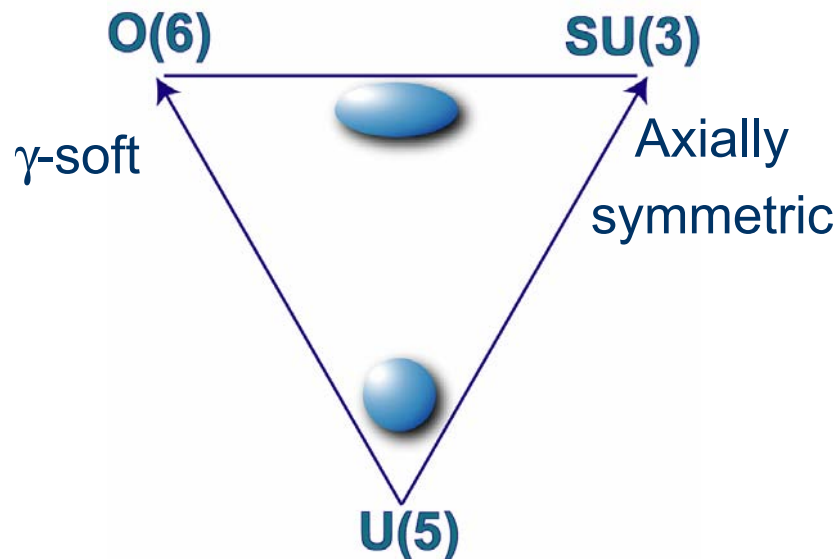

Shape phase transitions far from stability

Shape phases in collective nuclei

Stable quadrupole deformation



The three limits of the
Interacting Boson Model

“This three limits, associated with dynamical symmetries of the Hamiltonian, appear as shape phases at the classical level ($N \rightarrow \infty$)”

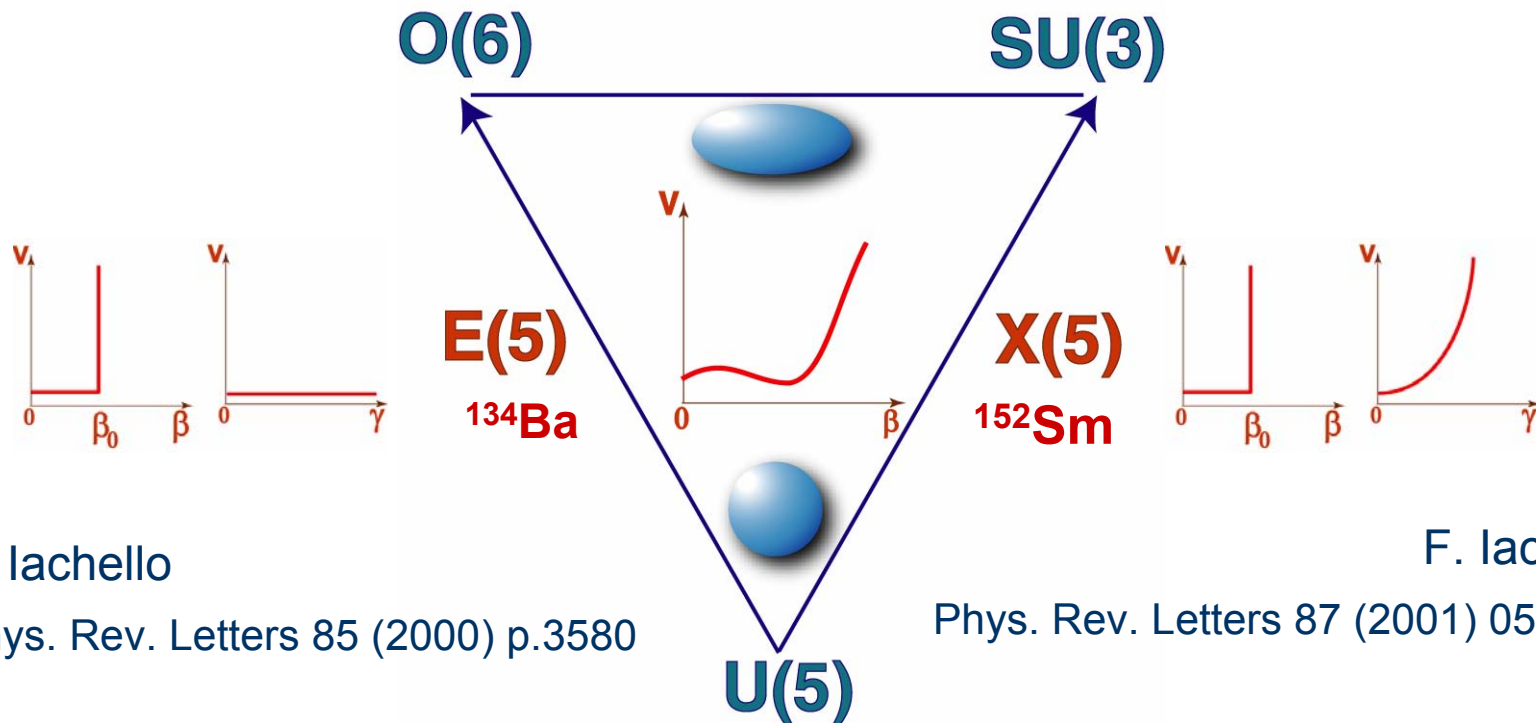
A.E.L. Dieperink and O. Scholten

Phys. Rev. Letters 44 (1980) p.1747

Vibration around spherical shape

Phase transitions and critical points

Parameter-free analytical approximations can be obtained for the critical points



F. Iachello

Phys. Rev. Letters 85 (2000) p.3580

F. Iachello

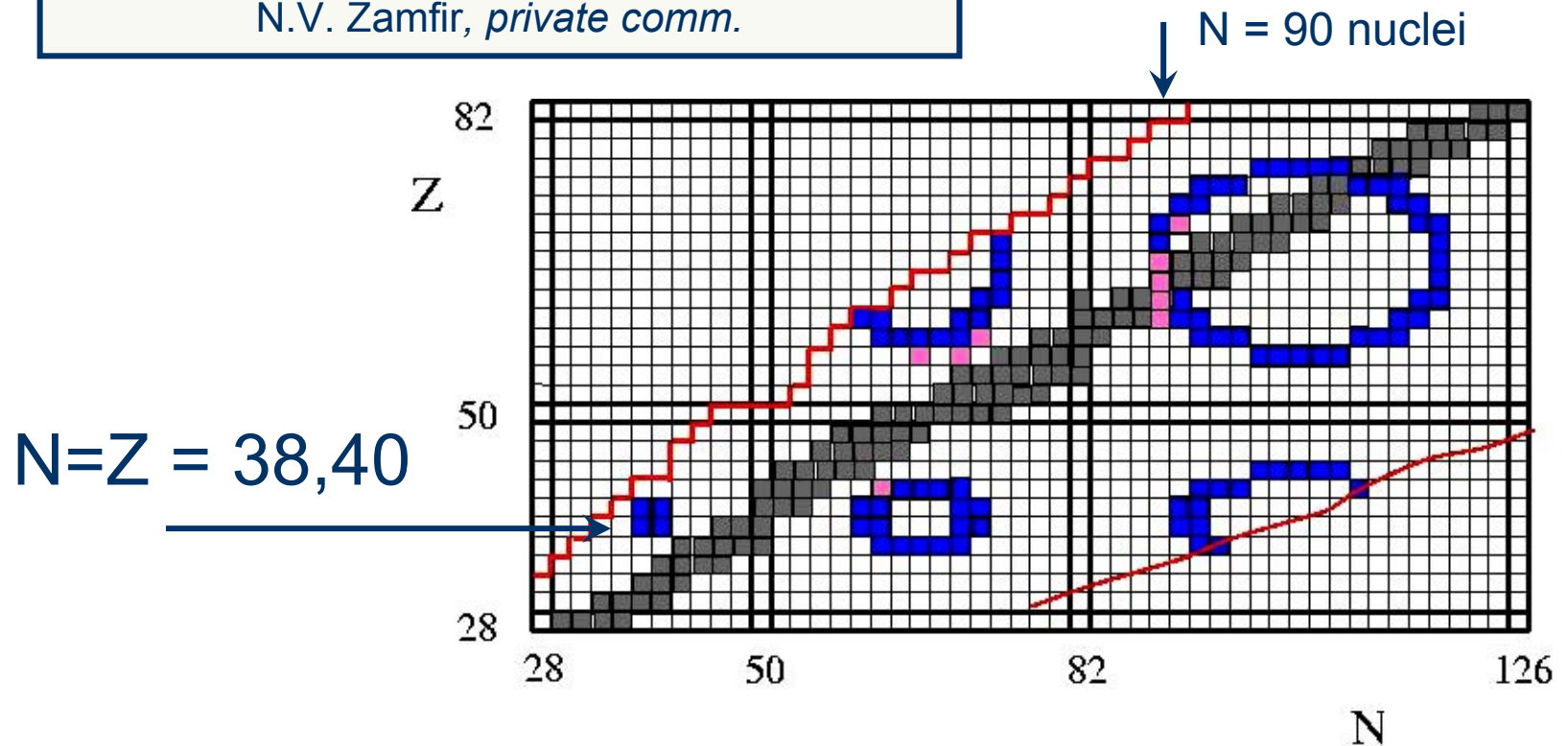
Phys. Rev. Letters 87 (2001) 052502

Critical points: not only close to stability

Empirical $X(5)$ search criterion

$$4.5 < N_p N_n / (N_p + N_n) < 5.5$$

N.V. Zamfir, *private comm.*



Quasi- γ Bands in $N \approx Z \approx 40$ region

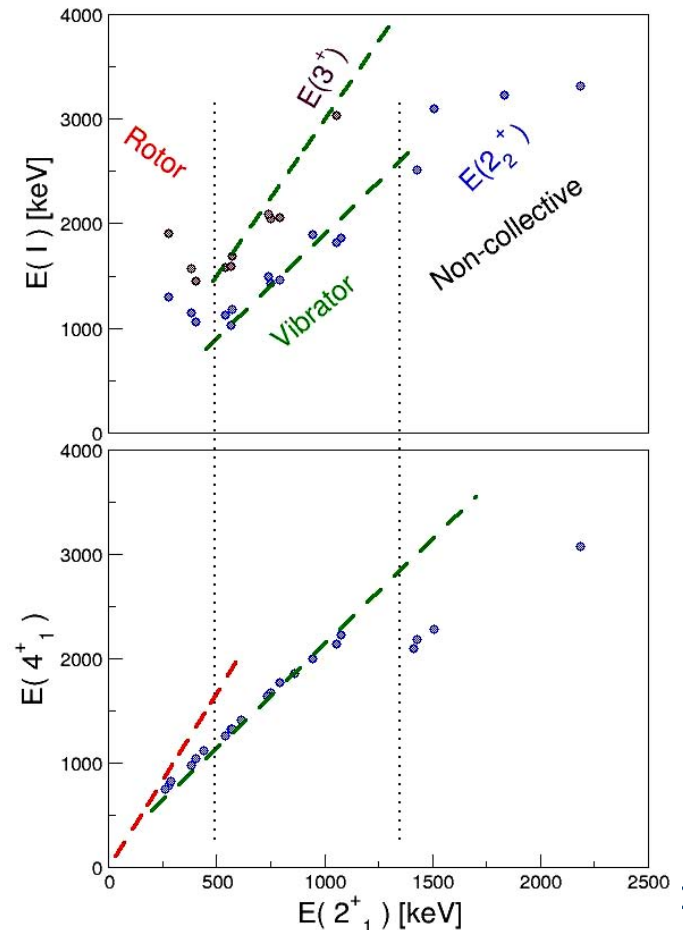
4 GASP experiments

Quasi- γ bands identified or completed in ^{78}Sr , ^{80}Sr , ^{82}Zr , ^{84}Zr , ^{86}Zr , ^{86}Mo , ^{88}Mo



The plot of $E(2^+_{\gamma}, 3^+_{\gamma})$ versus $E(2^+_1)$ clearly indicates the **Rotor-Vibrator phase transition**

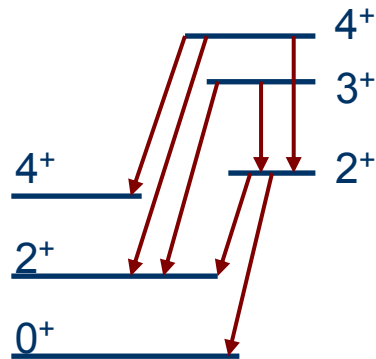
Even-even Sr-Zr-Mo with $N \leq 50$



IBA description

$$H_{IBA} = a \left[(1 - \zeta) n_d - \frac{\zeta}{4N} (Q \cdot Q) + \zeta' \cdot (L \cdot L) \right]$$

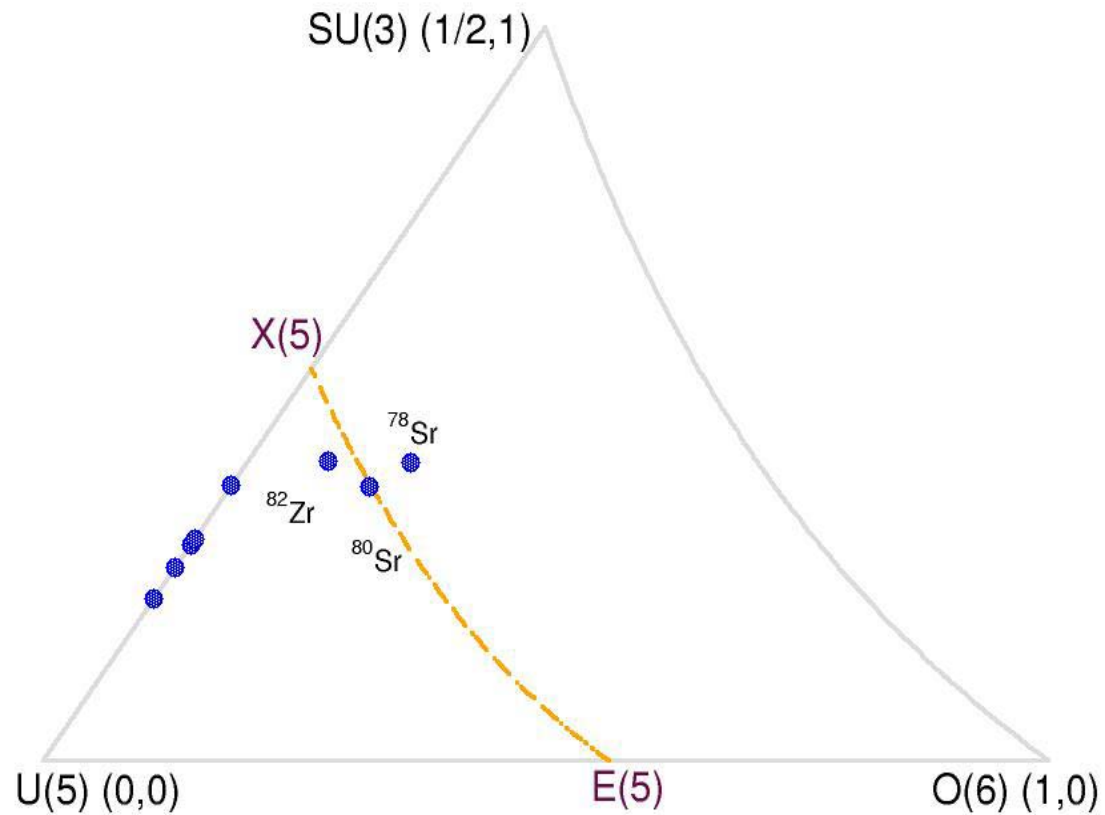
$$Q = s^+ \tilde{d} + d^+ \tilde{s} + \chi [d^+ \tilde{d}]^{(2)}$$



- ♦ Fine grid on parameter space
- ♦ χ^2 merit function including both energy and branching ratios

New parameters: $x = \zeta \cdot \frac{1}{1 + \frac{|\chi|}{\sqrt{7}/2}}$ $y = \frac{\zeta \cdot |\chi|}{\sqrt{7}/2}$

Phase Transition near N=Z line



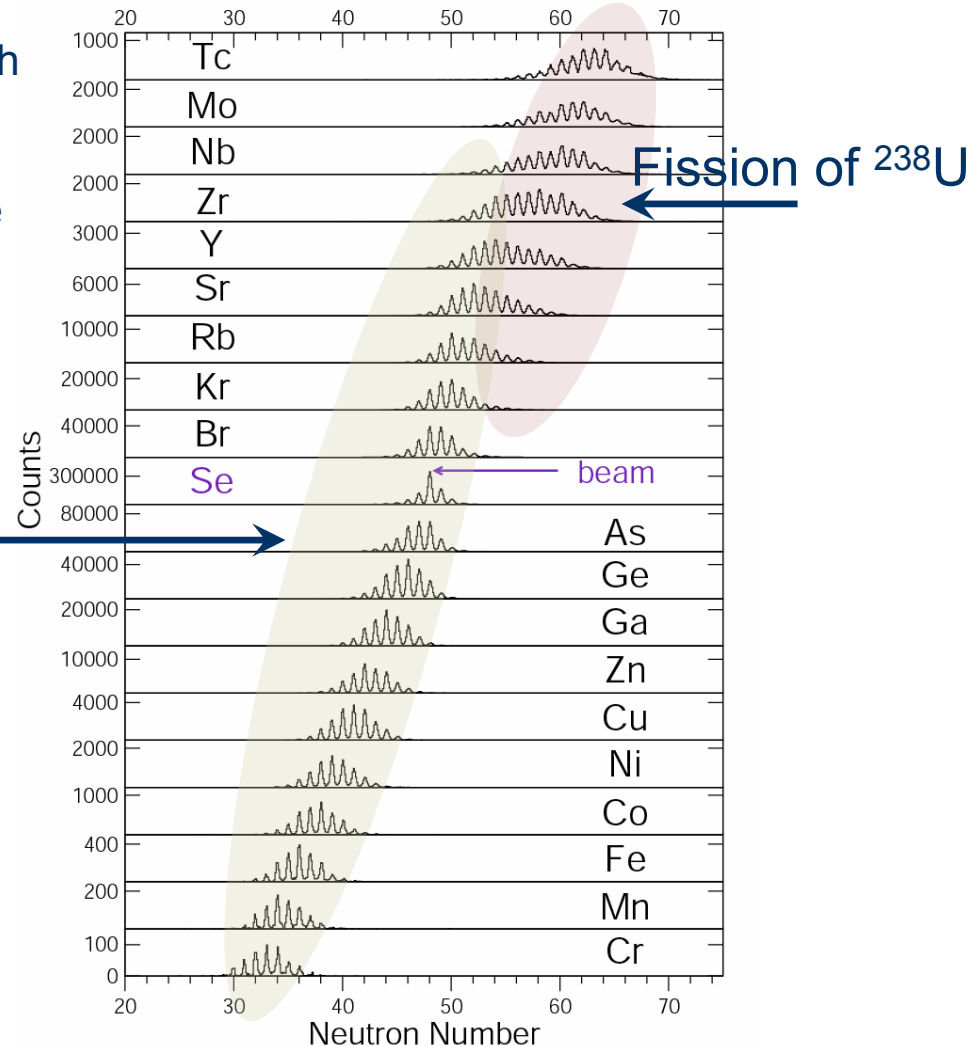
Nuclear structure studies using PRISMA/CLARA setup

- ♦ Multi-nucleon transfer reactions with neutron-rich, stable projectiles on heavy targets
- ♦ Projectile-like reaction products are detected with PRISMA placed around the grazing angle



Multi-nucleon transfer
Deep-inelastic collisions

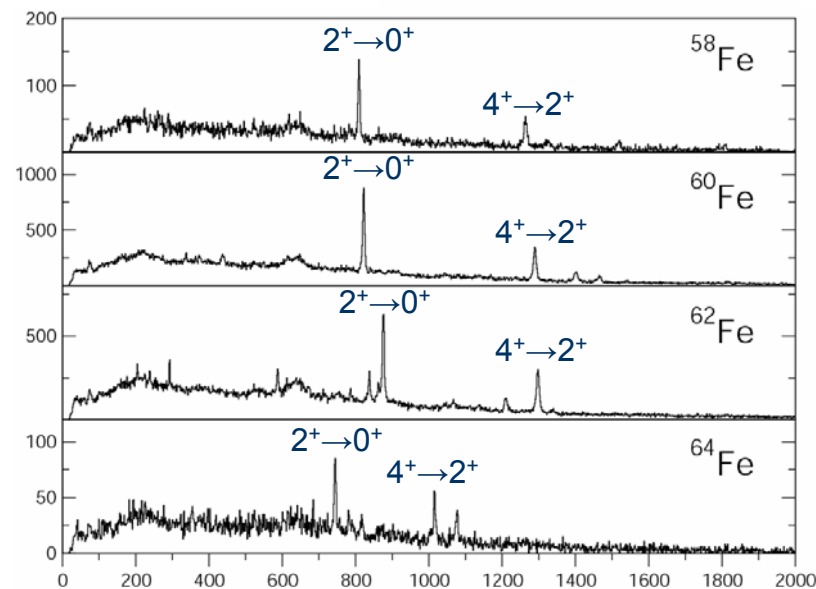
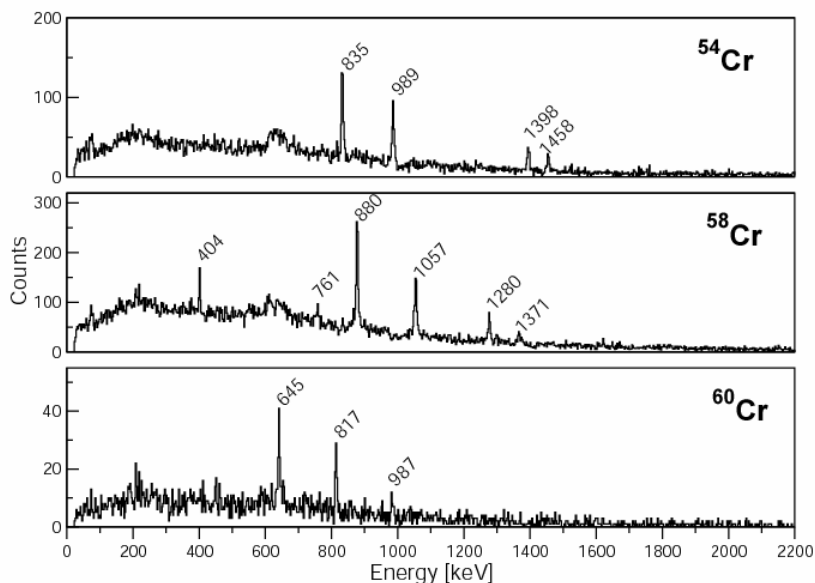
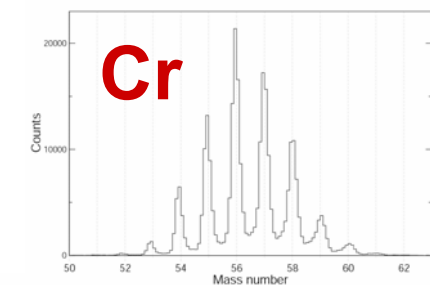
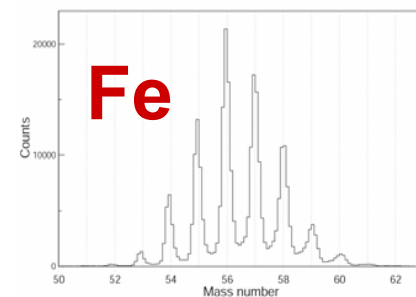
The evolution of the nuclear structure can be observed over large regions



Onset of deformation towards N=40

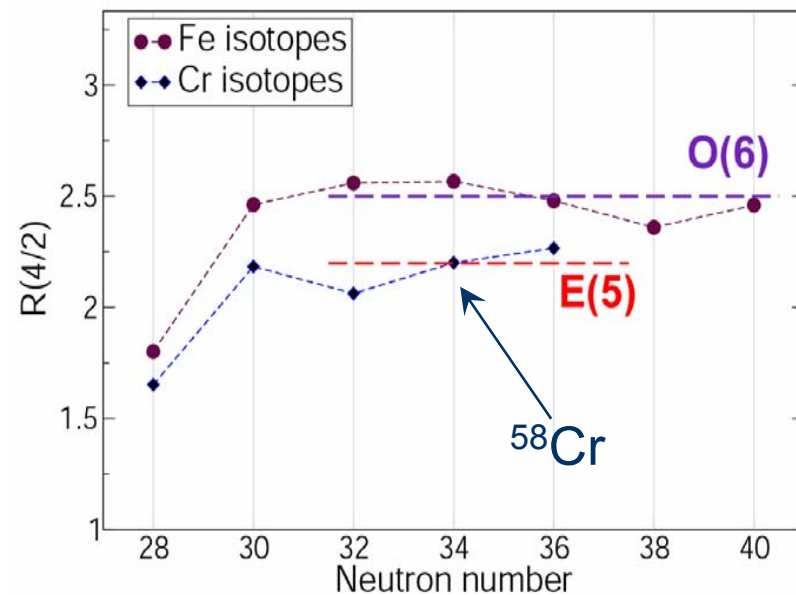
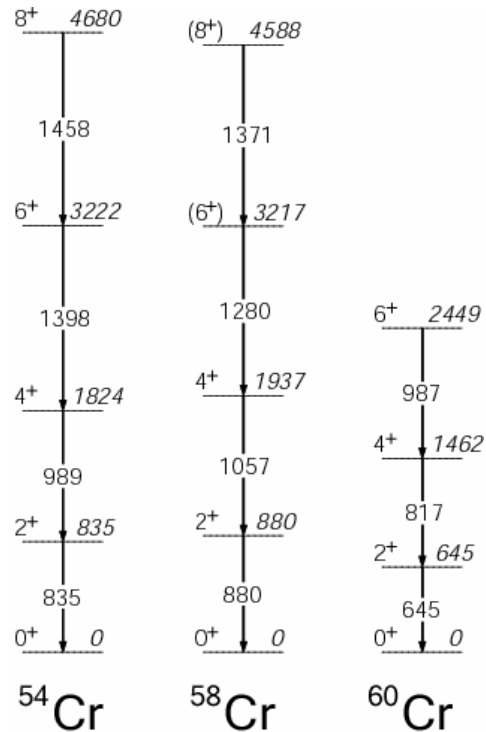
- ◆ First identification of 4^+ and possibly 6^+ states in ^{64}Fe
- ◆ First observation of γ rays from the yrast levels of ^{58}Cr

$^{64}\text{Ni}(404 \text{ MeV}) + ^{238}\text{U}$
PRISMA/CLARA

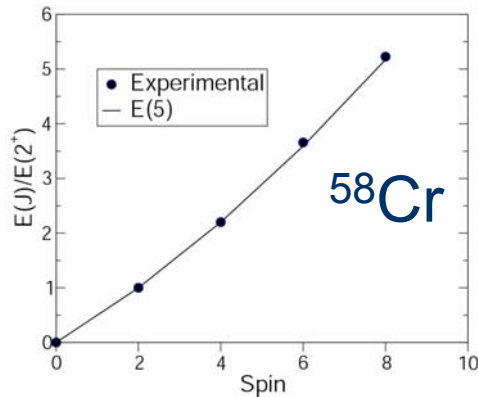


γ -softness in heavy Cr and Fe isotopes

The $R(4/2)$ of ^{58}Cr has exactly the value predicted for E(5) critical point



^{58}Cr : A shape phase transition critical point ?



$$H_{\text{IBA}} = \varepsilon n_d + A \cdot P^+ P$$

$$N = 5, \quad \text{empirical } e_B = 0.2 \cdot Z \text{ [efm}^2\text{]}$$

$$\text{Critical point } \varepsilon/A = 2(N-1)$$

$$B(E2; 2^+ \rightarrow 0^+)_{\text{IBA}} = 170 \text{ e}^2\text{fm}^4$$

$$B(E2; 2^+ \rightarrow 0^+)_{\text{exp}} = 197(56) \text{ e}^2\text{fm}^4$$

- ◆ The excitation energies for all states in the yrast band of ^{58}Cr are very close to the predictions of the E(5) symmetry
- ◆ Several large-scale Shell-Model results are also in good agreement with the E(5) solution

8+	4598	4550	4442	4447	4743	4946
6+	3219	3159	3130	2990	3188	3299
4+	1937	1936	1937	1770	1885	2051
2+	880	880	882	880	870	1102
0+	0	0	0	0	0	0
EXP.	E(5)	IBA	KB3G	FPD6	GXPF1	

N. Marginean et al. Phys. Lett. B 633(2006)696

^{58}Cr : A shape phase transition critical point ?

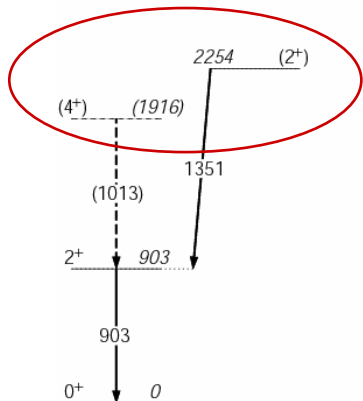
	Exp	IBM	KB3G	FPD6	GXPFI
$E_{4_1^+}/E_{2_1^+}$	2.20	2.20	2.01	2.17	1.86
$E_{6_1^+}/E_{2_1^+}$	3.66	3.55	3.40	3.66	2.99
$E_{8_1^+}/E_{2_1^+}$	5.22	5.04	5.05	5.45	4.49
$\frac{B(E2):4_1^+ \rightarrow 2_1^+}{B(E2):2_1^+ \rightarrow 0_1^+}$		1.39	1.15	1.38	1.13
$\frac{B(E2):6_1^+ \rightarrow 4_1^+}{B(E2):2_1^+ \rightarrow 0_1^+}$		1.41	1.13	1.24	0.93
$\frac{B(E2):8_1^+ \rightarrow 6_1^+}{B(E2):2_1^+ \rightarrow 0_1^+}$		1.16	1.18	1.16	1.01

More experimental B(E2) values are needed to firmly demonstrate the existence of E(5) symmetry in ^{58}Cr

Collectivity above N=20 shell closure

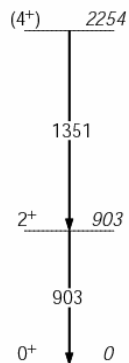
^{36}S (230MeV) + ^{208}Pb

^{40}Ar (205MeV) + ^{170}Er

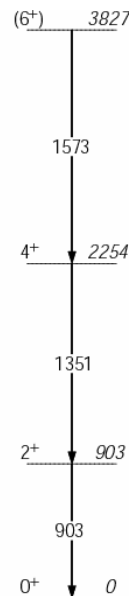


β decay
NSCL-MSU
(1)

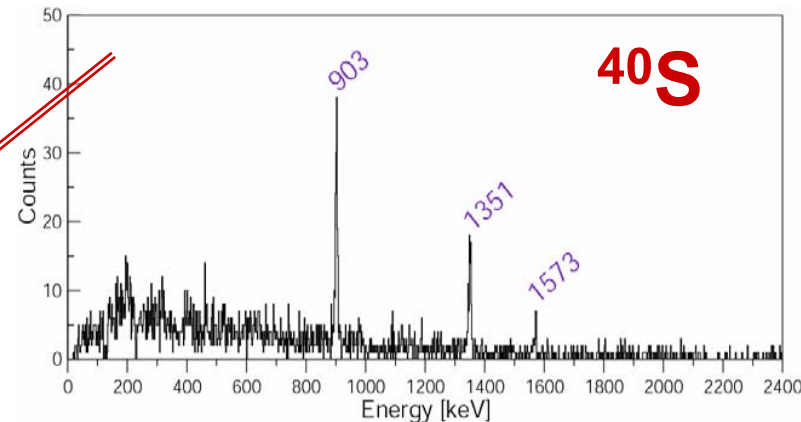
^{40}S



GANIL
(2)



PRISMA/CLARA



(1) *J.A. Wigner et al.*

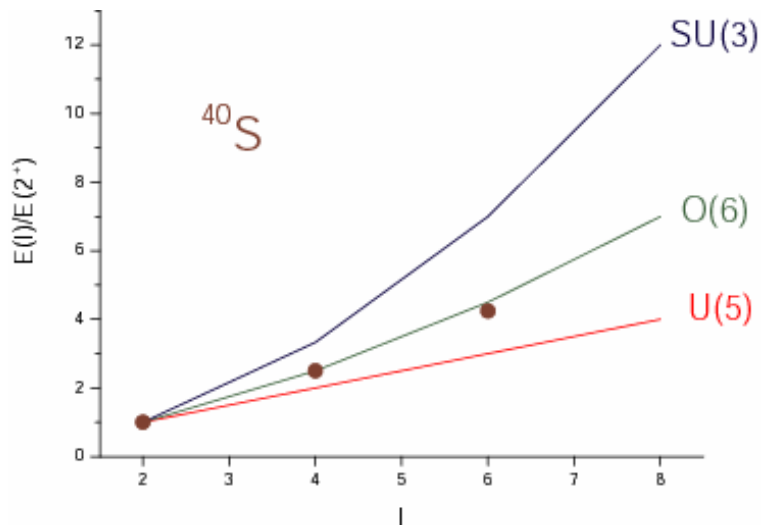
Phys. Rev C 64(2001)064318

(2) *D. Sohler et al.*

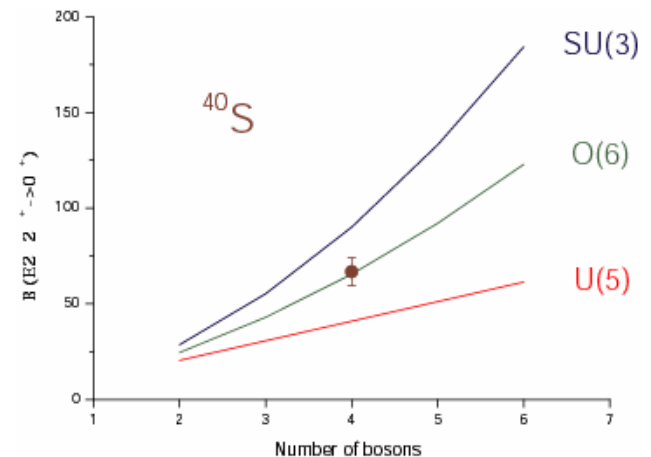
Phys. Rev C 66(2002)054302

γ -softness in heavy S isotopes

Analytic IBA formulas



Realistic effective charge $q_{\text{eff}} = 0.2 \times Z$



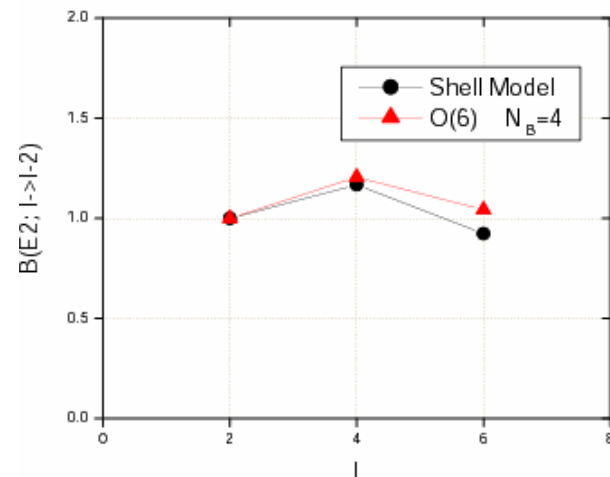
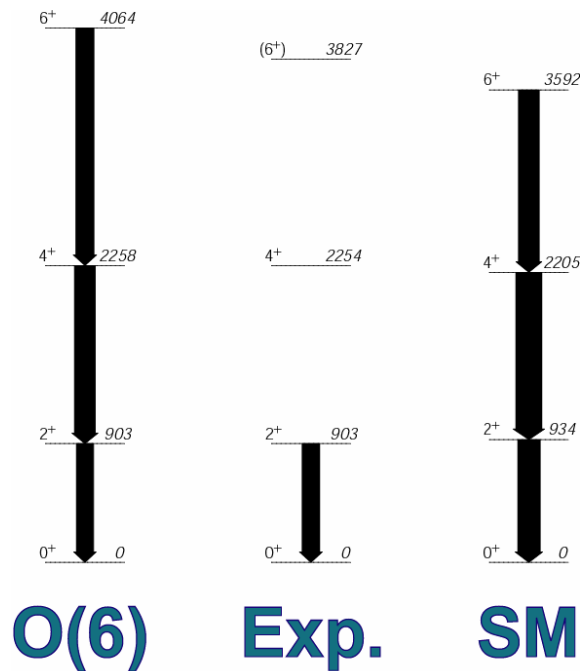
The level scheme and $B(E2)$ value suggest a significant degree of γ -softness in ^{40}S

^{40}S – Shell model and O(6) predictions

- ◆ Shell model : sd - fp interaction (USD+KB'+KLE)

Phys. Rev. C 55 (1997) 1266

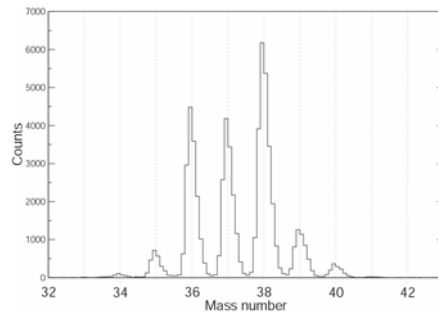
Phys. Rev. C 63 (2001) 044316



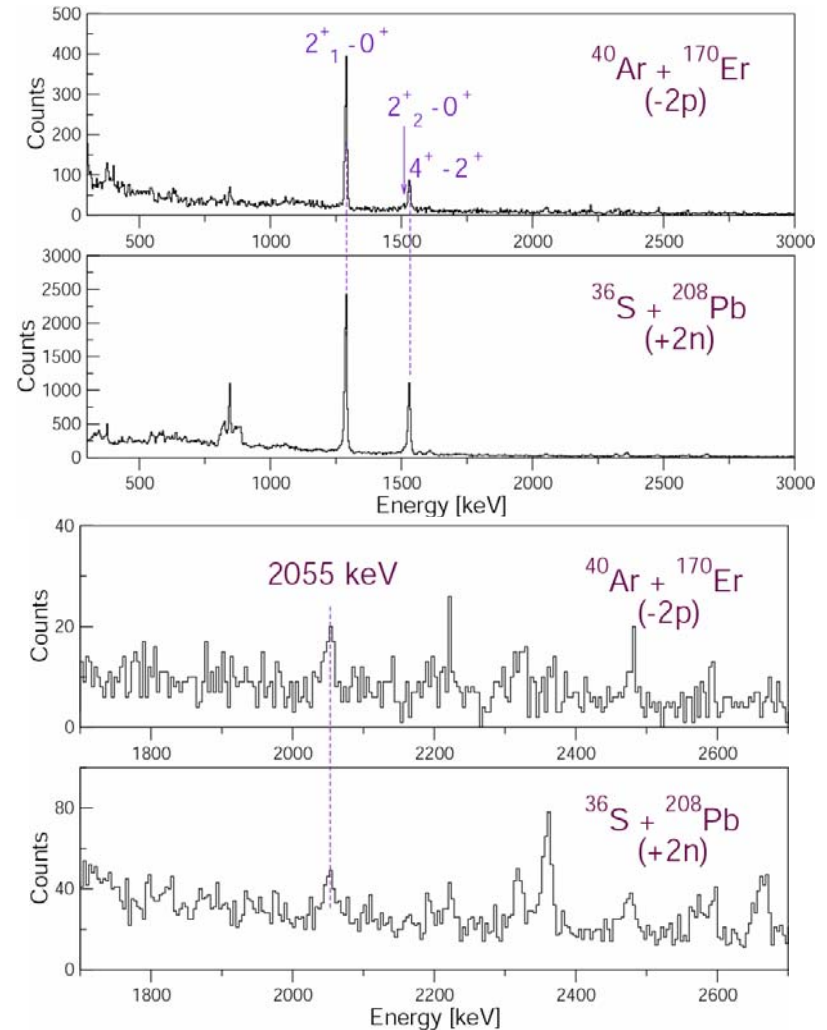
Spectroscopy of ^{38}S

^{36}S (230MeV) + ^{208}Pb

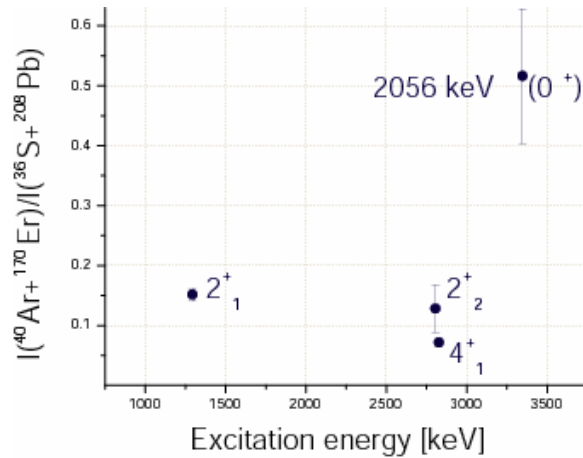
^{40}Ar (205MeV) + ^{170}Er



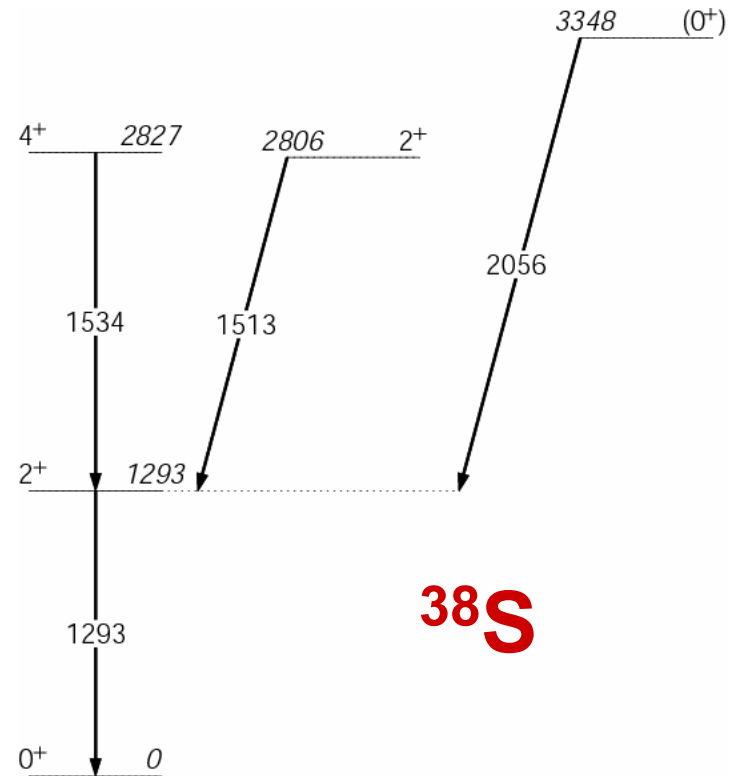
- ♦ The 2055 keV gamma ray corresponds to the fourth excited state of ^{38}S
- ♦ This state was previously observed only in (t,p) experiments



Low-energy states of ^{38}S

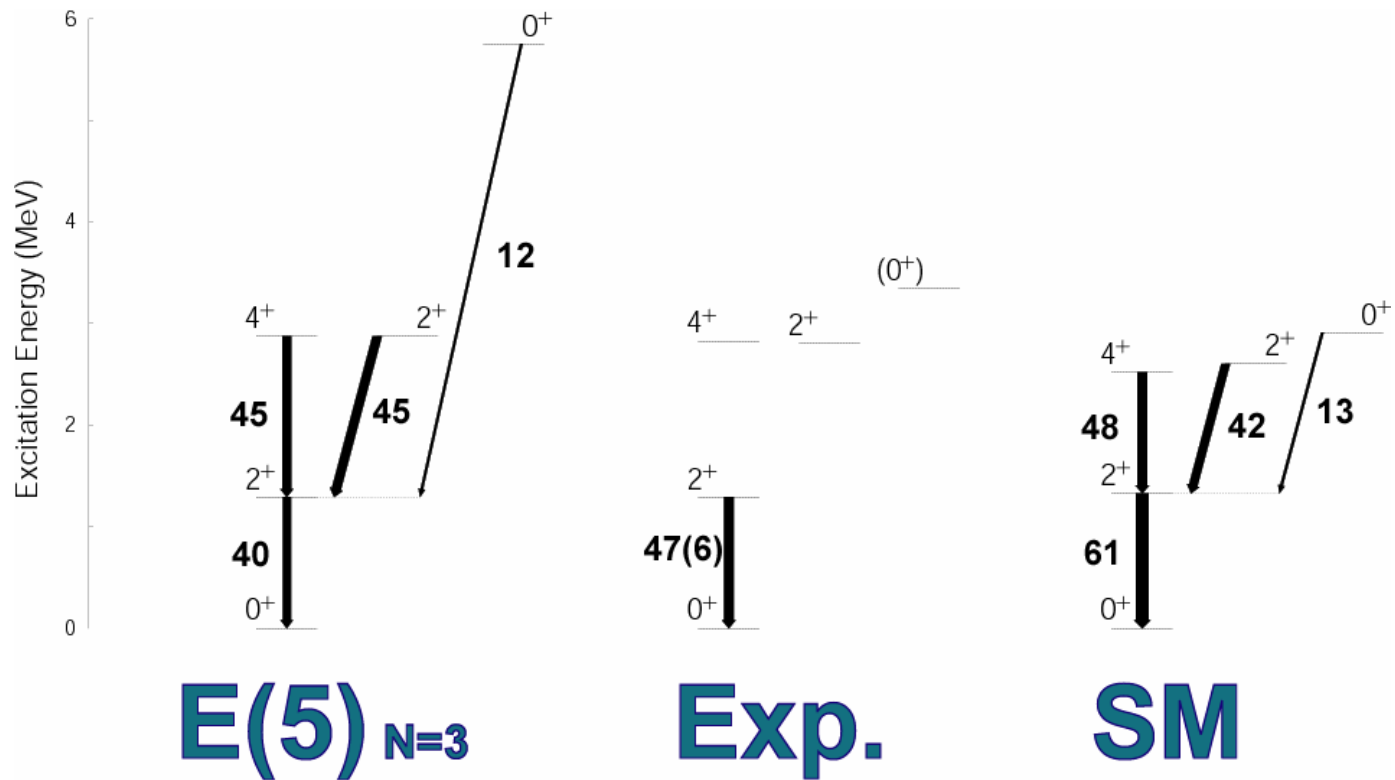


	Exp	E(5)
$E(4^+_1)$	2.19	2.20
$E(2^+_2)$	2.17	2.20
$E(0^+_2)$	2.59	3.03



^{38}S

Theoretical predictions for ^{38}S



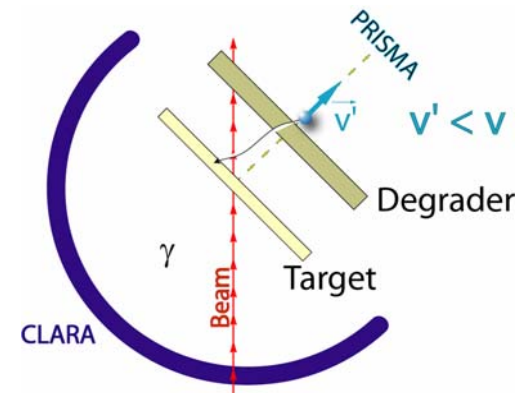
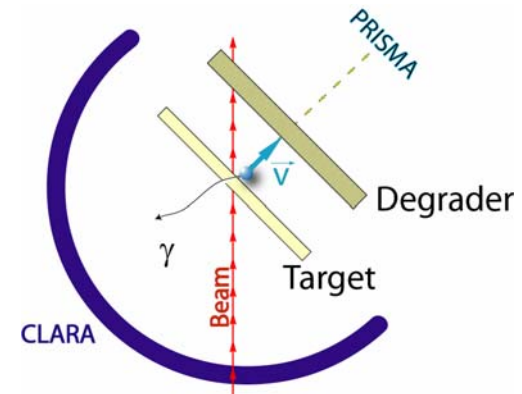
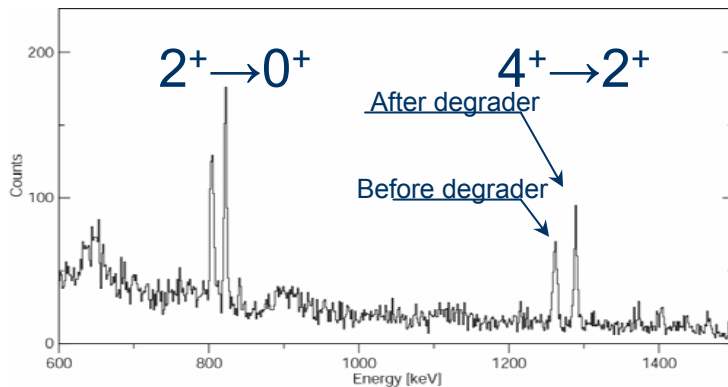
Development projects:

Differential plunger with PRISMA/CLARA

Collaboration with IKP-Köln

- ◆ Consists in having an energy degrader at fixed distance after the target
- ◆ The gamma rays emitted before or after the recoil passes the degrader will have different Doppler shifts
- ◆ The lifetimes will be obtained from the intensity ratio before/after degrader

^{60}Fe – simulation based on existing experimental data



Summary

- ◆ Shape phase transitions are encountered also far from stability, both on proton-rich and neutron-rich regions
- ◆ The ^{58}Cr nucleus is a good E(5) candidate and could provide the opportunity to compare the E(5) model with large-scale shell-model calculations
- ◆ New experimental information obtained with PRISMA/CLARA suggests that the deformation in heavy S isotopes could be characterized by γ softness
- ◆ Further developments will provide the possibility to measure lifetimes with PRISMA/CLARA