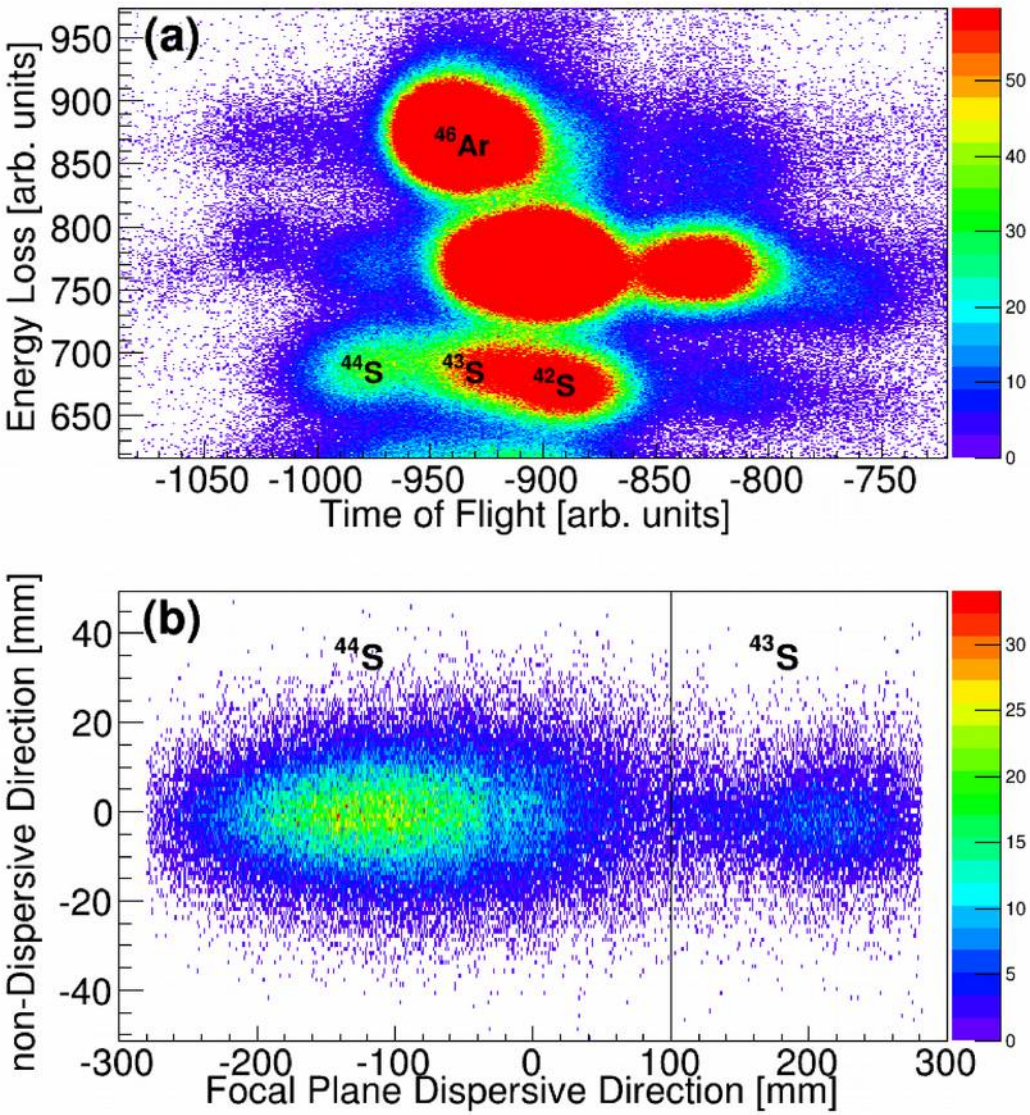
Extra Slides

S-800 reaction-residue detection

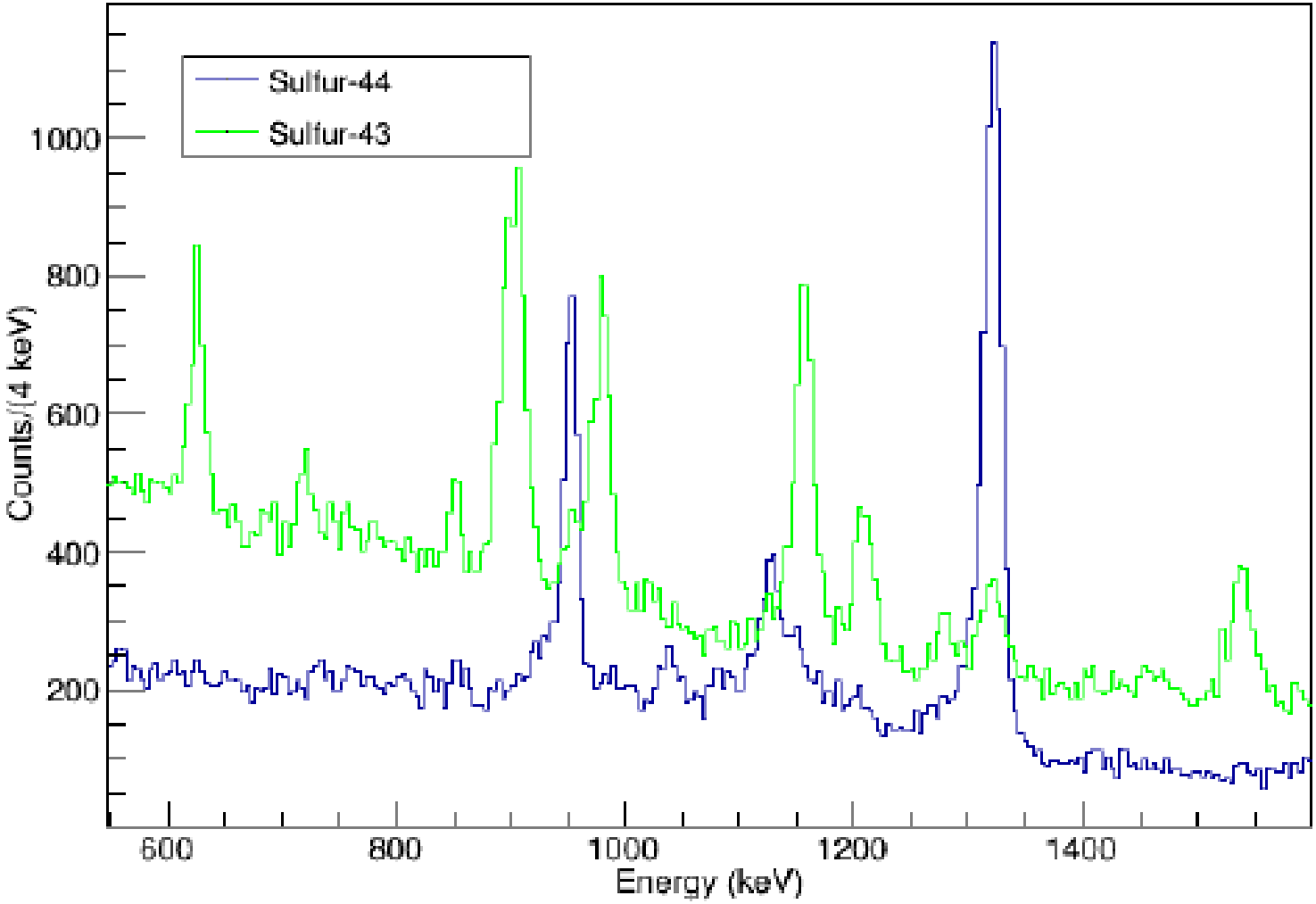
Selection of reaction residues through energy-loss,

Time-of flight

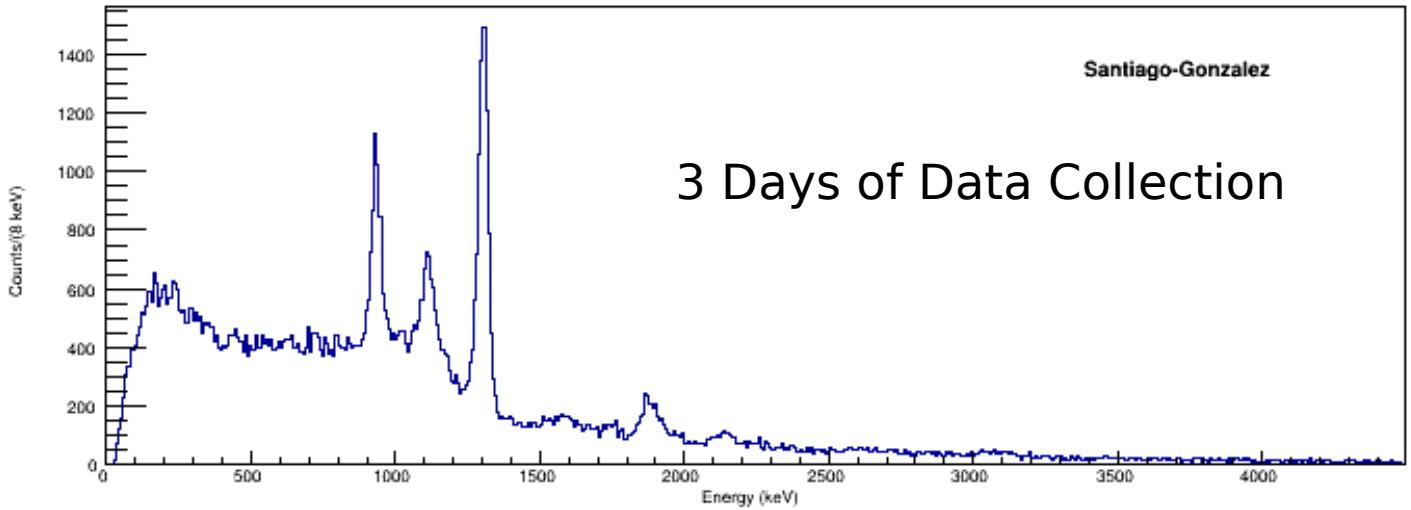
Focal-Plane position



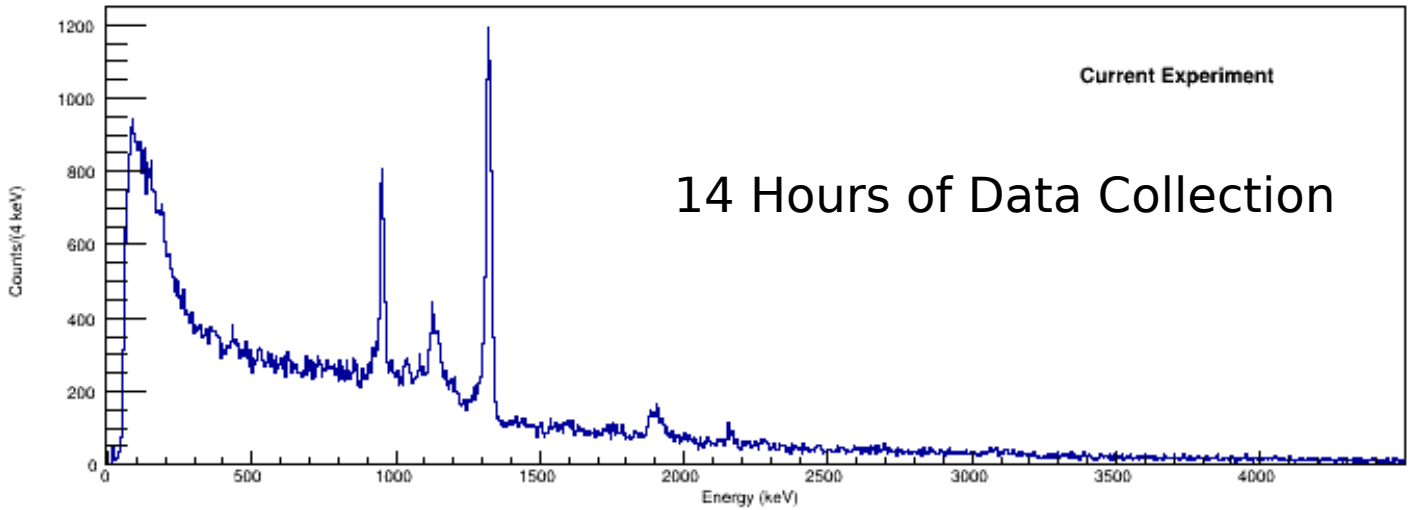
How Clean is the PID?



GRETINA vs SeGA



375 mg/cm^2 target

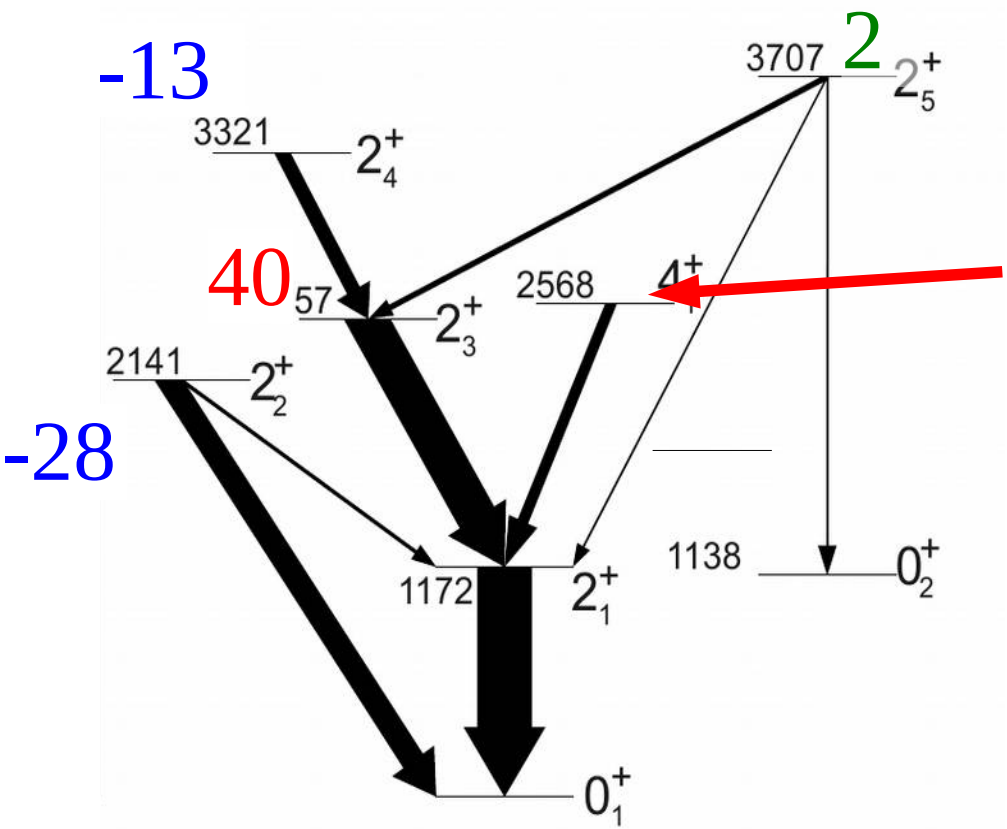


92 mg/cm^2 target

What shape is a shell?

- Extract intrinsic Quadrupole moments for axial symmetry from sm wave-functions

Use K=0 hypothesis for 2^+_1 4^+_2 Q_{intr} = 69, 72 efm^2
Use K=4 hypothesis for 4^+_1 5^+_1 Q_{intr} =51, 58 efm^2

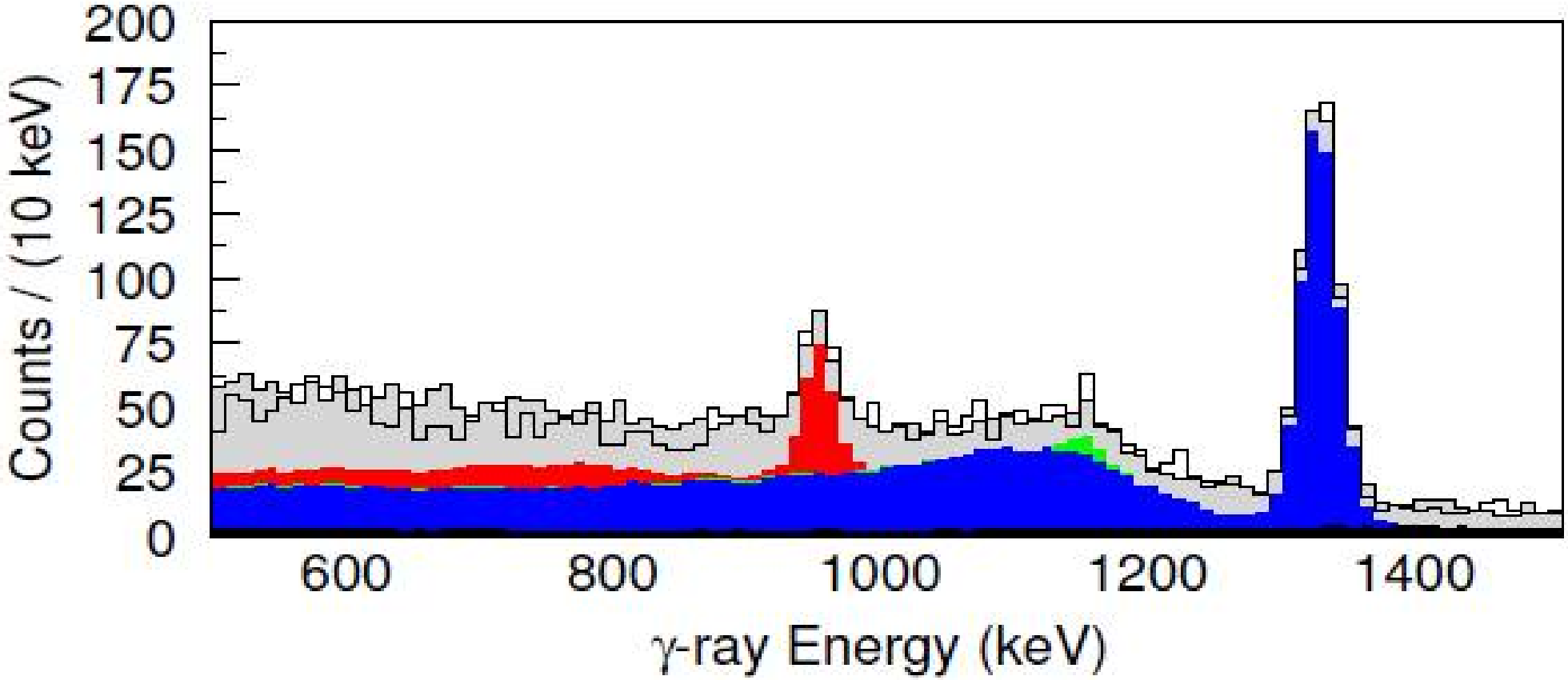


$Q_{intr=}$+51 efm^2 if K=4
Q_{intr}=-72 efm^2 if K=0

$$Q_{\text{intr}} = Q_{\text{lab}} \frac{K^2 - (I(I+1))}{(I+1)(2I+3)}$$

Q_0 in $e\,fm^2$

Inelastic Proton-Scattering C.Campbell (Ph.D. Thesis MSU 2007)



- Inelastic proton scattering observes 1319, 949 keV gamma-rays.
- Very little of the 1124 keV transition