# Clustering - possible origin of deformation in $^{32}S$?

- Excursions of Experimentalists in Theory:

  - The main aim is usually data interpretation for understanding Nuclear Structure

  - Sometimes ideas appear that need support by further experiments and new theory

- Starting point: $\alpha$-clusters in heavy ${}^{212}_{84}Po_{128} = \alpha({}^{4}_{2}He_{2}) + {}^{208}_{82}Pb_{126}$

- Idea: Magic clustering as one possible origin of nuclear shape deformations

- Example in $^{32}S$ showing the impact of knowing reduced transition elements

- Plans for the future

- Conclusions

P. Petkov, INRNE

# Why lifetimes are important for nuclear structure studies?

Lifetimes provide information about absolute probabilities (decays per second) for transitions between two nuclear states and thus shed light on their structure. Normally, the modulus of the reduced transition matrix element

$$<\Phi_f||O(\sigma,\lambda)||\Phi_i>$$

is determined. The electromagnetic interaction is well understood and this gives us the possibility to extract pure nuclear structure information. Electromagnetic transition probabilities are sensitive to the wave functions of both initial and final states and thus represent an important tool for testing nuclear models.

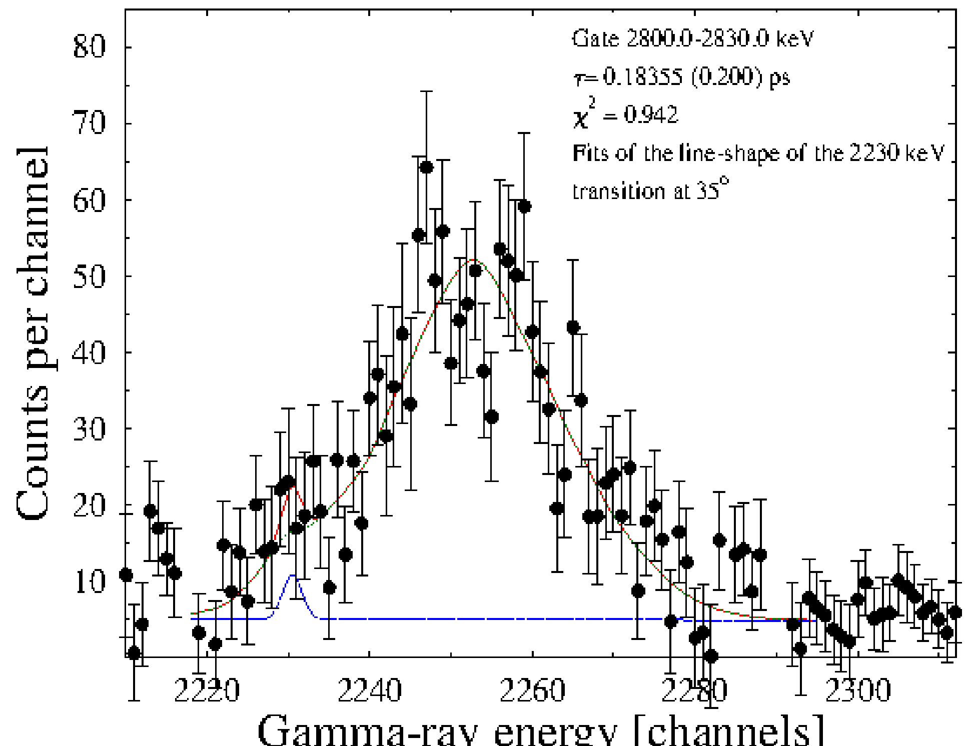
# DSAM lifetime measurement in $^{32}_{16}S$ for $\tau(2^+_1)$

The result from the Bachelor's work of Milena Stoyanova (Uni-Sofia) confirms the large $B(E2, 2^+_1 \rightarrow 0^+_1)$ value which is only to about 60% accounted for even by the most modern Shell-model calculations

Idea: $^{32}_{16}S_{16} = 2 \times {}^{16}_{8}O_8$

and displacement or vibrations involving the two $^{16}O$ clusters may lead to deformation and large E2 strengths

Line shape analysis and lifetime determination according to the DDCM

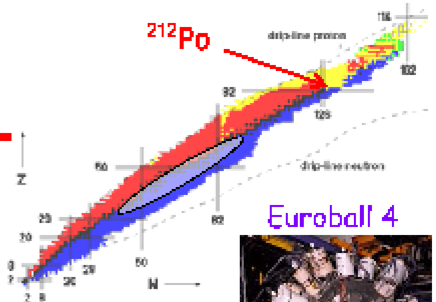


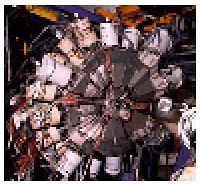
# Starting point: First observation of $\alpha$-clustering in heavy nuclei ($^{212}Po$)

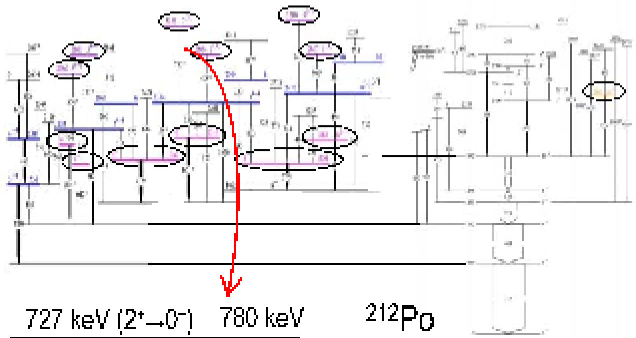
## Evidence of $\alpha$ clustering in $^{212}Po$

Goal: Spectroscopy of fission fragments via the $^{208}Pb(^{18}O,f)$ reaction

Also in the data: the $^{208}Pb(^{18}O,^{14}C)^{212}Po$ transfer reaction!



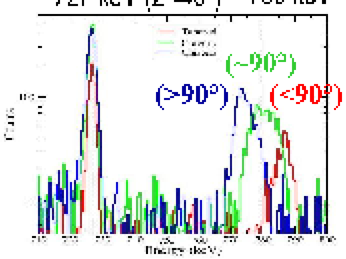



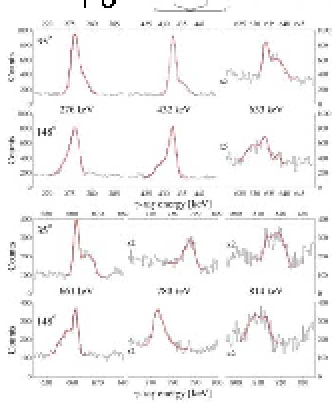
Level scheme widely extended:

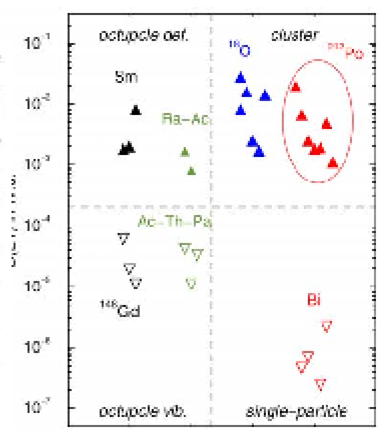
50 $\gamma$ rays added

35 new states, some of them extremely interesting:

Decay by a very enhanced E1 (with $\Delta I=0$) transition, observed with Doppler broadenings & shifts




Lifetimes extracted from DSAM analysis: in the range **[0.1-0.6] ps**

Huge B(E1)'s

Up to **1000 times** the values of typical B(E1)'s generated by only one nucleon!

Interpretation:

Coexistence of "$\alpha+^{208}Po$" cluster structures and single-particle excitations in $^{212}Po$

# Some related publications for $^{212}Po=\alpha + {}^{208}Pb$

## Not too bad for a by-product…

Selected for a Viewpoint in *Physics*
PRL 104, 042701 (2010) PHYSICAL REVIEW LETTERS week ending 29 JANUARY 2010

**Novel Manifestation of $\alpha$-Clustering Structures: New "$\alpha + {}^{208}Pb$" States in $^{212}Po$ Revealed by Their Enhanced $E1$ Decays**

A. Astier,[1] P. Petkov,[1,2] M.-G. Porquet,[1] D. S. Delion,[3,4] and P. Schuck[5]
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DOI 10.1140/epja/i2010-11053-6
THE EUROPEAN PHYSICAL JOURNAL A
Regular Article – Experimental Physics

**Coexistence of "$\alpha + {}^{208}Pb$" cluster structures and single-particle excitations in $^{212}_{84}Po_{128}$**

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☞ Interpretation:
Coexistence of "$\alpha + {}^{208}Po$" cluster structures and single-particle excitations in $^{212}Po$

# Mutual displacement and/or vibrations of “magic” clusters as driving deformations

Q

PHYSICAL REVIEW C 89, 011306(R) (2014)

$Q_{th} < Q_{exp}$

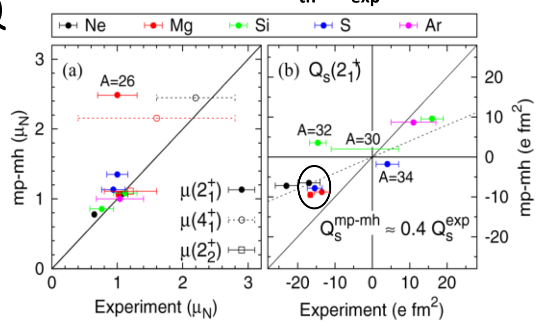



FIG. 4. (Color online) Comparison of experimental and theoretical (a) magnetic moments $\mu$ (in $\mu_N$ unit) and (b) quadrupole spectroscopic moments $Q_s$ (in efm$^2$).

B(E2)

PHYSICAL REVIEW C 89, 011306(R) (2014)

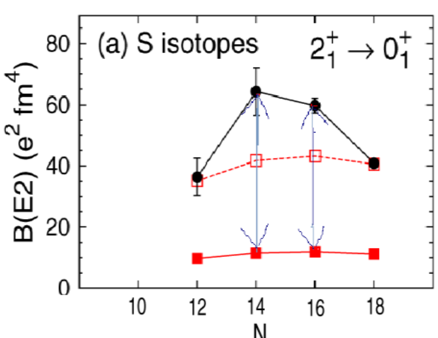
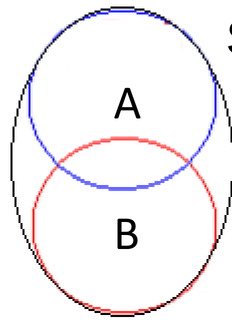



FIG. 6. (Color online) Examples of reduced transition probabilities $B(E2, 2_1^+ \rightarrow 0_1^+)$ for isotopic (left) and isotonic (right) chains. Theoretical (experimental) values are in red (black).

## Symmetric

Ellipsoidal Shape (?)



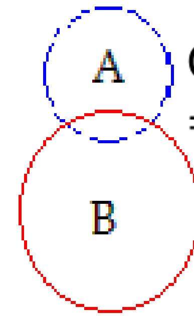

B=A

Enhanced E2’s

$$^{32}_{16}S_{16} = {}^{16}_{8}O_8 + {}^{16}_{8}O_8$$

Our new data seem to support this possibility

## Asymmetric




Center of mass ≠ center of charge

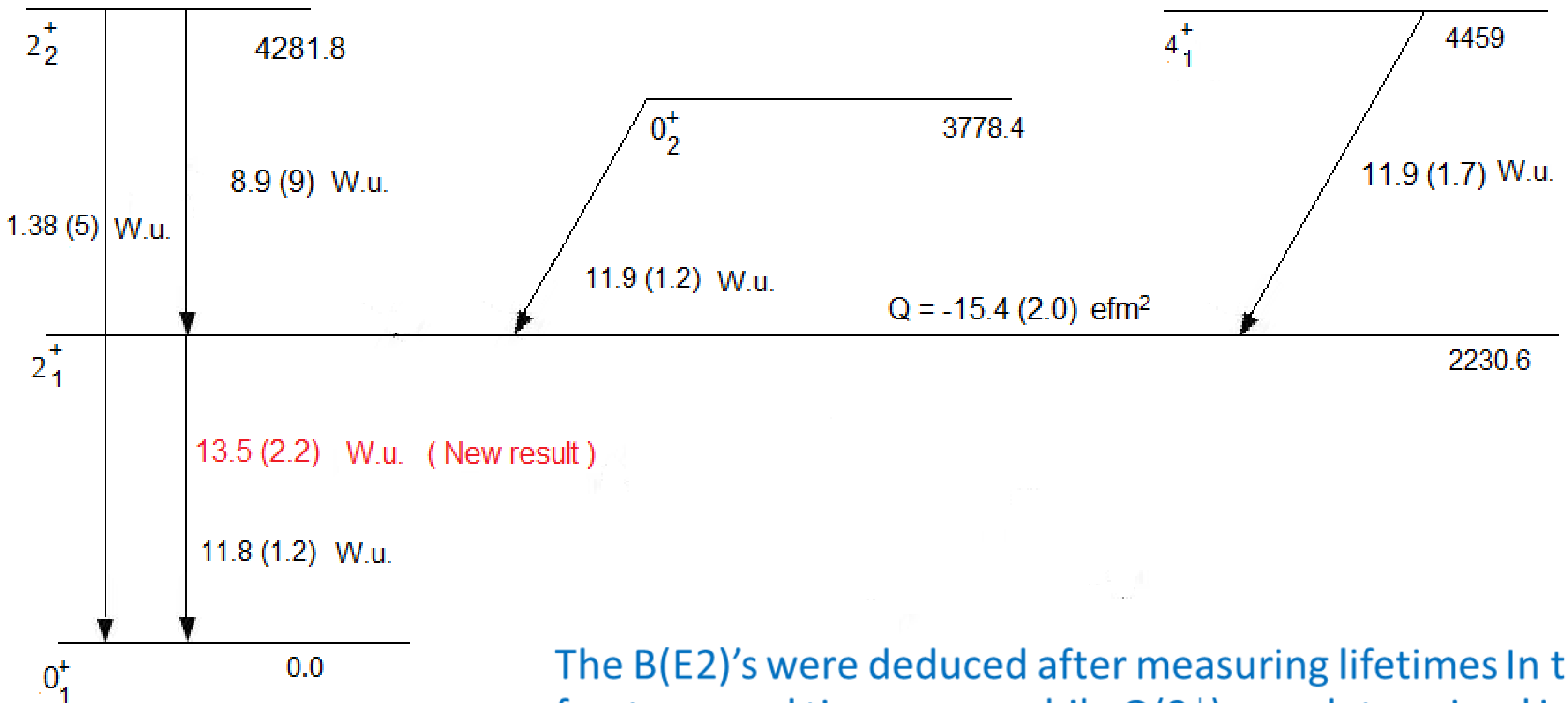
B≠A

Enhanced E1’s

$$^{212}_{84}Po_{128} = {}^{4}_{2}He_2(\alpha) + {}^{208}_{82}Pb_{126}$$

A. Astier,et al PRL 104 (2010) 042701

# Level energies and E2 transition strengths in $^{32}$S




The B(E2)'s were deduced after measuring lifetimes In the femtosecond time range while Q($2_1^+$) was determined in earlier Coulomb excitation experiments

# How these short lifetimes have been measured: Principle of DSAM

Measurable lifetimes are of the order or smaller than the slowing down time of Ions in solids (~1 ps)

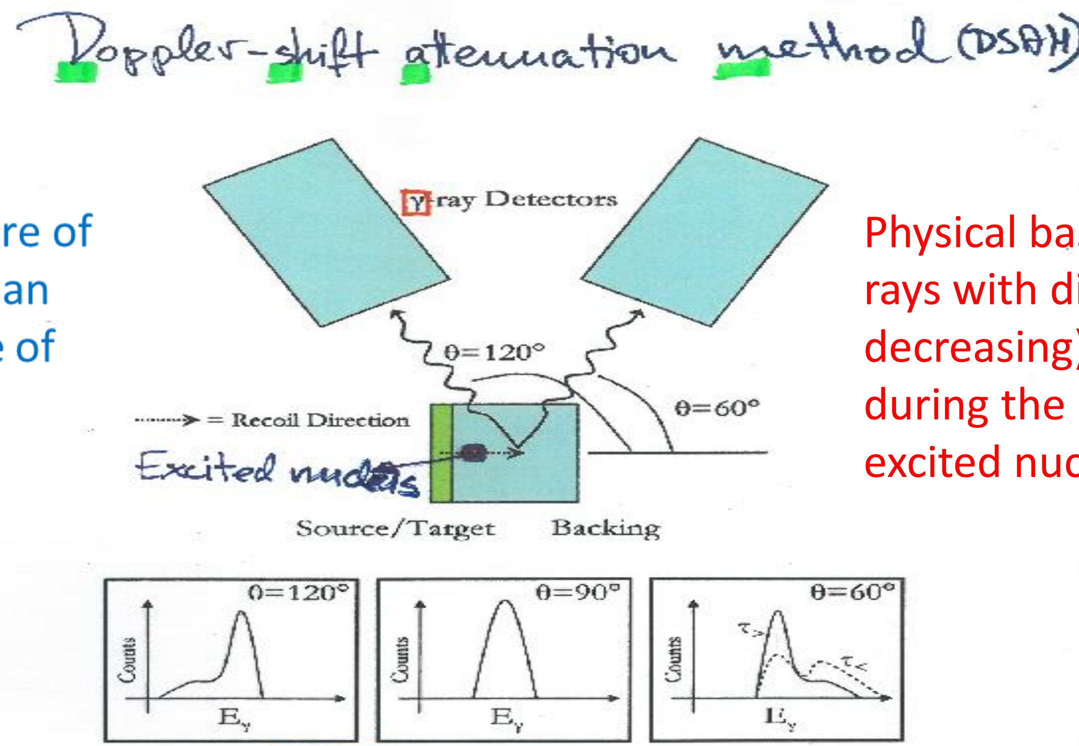



Figure 2-11: Principle of a DSAM setup and schematic display of γ-ray lineshapes at representative forward (θ=60°), backward (θ=120°), and 90° angles of detectors with respect to the direction of the moving γ ray emitter. For the spectrum at θ=60°, the lineshapes for a lifetime τ=τ, and a lifetime τ<τ, are sketched.

$$E_\gamma = E_{\gamma_0}\left(1 + \frac{v(t)}{c}\cos\theta(t)\right)$$

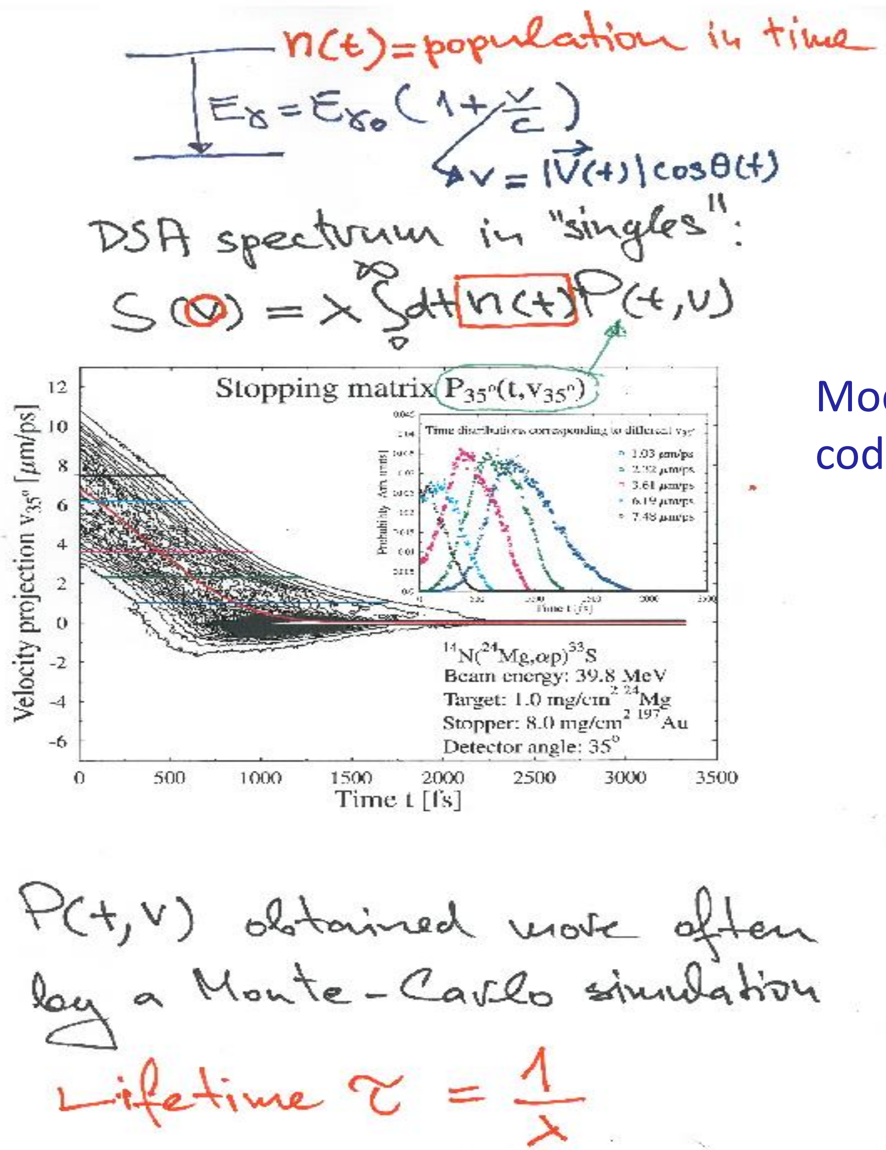
38

(Non-relativistic formula)

Physical basis: Emission of γ-rays with different (generally decreasing) Doppler-shifts during the deceleration of excited nuclei

# Generating velocity projection spectra on observation axis

Stopping process:
- electron (continuous)
- nuclear (scattering with discrete energy losses)




Modified Monte-Carlo code of Georg Winter

# Example of GFA analysis from NIM A 437 (1999) 274

$^{116}Cd(^{16}O,4n)^{128}Ba$ at E = 76 MeV
1.1 mg/cm$^2$ target and Au stopper

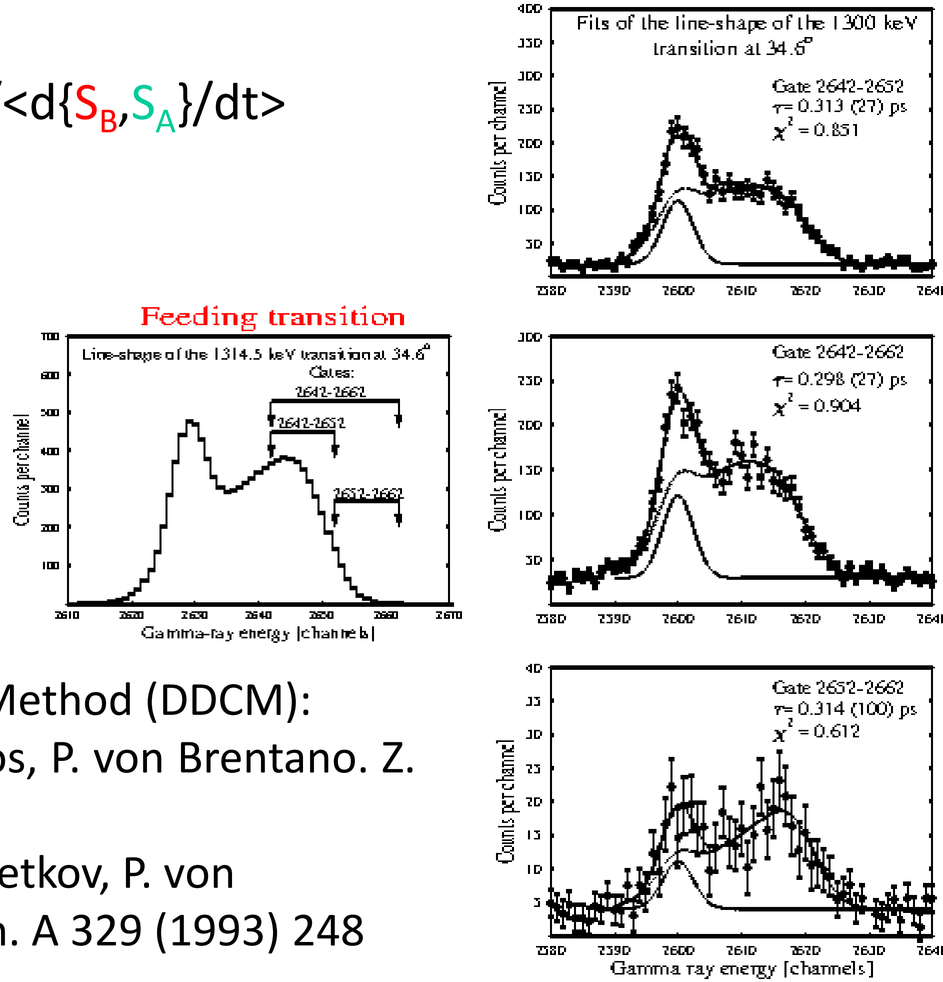
Lifetime: $\tau = \{S_B,U_A\}/\langle d\{S_B,S_A\}/dt \rangle$

A la DDCM:

U – unshifted
S-shifted
{X,Y}-number of coincident events

Depopulating transition

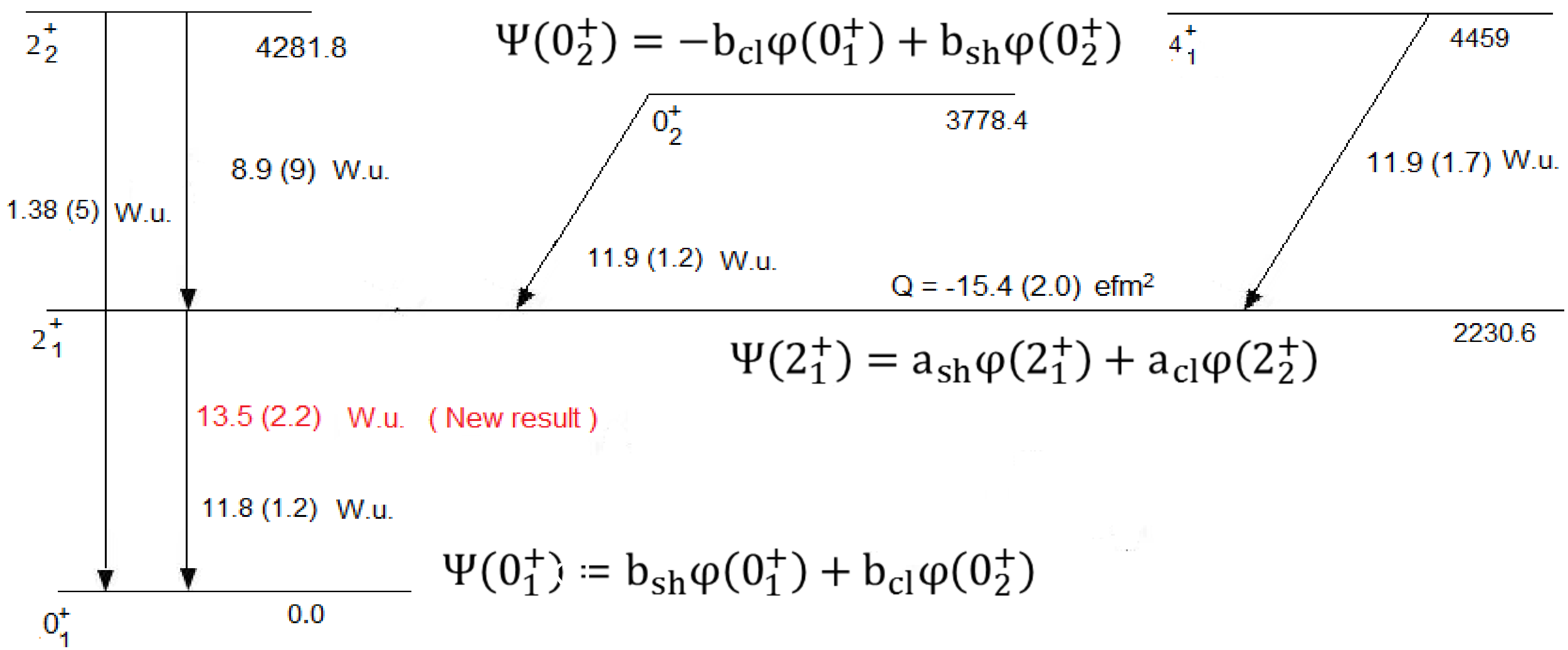
Feeding transition




Differential Decay Curve Method (DDCM):
A. Dewald, S. Harissopulos, P. von Brentano. Z. Phys. A334 (1989)163
G. Boehm, A. Dewald, P. Petkov, P. von Brentano, Nucl. Inst. Meth. A 329 (1993) 248

# Idea for two-level mixing calculation involving Shell-model states (sh) + clustering induced vibrations/deformations (cl)

$$\Psi(2_2^+) = -a_{cl}\varphi(2_1^+) + a_{sh}\varphi(2_2^+)$$




ψ---->|Physical states>, φ––>|Unperturbed sates>

# Experimental data on some electromagnetic transition and static E2 matrix elements in $^{32}$S

$$Q(2_1^+) = 0.7579\,(a_1^2 <2_{sh}||E2||2_{sh}> + a_2^2 <2_{cl}||E2||2_{cl}> + 2a_1a_2<2_{sh}||E2||2_{cl}>)$$
$$= -15.4(2.0)\ \mathrm{efm}^2$$

$$|<0_1^+||E2||2_1^+>| = a_1b_1 <0_{sh}||E2||2_{sh}> + a_2b_2<0_{cl}||E2||2_{cl}> + a_1b_2<0_{cl}||E2||2_{sh}>$$
$$+a_2b_1<0_{sh}||E2||2_{cl}> = 17.5(6)\ \mathrm{efm}^2$$

$$|<0_1^+||E2||2_2^+>| = -a_2b_1 <0_{sh}||E2||2_{sh}> + a_1b_2<0_{cl}||E2||2_{cl}> - a_2b_2<0_{cl}||E2||2_{sh}>$$
$$+a_1b_1<0_{sh}||E2||2_{cl}> = 6.4(3)\ \mathrm{efm}^2$$

$$|<2_1^+||E2||2_2^+>| = a_2a_1 <2_{sh}||E2||2_{sh}> + a_1a_2<2_{cl}||E2||2_{cl}> - a_2^2 <2_{cl}||E2||2_{sh}>$$
$$+a_1^2<2_{sh}||E2||2_{cl}>> = 15.4(7)\ \mathrm{efm}^2$$

$$|<2_1^+||E2||0_2^+>| = -b_2a_1 <2_{sh}||E2||0_{sh}> + b_1a_2<2_{cl}||E2||0_{cl}> - b_2a_2<2_{cl}||E2||0_{sh}>$$
$$+b_1a_1<2_{sh}||E2||0_{cl}> = 8.4(4)\ \mathrm{efm}^2$$

# Two level mixing calculation and fitting procedure

- Mixing of the lowest two $0^+$ and $2^+$ level belonging to the Shell-model space and to the deformed (statically or dynamically) two-cluster space

- Since the level energies are known, a given interaction strength for each spin uniquely determines the mixing amplitudes

-The intra-structure E2 matrix elements are "theoretical" – taken from the literature or calculated by us within some simplifications for fixed average distance between the two magic clusters while the inter-structure are subject of variation. It was found that without them the entire date set cannot be consistently reproduced

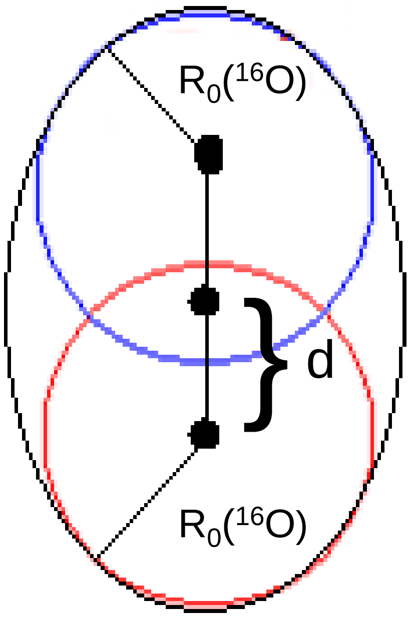
-A computer code was developed which performs the fitting procedure by varying the Interaction strengths and the unknown E2 matrix elements between the unperturbed states with the aim to minimize $\chi 2$

# Results

| Quantity | Experimental value | Deduced value | Theoretical values from the PRC58 (1998) 699 |
|---|---|---|---|
| $Q(2^+_1) =$ | -15.4 (2.0) $efm^2$ | -14.4 $efm^2$ | |
| $\vert\langle 0^+_1 \Vert E2 \Vert 2^+_1 \rangle\vert =$ | 17.5 (6) $efm^2$<br>New result: 20.1(1.6) $efm^2$ | 18.5 $efm^2$ | 15.7 $efm^2$ |
| $\vert\langle 0^+_1 \Vert E2 \Vert 2^+_2 \rangle\vert =$ | 6.4(3) $efm^2$ | -4.9 $efm^2$ | 7.8$efm^2$ |
| $\vert\langle 2^+_1 \Vert E2 \Vert 2^+_2 \rangle\vert =$ | 15.4 (7) $efm^2$ | 15.8 $efm^2$ | 16.3 $efm^2$ |
| $\vert\langle 2^+_1 \Vert E2 \Vert 0^+_2 \rangle\vert =$ | 8.4 (4) $efm^2$ | 8.1 $efm^2$ | 6.7 $efm^2$ |

- Necessity to vary the off-diagonal E2 matrix elements
- Interactions: $V(0^+)$ = 740 keV , $V(2^+)$=610 keV
- Mixing at $0^+$: 4%  Mixing at $2^+$: 10%

Approximation with an ellipsoid:




$$Q_0 = \frac{2}{5} Ze(c^2-a^2)$$

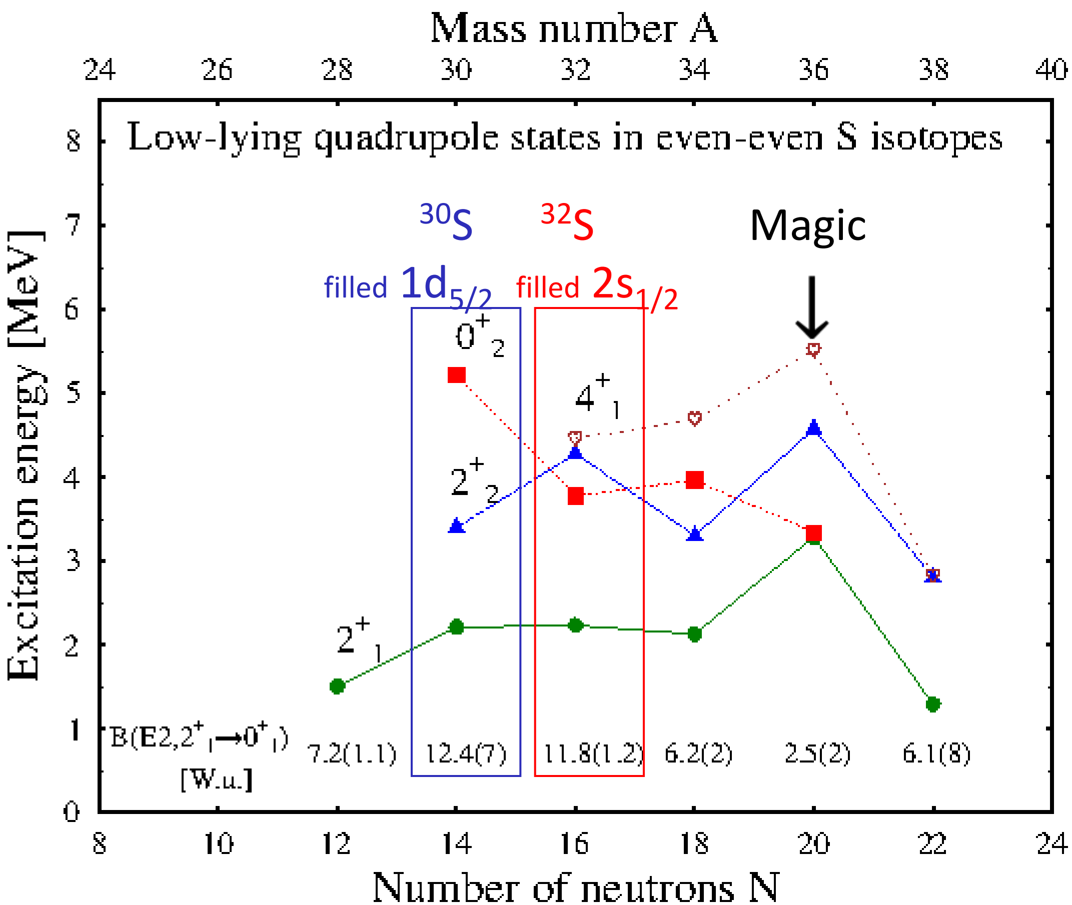
$$c \simeq R_0(^{16}O)+d$$

$$a=\sqrt{\frac{R_0}{c}(^{32}S)}$$

$$<2^+_{cl}||E2||2^+_{cl}> \simeq -15 \text{ efm}^2 \rightarrow Q \rightarrow Q_0 = -\frac{7}{2}Q \rightarrow d \simeq 2 \text{ fm}$$

Not so much unreasonable ….($R_0(^{32}S) = 4.2$ fm)

# Systematics of level energies and $B(E2,2^+_1 \rightarrow 0^+_1)$ in even-even S isotopes



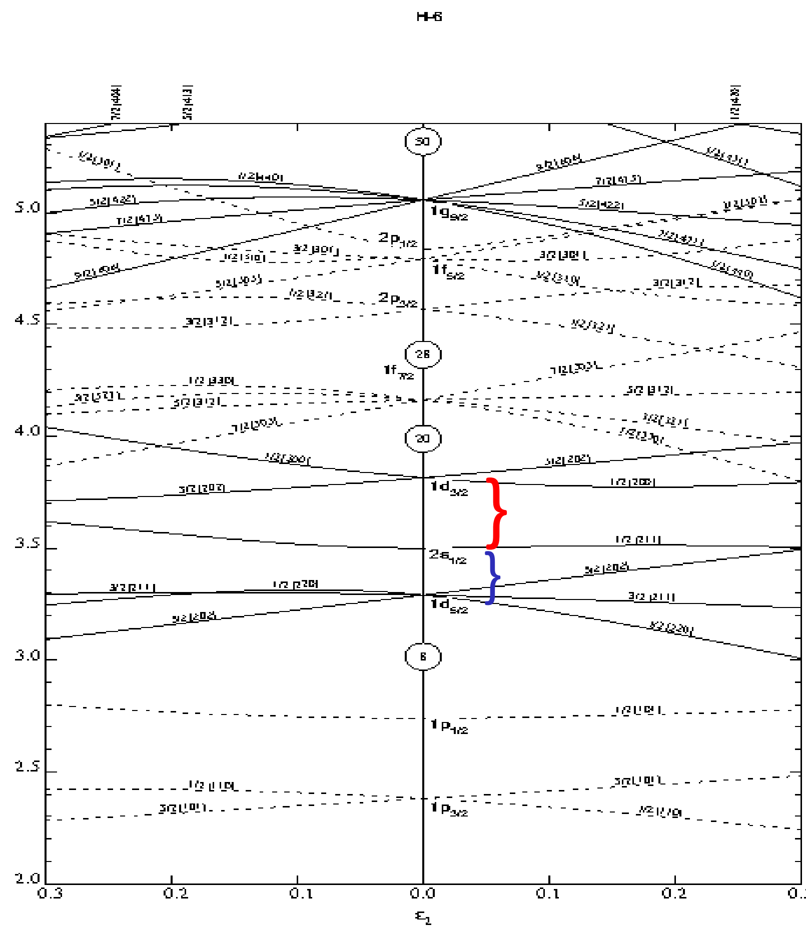




Figure 4. Nilsson diagram for protons or neutrons, Z or N ≤ 50 ($\varepsilon_4 = 0$).

# Plan for future investigations

| | ${}^{8}_{4}\mathrm{Be}_{4}$ | ${}^{16}_{8}\mathrm{O}_{8}$ | ${}^{32}_{16}\mathrm{S}_{16}$ | ${}^{80}_{40}\mathrm{Zr}_{40}$ |
|---|---|---|---|---|
| | ↑ | ↑ | ↑ | ↑ |
| | 2x ${}^{4}_{2}\mathrm{He}_{2}$ | 2x ${}^{8}_{4}\mathrm{Be}_{4}$ | 2x ${}^{16}_{8}\mathrm{O}_{8}$ | 2x ${}^{40}_{20}\mathrm{Ca}_{20}$ |
| $E(2^+_1)$ [MeV] | 3.03 | 6.92 | 2.23 | 0.29 |
| $E(0^+_1)$ [MeV] | 20.20 | 6.05 (lowest excited state) | 3.78 | - |
| $E(4^+_1)$ [MeV] | 11.35 | 10.36 | 4.46 | 0.83 |
| | unstable | stable | stable | unstable |

# Study of $^{80}Zr$

- Nucleus of general importance

  - Waiting-point (N=Z) in the rp-process of nucleosynthesis

  - x-ray burst simulations

- Previous experimental study by C.J.Lister et al. , PRL59(1987)1278

  - Yrast γ's in $^{24}Mg(^{58}Ni, 2n\gamma)$ at 190 MeV

  - $E(2_1^+)$ , $E(4_1^+)$ $\rightarrow \beta \sim 0.4$

  - Interpretation as superdeformation by D.C. Zheng and L.Zamick, PLB 266(1991)5

  - Lifetimes, extensions of the level scheme planned

# Conclusions

Interesting (sometimes crucial) nuclear structure information can be obtained by measuring lifetimes and comparing experimental and theoretical transition matrix elements

Large scale clustering, especially the one involving magic clusters, may lead to a new type collective motion (relative displacement/vibrations) at relatively lower excitation energy

This effect was shown to be a possible origin of the enhanced quadrupole collectivity in $^{32}S$ within some correlation with filling of subshells i.e. single particle properties

Further investigations are in progress

**Thank you very much for your attention!**

Special thanks to Alain Astier, Marie-Genevieve Porquet, Peter Schuck, Jan Jolie, Milena Stoyanova and Orlin Yordanov.