PARIS Collaboration Meeting INFN LNL, 28-29 Nov 2019

Investigation of a high spin structure in nuclei near ^{40}Ca via discrete and continuum γ spectroscopy with PARIS+AGATA arrays and ancillary detectors (RFD+EUCLIDES)

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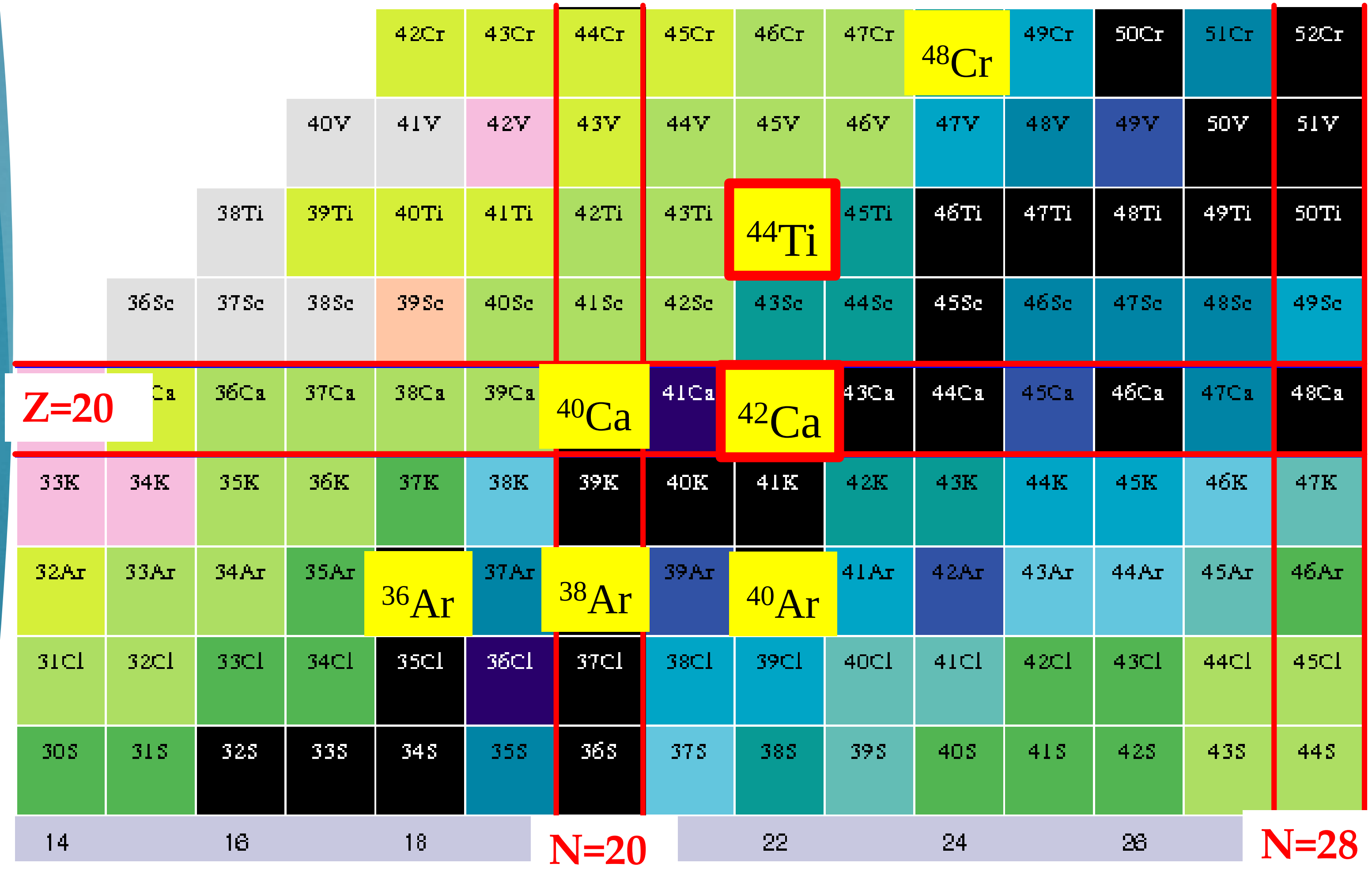
THE HENRYK NIEWODNICZAŃSKI
INSTITUTE OF NUCLEAR PHYSICS
POLISH ACADEMY OF SCIENCES

Region of interest

- The most deformed nucleus at low excitation energy is ^{48}Cr
- Superdeformation in ^{36,38,40}Ar, ^{40,42}Ca and ^{44}Ti
- ^{42}Ca and ^{44}Ti are studied in different Theory Models/Approaches
- LSSM calculations get in general very good agreement with experimental data
- Cluster (α clustering) and molecular
- ^{44}Ti is described as ^{40}Ca+alpha
- SD band in ^{40}Ca corresponds to a ^{28}Si+^{12}C
- excitation in ^{44}Ti may be associated with a ^{28}Si+^{16}O cluster
- Open question whether the Jacobi shape transition is a general phenomenon in light mass nuclei



High Spin deformed bands close to ^{40}Ca

Covariant Density Functional Theory (CDFT)

deformed „cluster states" are favoured at high spin

A. V. Afanasjev, H. Abusara, PRC 97, 024329 (2018)
D. Ray and A. V. Afanasjev, PRC 94, 014310 (2016)

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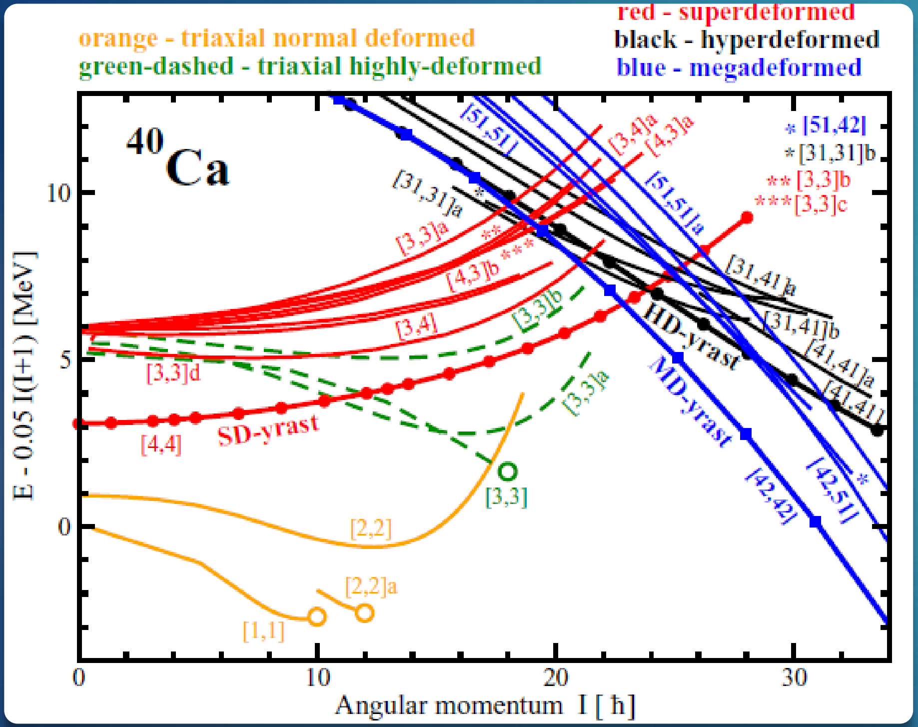

Energies of the calculated configurations

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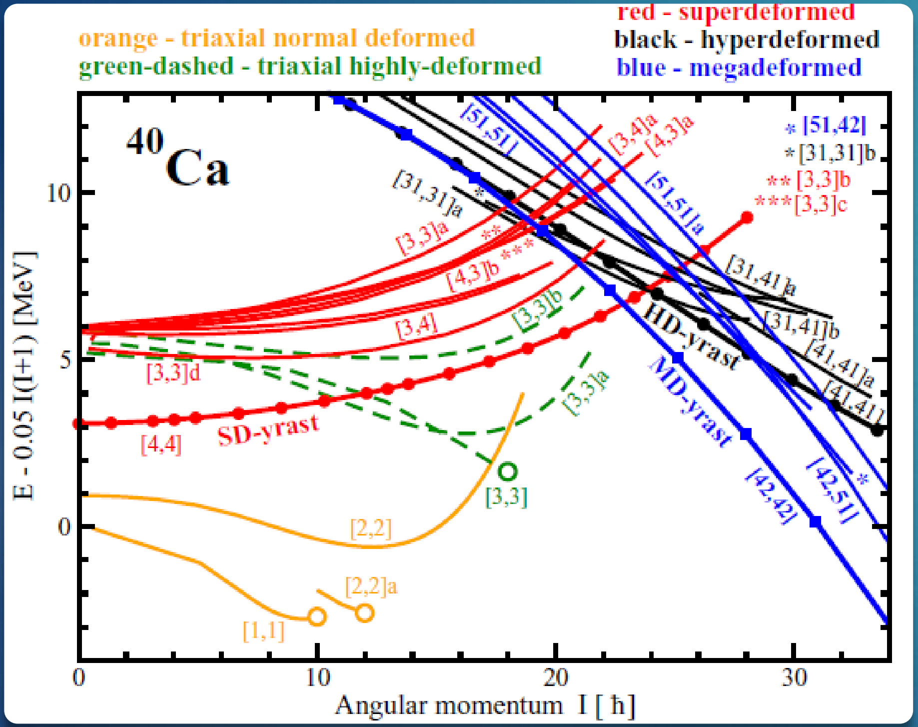

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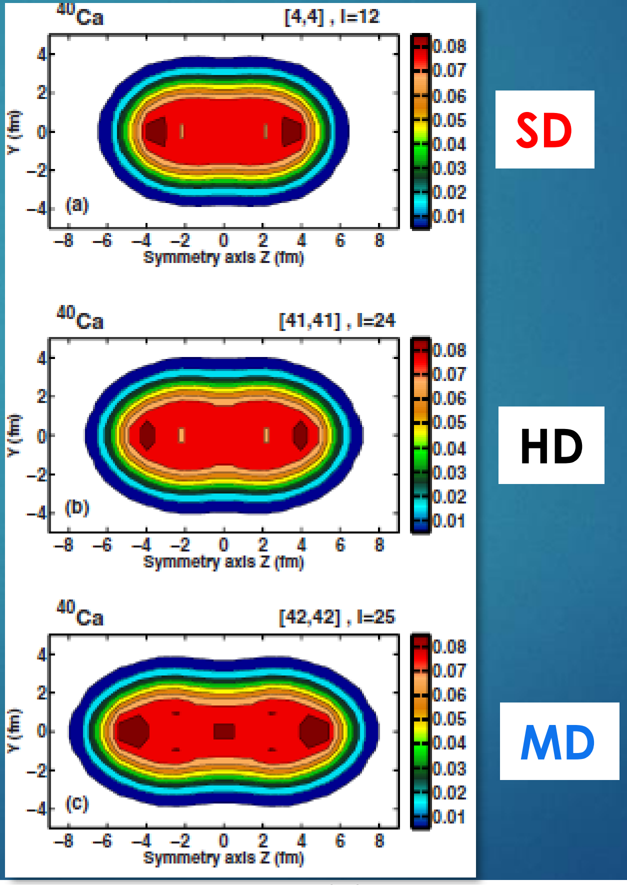

proton densities

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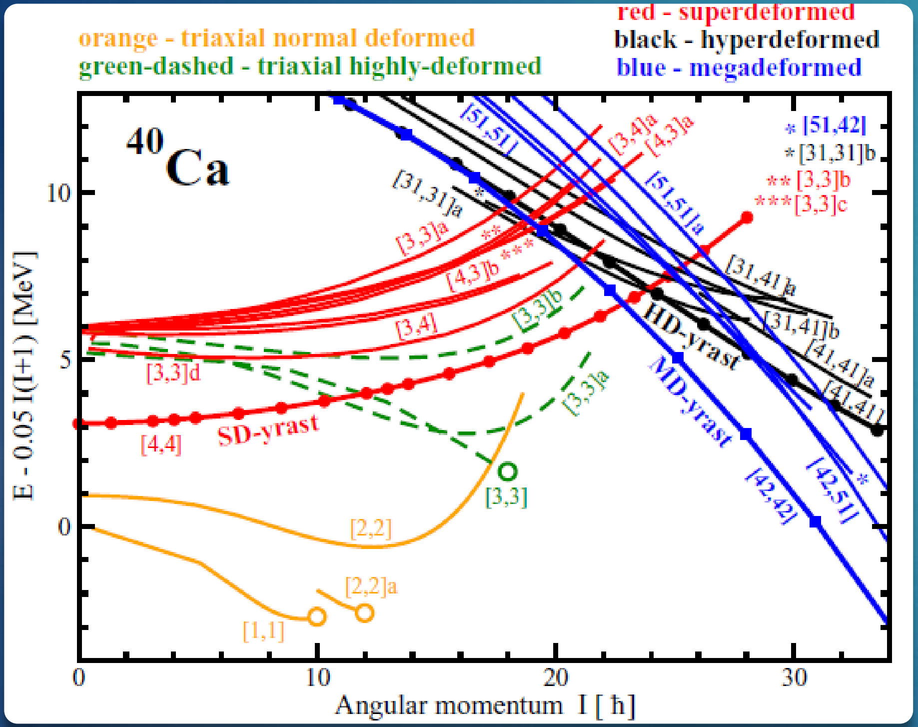

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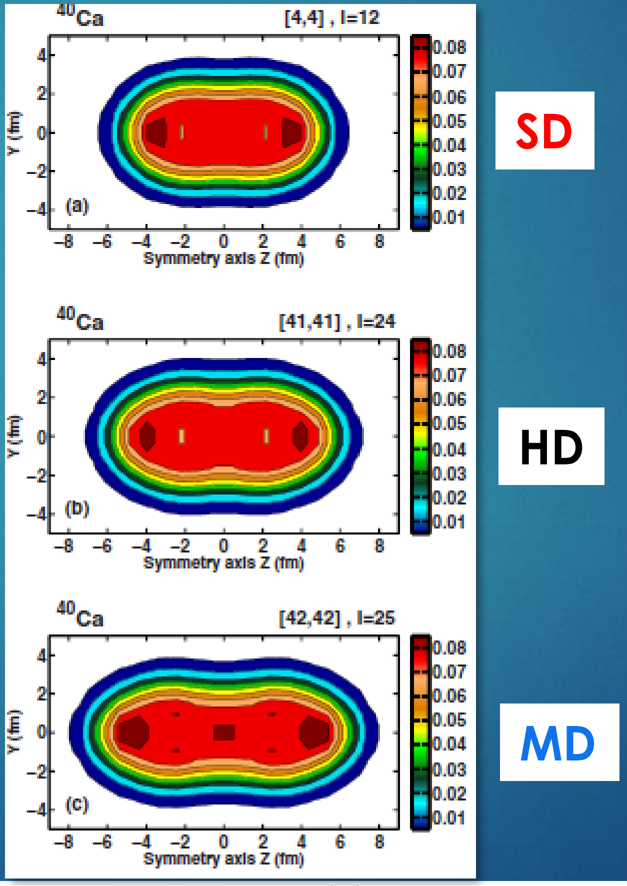

proton densities

The advantage of the CDFT is the fact that it **does not assume** the existence of cluster structures – formation of cluster structures results from microscopic single-nucleon degrees of freedom via many-body correlation.

PHYSICAL REVIEW C **94**, 014310 (2016)

From superdeformation to extreme deformation and clusterization in the $N \approx Z$ nuclei of the $A \approx 40$ mass region

D. Ray and A. V. Afanasjev
Department of Physics and Astronomy, Mississippi State University, Mississippi 39762, USA
(Received 20 April 2016; revised manuscript received 4 June 2016; published 14 July 2016)

A systematic search for extremely deformed structures in the $N \approx Z$ nuclei of the $A \approx 40$ mass region has been performed for the first time in the framework of covariant density functional theory. At spin zero such structures are located at high excitation energies, which prevents their experimental observation. The rotation acts as a tool to bring these exotic shapes to the yrast line or its vicinity so that their observation could become possible with future generation of γ-tracking (or similar) detectors such as GRETA and AGATA. The major physical observables of such structures (such as transition quadrupole moments, as well as kinematic and dynamic moments of inertia), the underlying single-particle structure and the spins at which they become yrast or near yrast, are defined. The search for the fingerprints of clusterization and molecular structures is performed and the configurations with such features are discussed. The best candidates for observation of extremely deformed structures are identified. For several nuclei in this study (such as ^{36}Ar), the addition of several spin units above the currently measured maximum spin of $16\hbar$ will inevitably trigger the transition to hyper- and megadeformed nuclear shapes.

DOI: 10.1103/PhysRevC.94.014310

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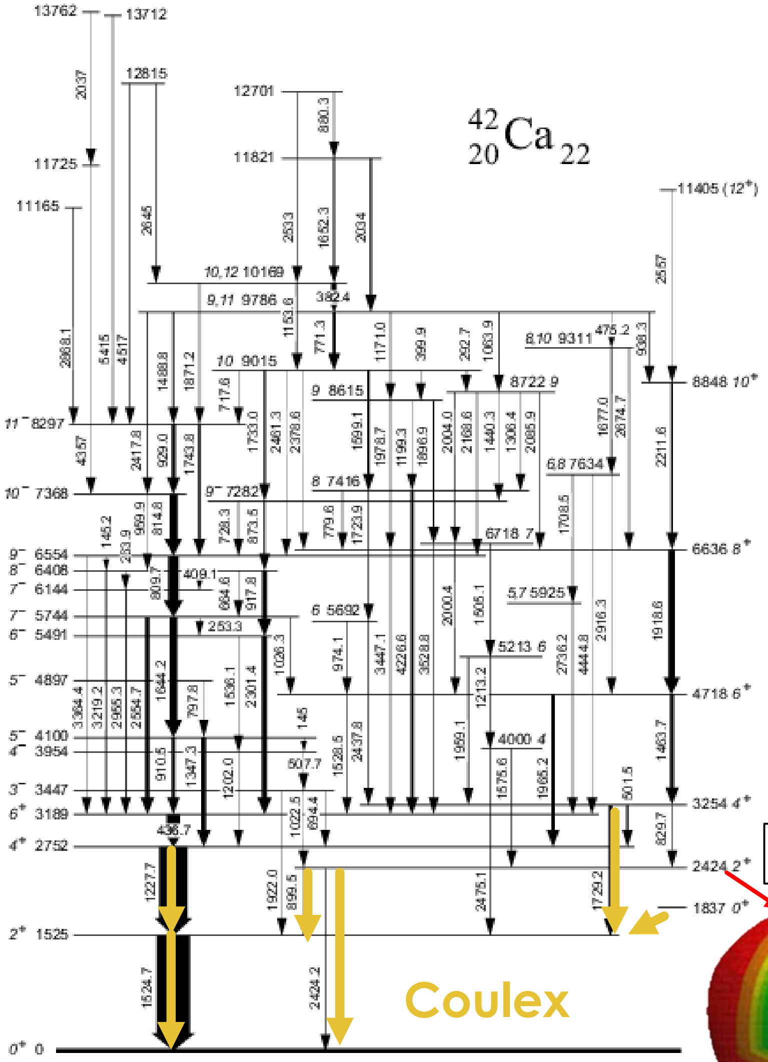
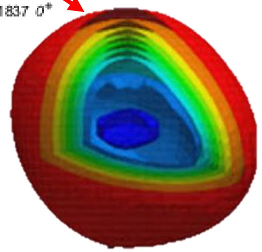
^{42}Ca

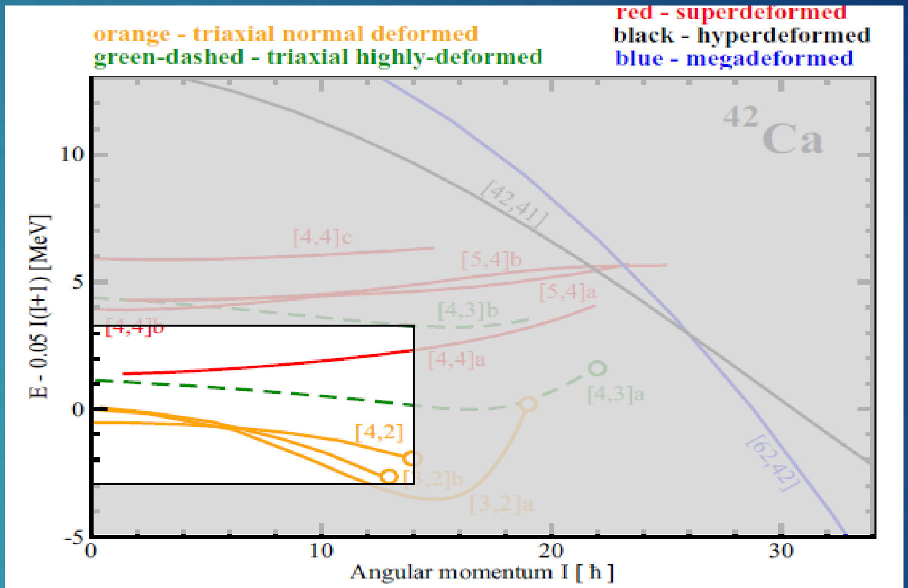


M. Lach et al., Eur Phys J. A **16**, 309 (2003).

β_2=0.43(4), γ=13(+5,−6)°



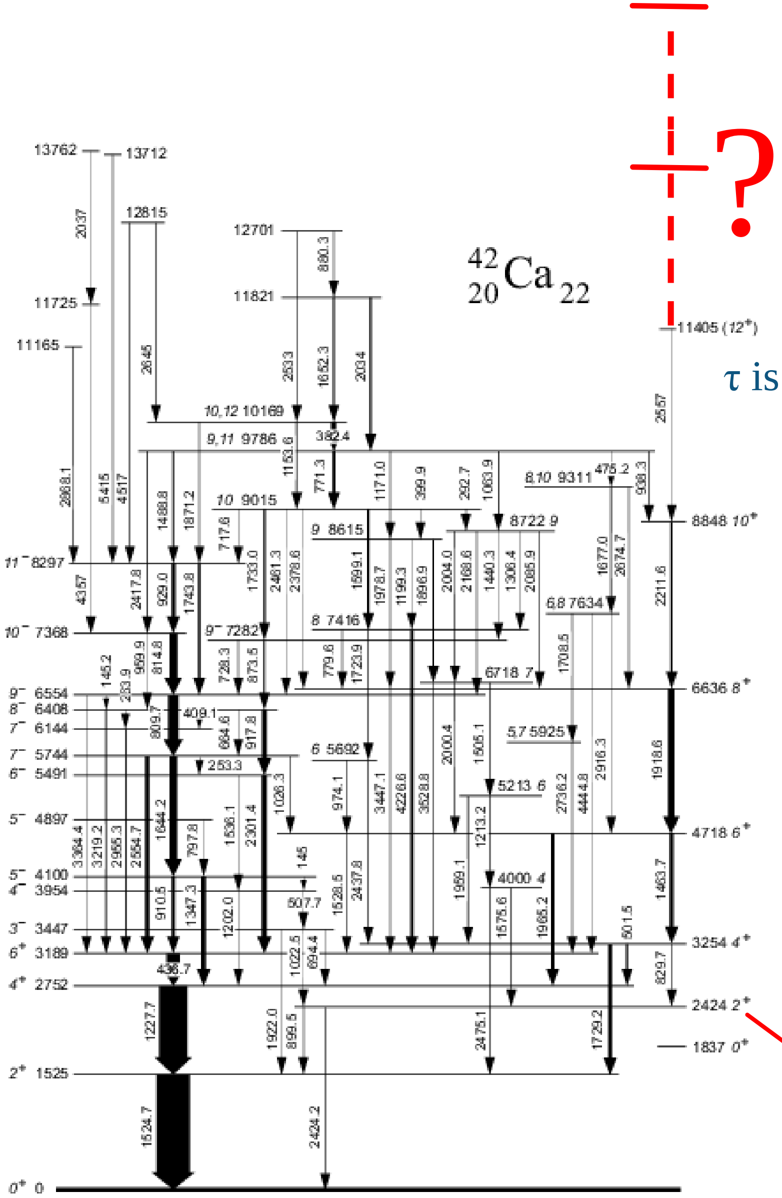
K. Hadyńska-Klęk et al, Phys. Rev. Lett. **117**, 062501 (2016)

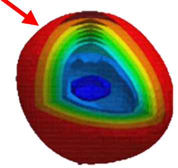


D. Ray and A.V.Afanasjev Phys. Rev. C 94, 014310 (2016)

- Recent covariant density functional theory(CDFT) calculations, energies of the calculated configurations relative to liquid drop reference
- From the Coulomb-excitation experiment - triaxial shape of the band head (2^+_2 state) was determined: β = 0.43(2) and γ = 13(+5, -6).

^{42}Ca





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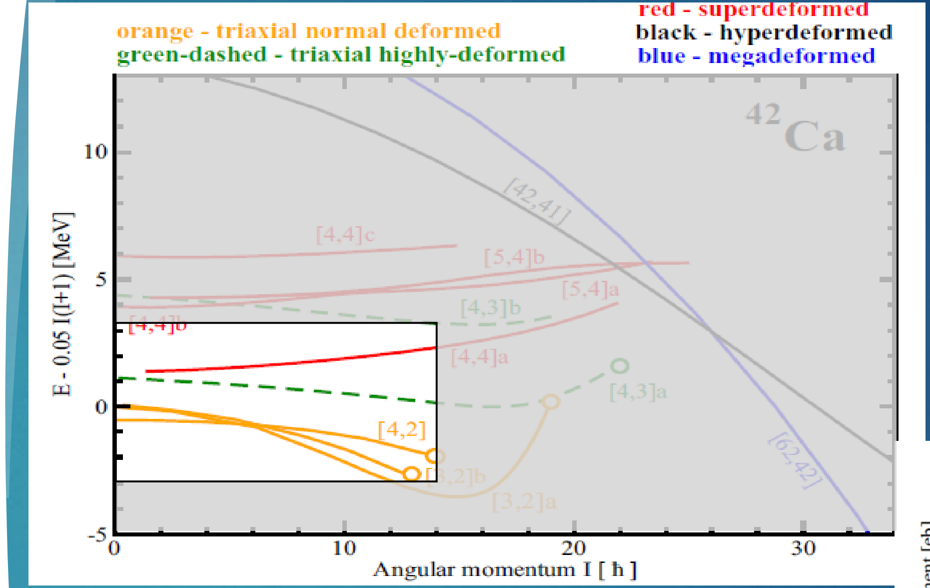

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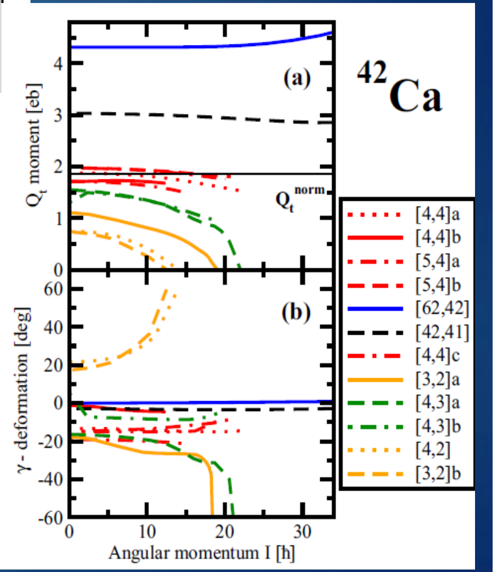
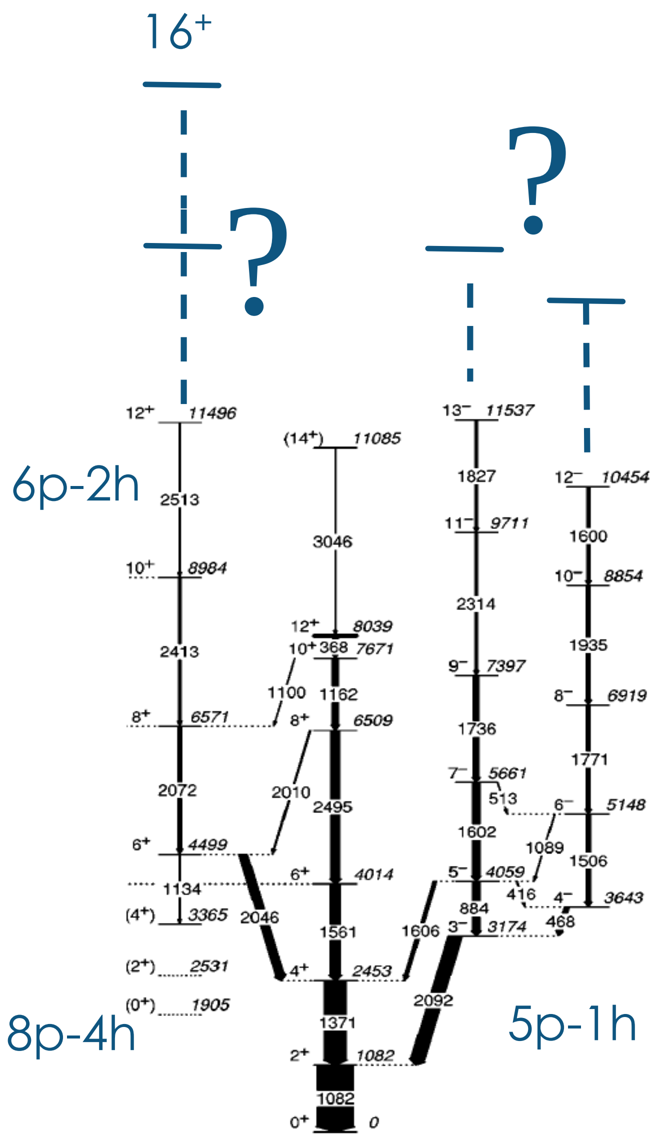


- Investigate ^{42}Ca at high spins, in order to extend known structures and/or look for other candidates
- Estimate lifetimes -> deformation and Q_t

K. Hadyńska-Klęk et al, Phys. Rev. Lett. **117**, 062501 (2016)

^{44}Ti – shell model and CDFT

- df-valence space calculations works very well
- mixture of p-h cof.
- with Jmax=16 – not observed so far



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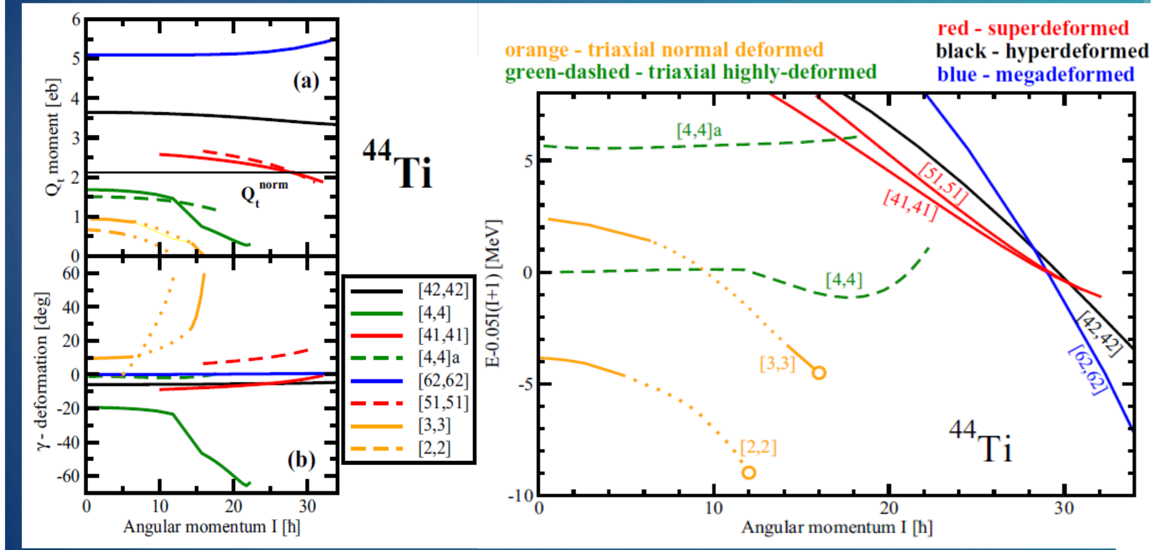

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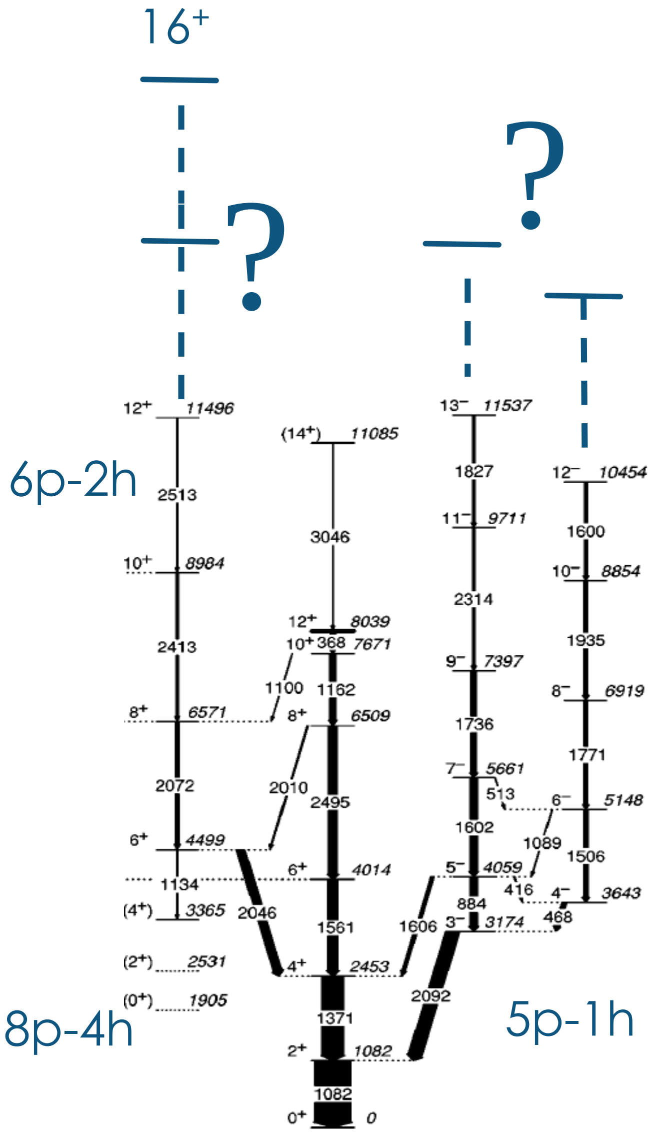

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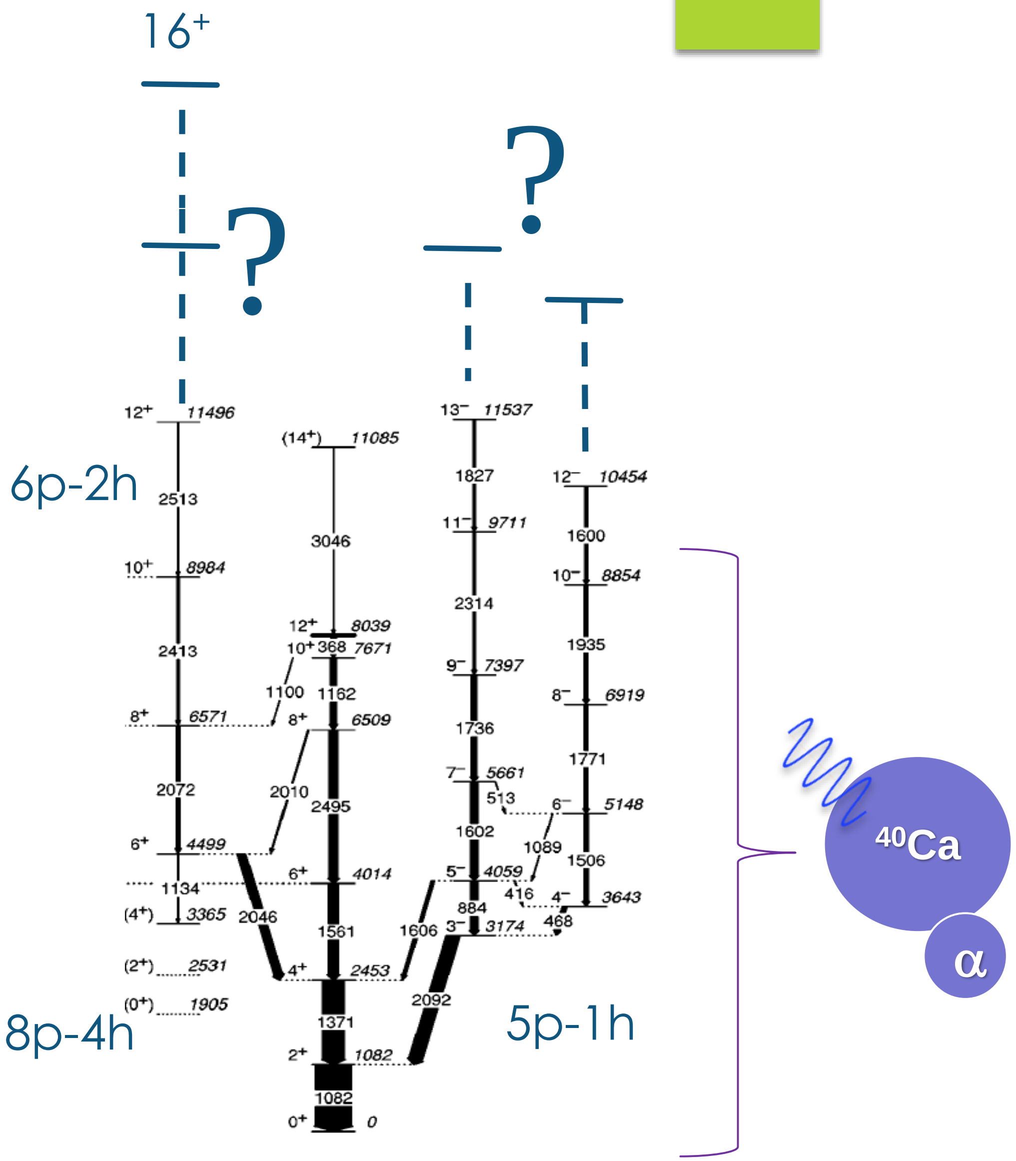
^{44}Ti – cluster/ molecular approach



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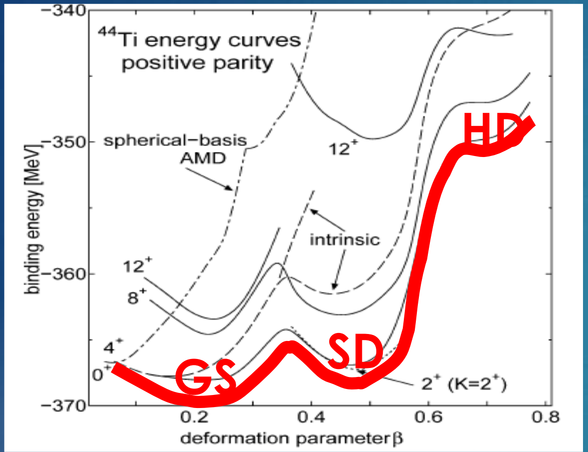
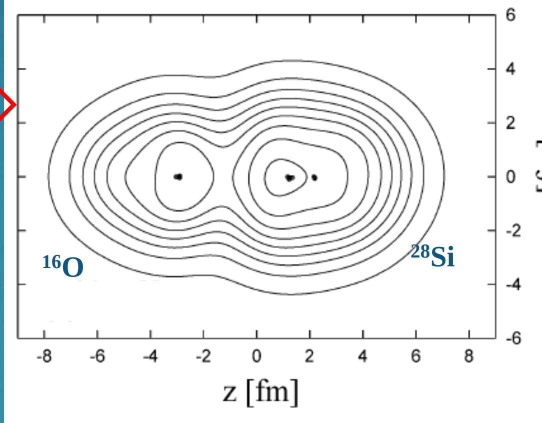
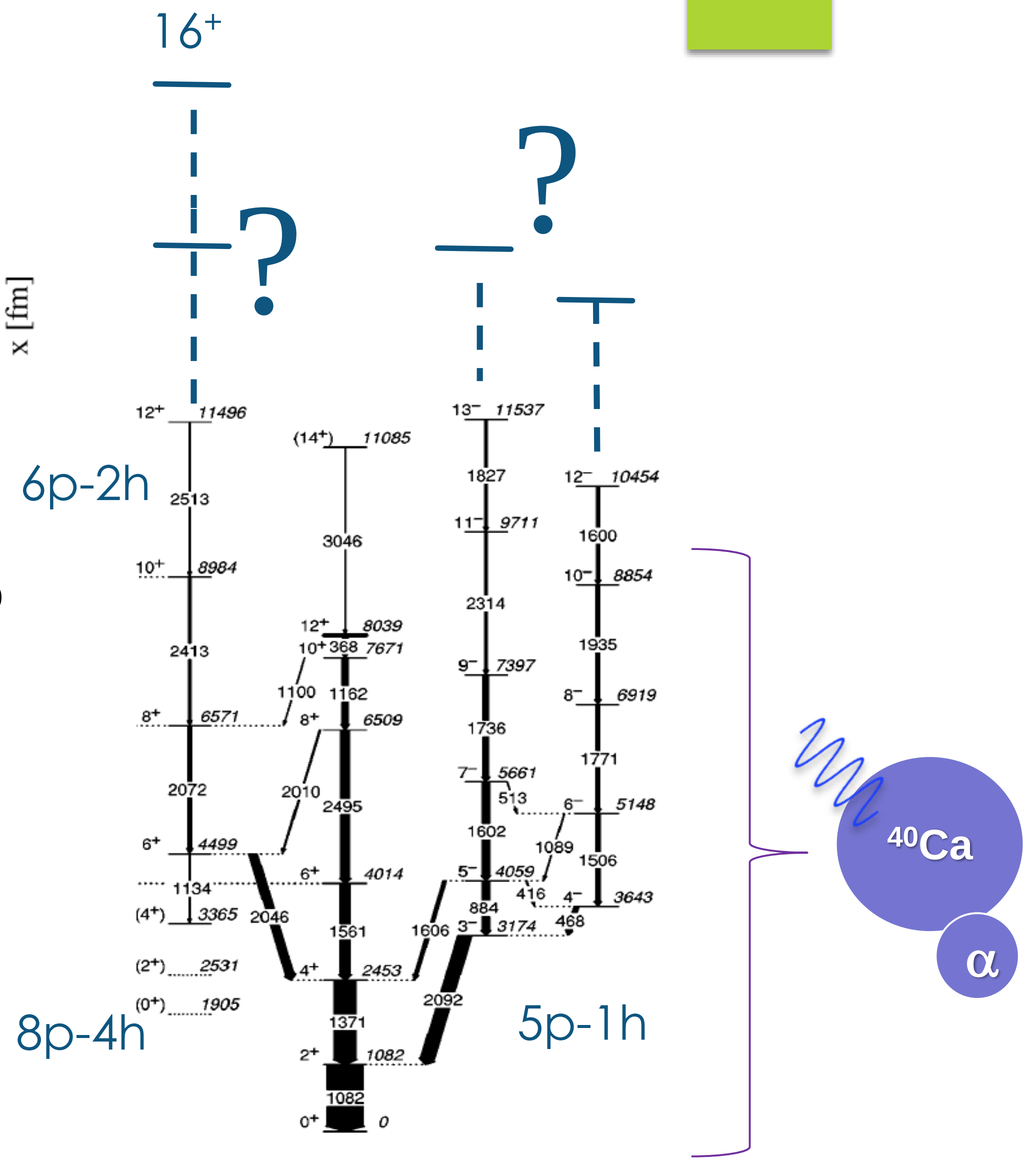


Predicted at high E*



M.Kimura, H.Horiuchi NPA 767 58 (2006)



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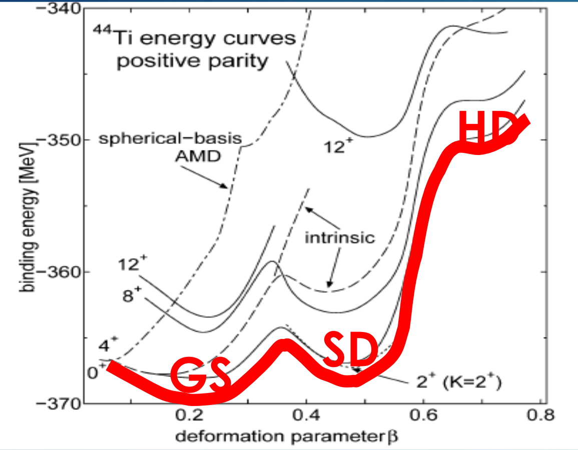

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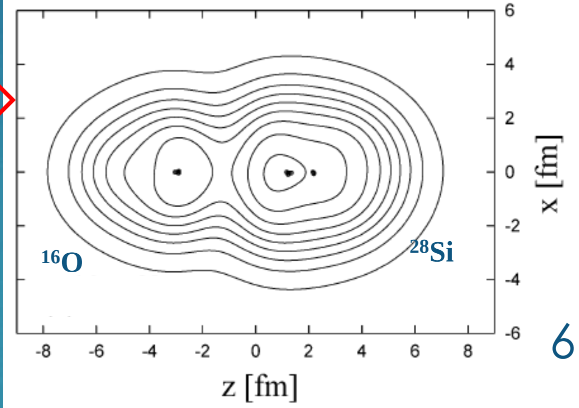

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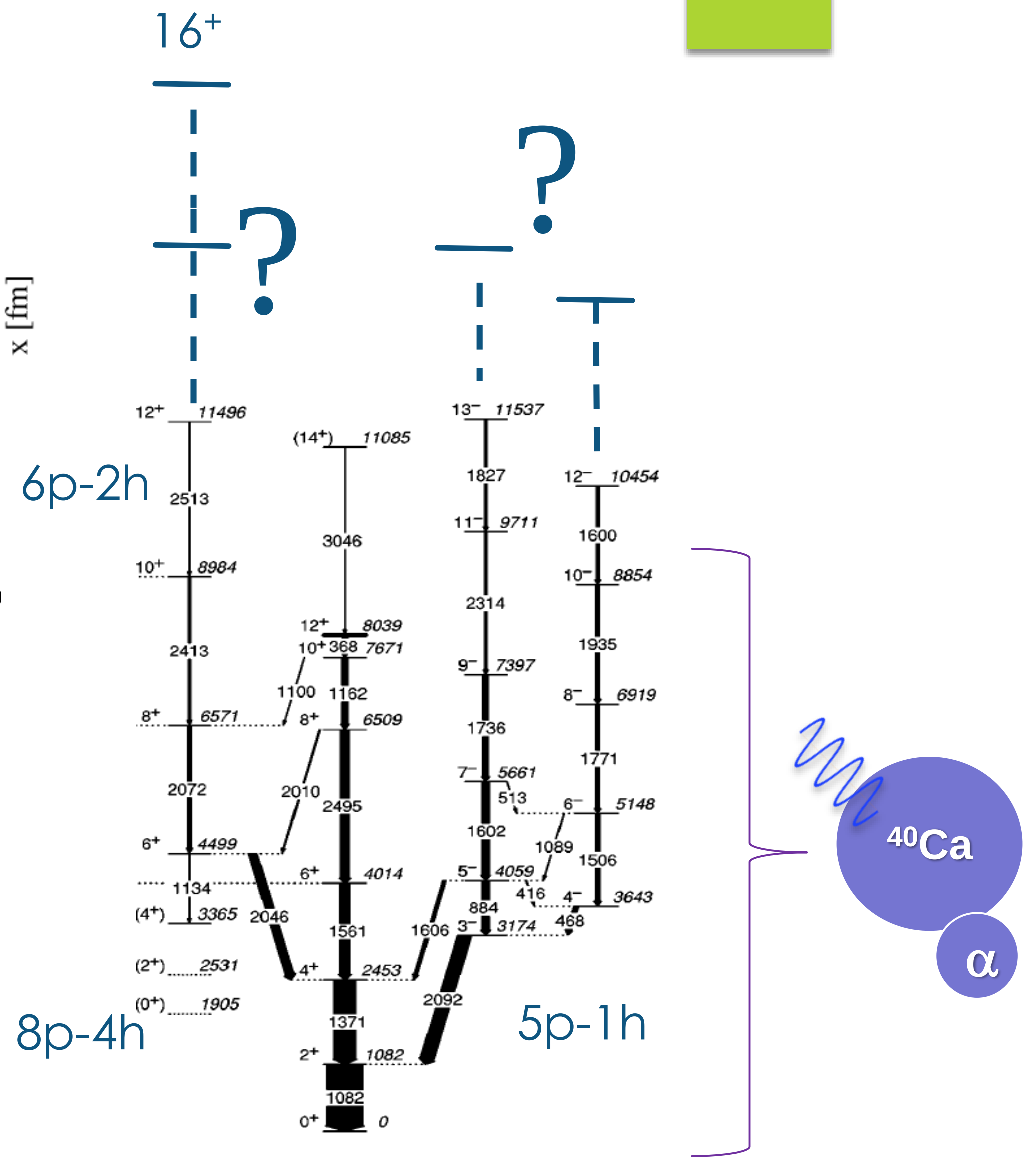

- Investigate ^{44}Ti at high spins, in order to extend the known and unknown structures up to or beyond the terminating states,
- Estimate the lifetimes -> deformation and Q_t
- Compare any new structures with calculations.

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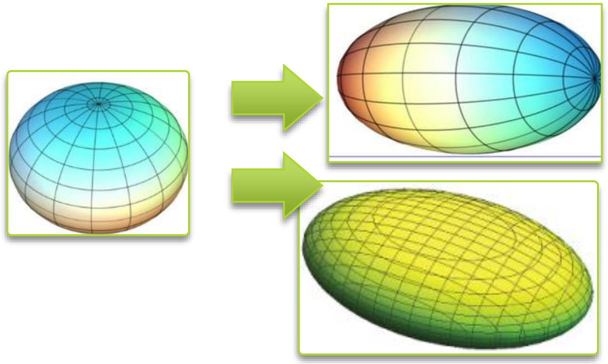
Jacobi shape transition

- In 1834 C.G.J. Jacobi made a discovery that: at certain critical angular momentum, shape of gravitating mass (stars) rotating synchonously changes abruptly from **noncollective oblate** to **collective triaxial** or **prolate** rotating around its shortest axis



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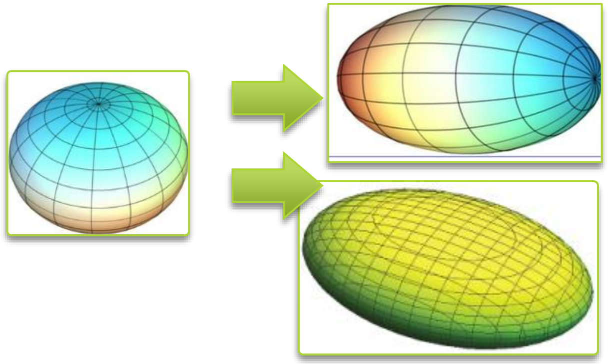
- For spin close to the fission limit and with axis ratio **(2:1)**



- In light and medium mass nuclei -- high rotational frequencies are achieved before the excited nucleus undergo fission
- The GDR γ ray emission occurs at the early stage of CN decay and can probe the nuclear shape

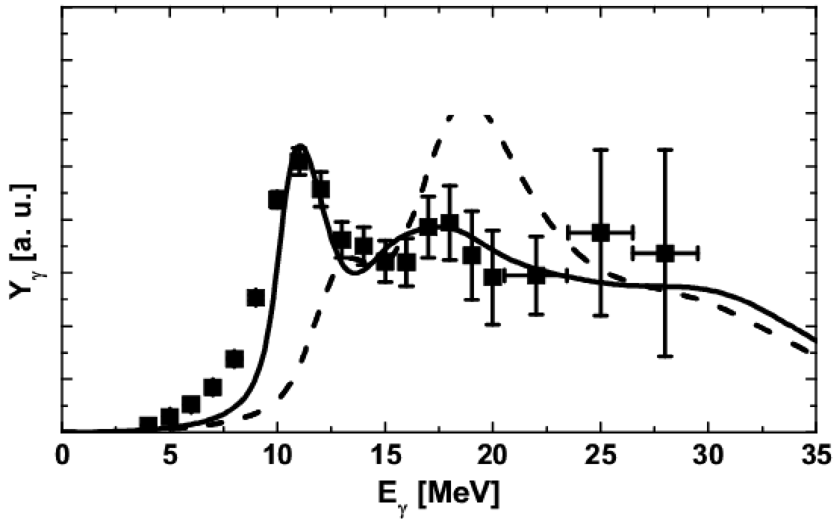
- In the A~40 region: experimentally studied in
  - ^{45}Sc (M. Kicińska-Habior et al. Phys. Lett. B. 308, 225 (1993)
  - ^{46}Ti (A. Maj and M. Kmiecik)
- Theoretically in ^{44}Ti -- G. Shanmugam et al., PRC 63, 064311(2001)

Jacobi shape transition in ^{46}Ti

- The GDR strength function splits into multiple components with a narrow well-separated peak around 8 -10 MeV - - **which is a signature of Jacobi transition**

- It is expected that Jacobi shape transition should be a common feature over a wide range of nuclei

105 MeV $^{18}O + ^{28}Si \Rightarrow ^{46}Ti^*$



EUROBALL + HECTOR

A.Maj et al., N.Phys. A731, 319 (2004)

M. Kmiecik et al., Acta Phys. Pol. B36 1169 (2005)

Jacobi shape transition in ^{46}Ti

^{42}Ca ← 2p2n — ^{46}Ti

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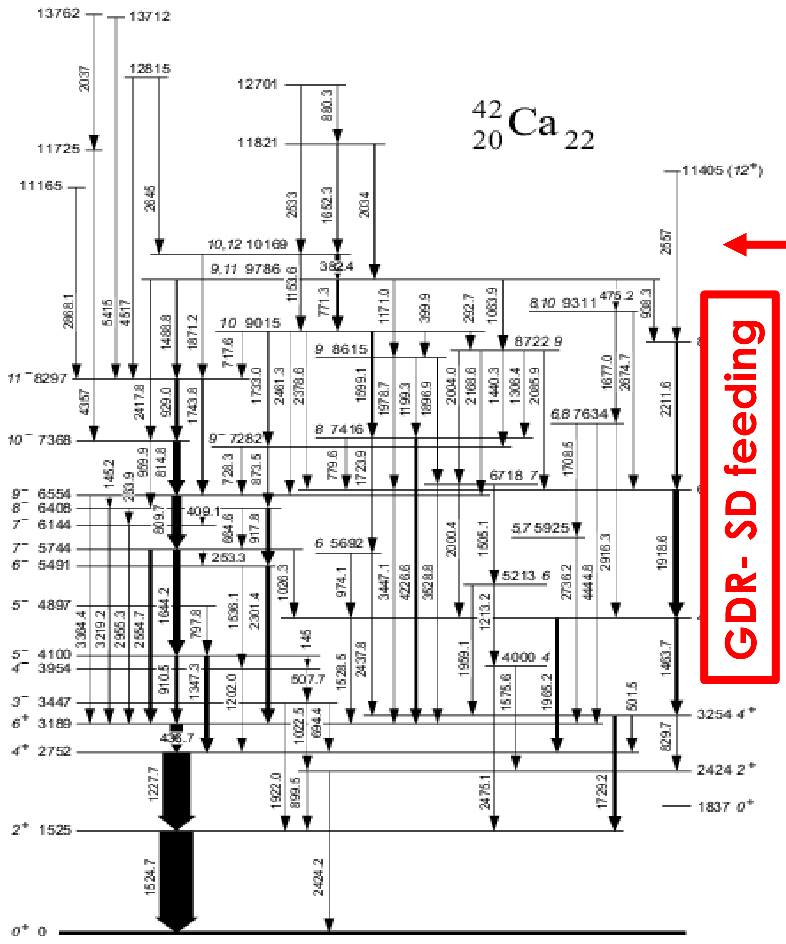
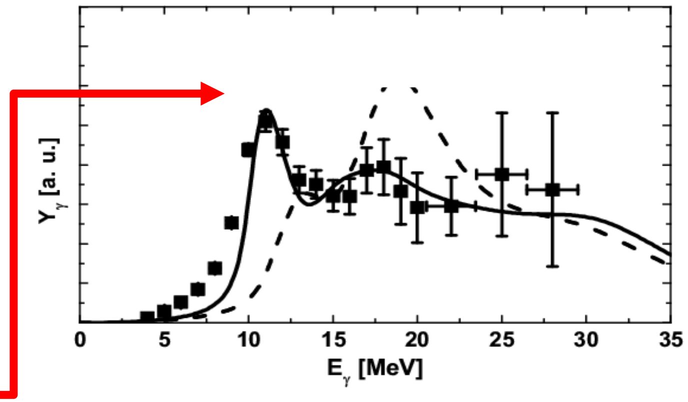
- It is expected that Jacobi shape transition should be a common feature over a wide range of nuclei
- The low energy GDR component ~10MeV seems to feed preferentially the highly-deformed band in ^{42}Ca
- Link between deformed states (resonances) in a hot CN and yrast SD in a cold ER



M. Lach et al., Eur Phys J. A12, 381 (2001)



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Proposed Experiment I (GANIL)

- „Investigation of a high spin structure in ^{44}Ti via discrete and continuum γ spectroscopy with AGATA, PARIS and DIAMANT at GANIL"
- Approved by the GANIL PAC in 2015 (postponed in 2018, not yet performed...)

Proposed Experiment II (LNL)

- Investigation of a high spin structure in nuclei near ^{40}Ca via discrete and continuum γ spectroscopy with PARIS+AGATA arrays and ancillary detectors (RFD+EUCLIDES)"
- AGATA@LNL will be opportunity to perform such measurement with better selectivity and efficiency, more PARIS clusters and ancillary detectors

Concept of the measurement

Fusion-evaporation reaction: 160 MeV ^{24}Mg+ 1mg/cm^{2} ^{28}Si

Gamma rays in coincidence with recoils and charged particles

AGATA: extension/termination of rotational bands discrete γ-rays, angular sensitivity,

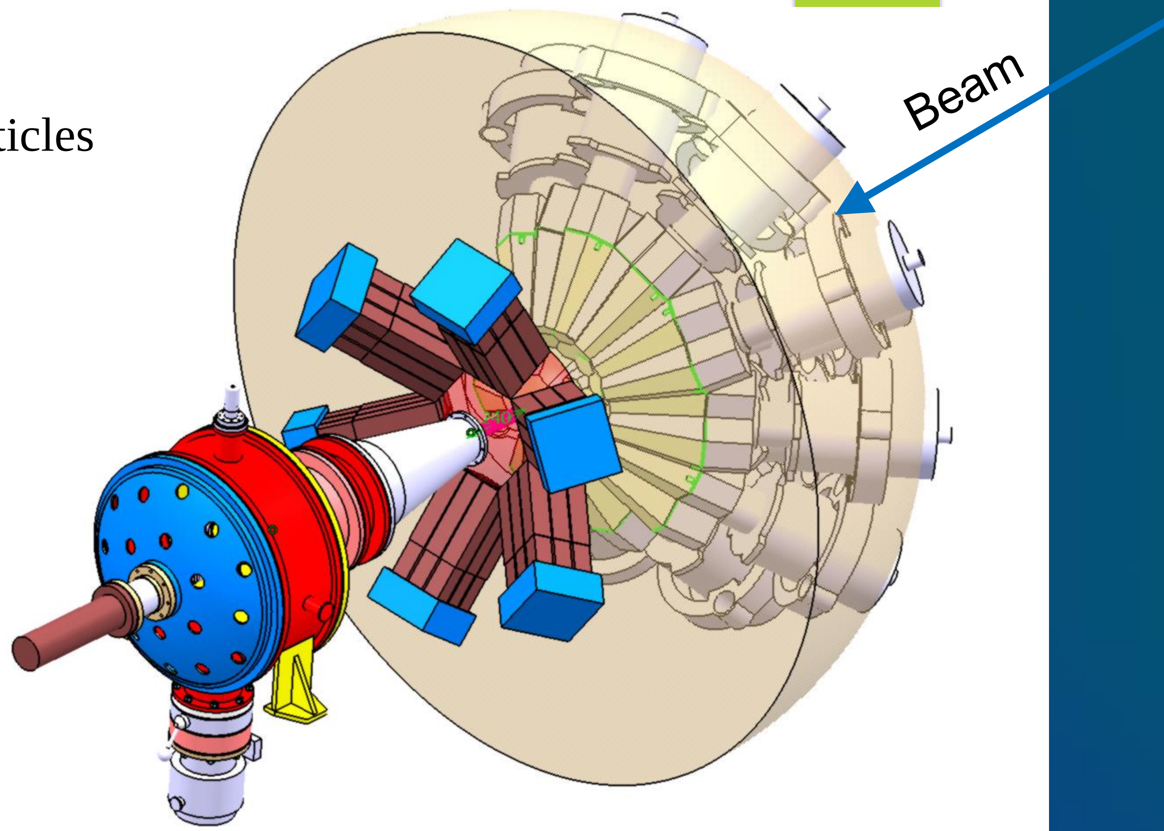
PARIS: SD band feeding by high energy γ-rays (>5MeV) (E1, GDR)

RFD: recoil filter detector (18 elements)

- Precise Doppler correction (v/c ~ 6%)
- Lifetime estimation

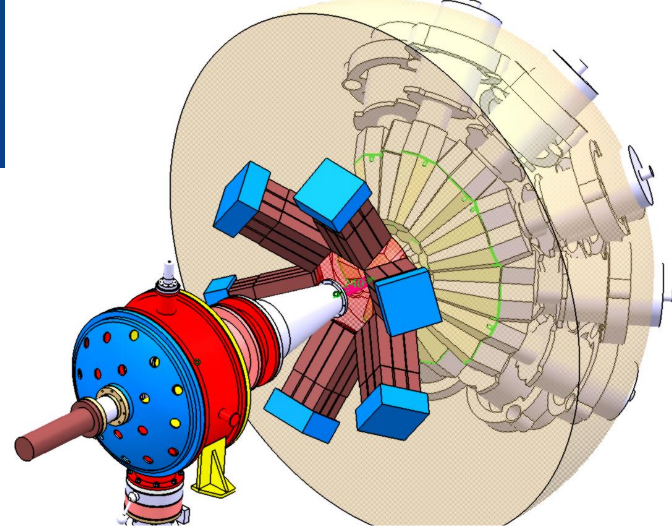
EUCLIDES: light charge particle detector (α,p...)

- Reaction channel selection
- γ–α correlations



- **AGATA $\leq 2\pi$**
- **PARIS - 6 Clusters @ 60°**
- **RFD (2^{o}--7^{o})**
- **EUCLIDES**

Concept of the measurement



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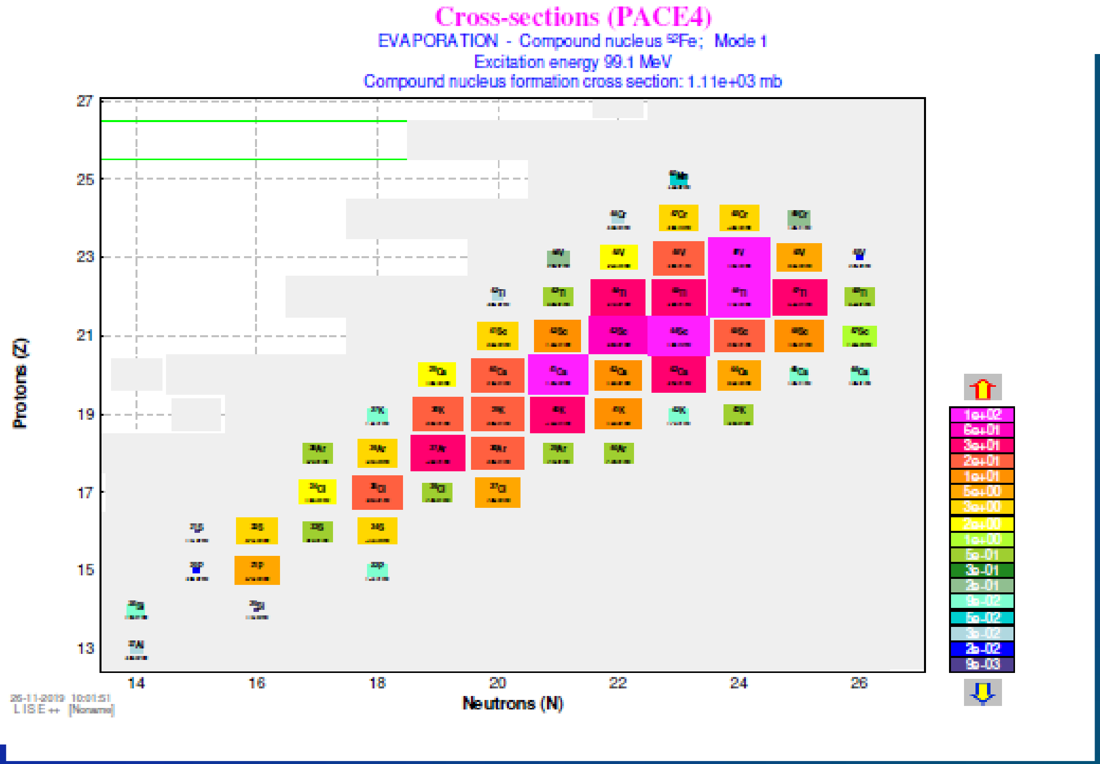

Lifetime measurements of short-lived excited states in A~70 nuclei at LNL

A.M. Bruce, *et al.*, Phys. Rev. C 62, 027303 (2000)

SD structures were predicted for ^{69}As

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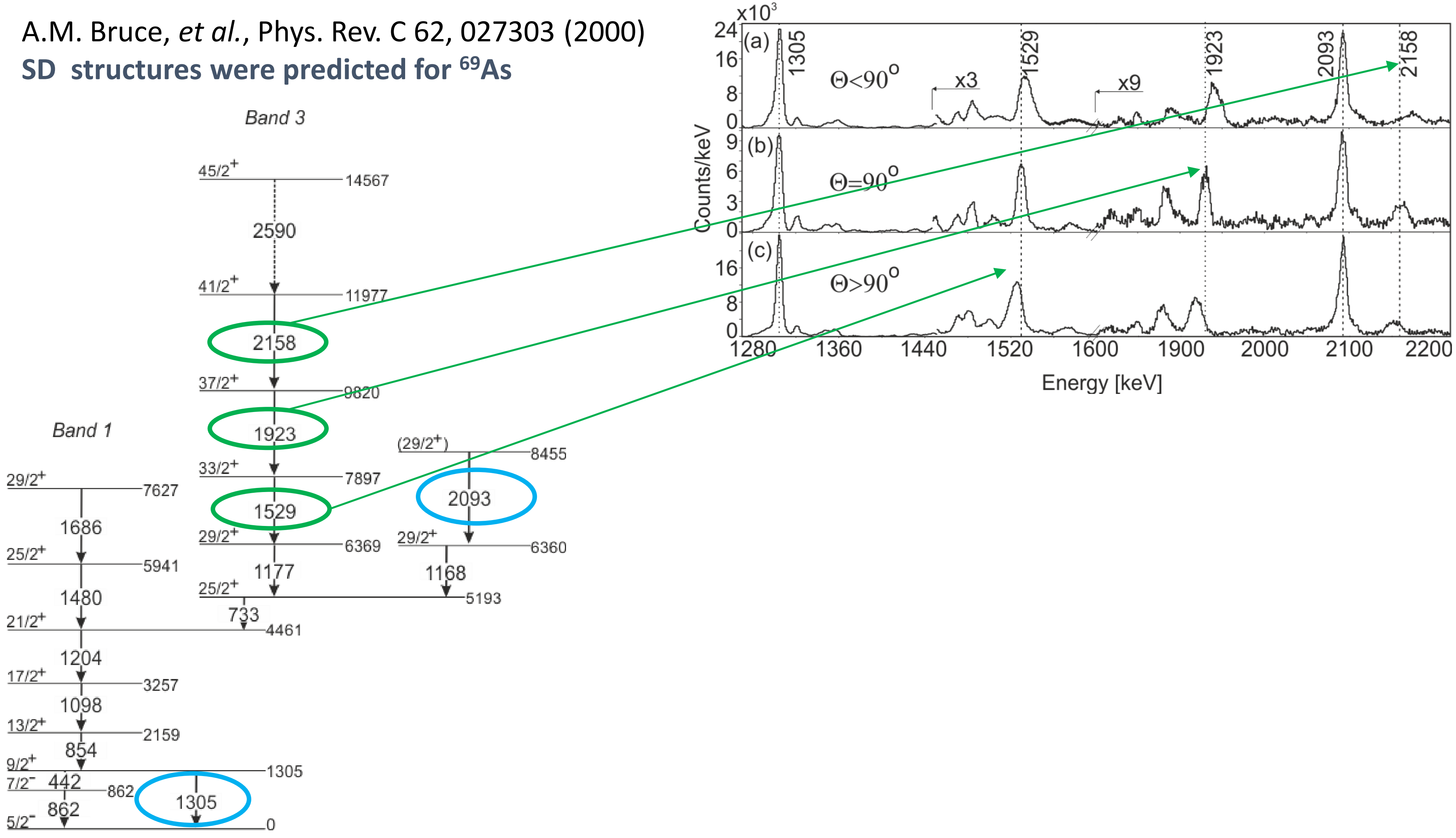

Partial level scheme of ^{69}As obtained in the GASP+RFD.

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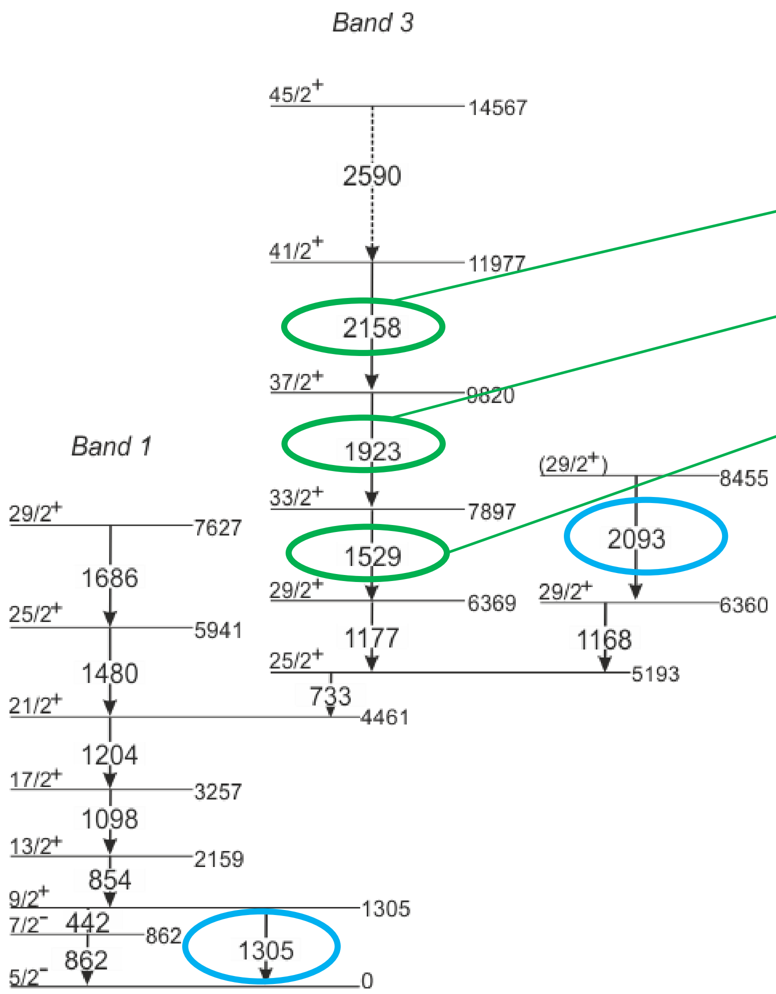

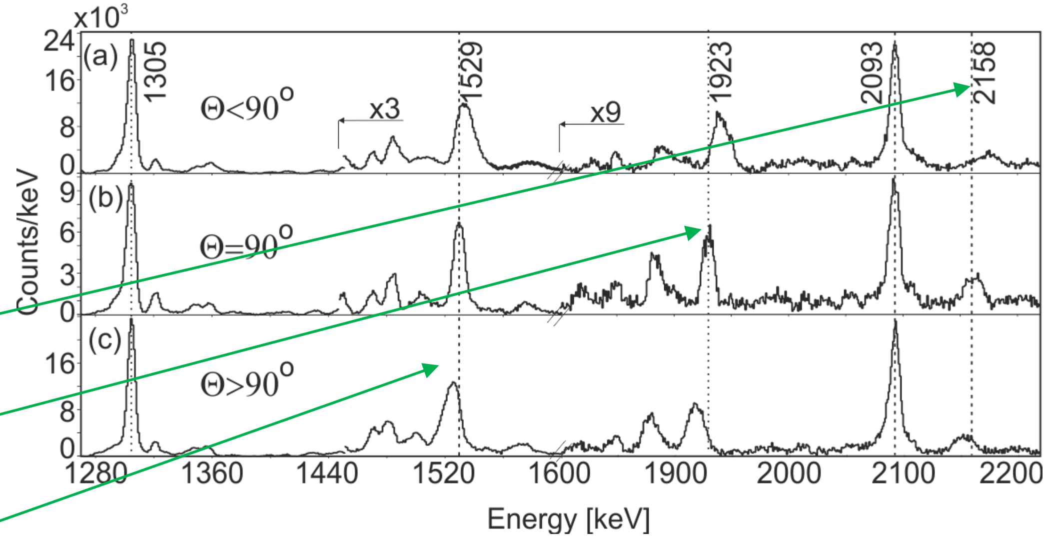

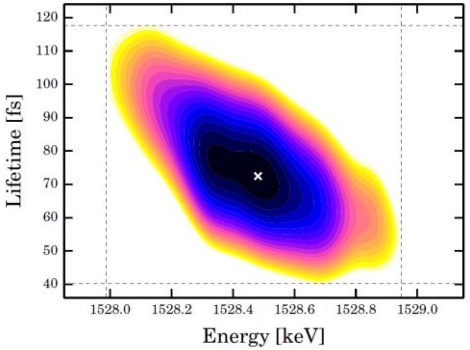

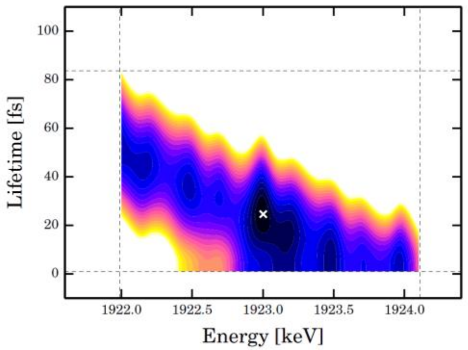

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E = 1528.5 (-0.5, +0.4) keV

τ < 85 fs

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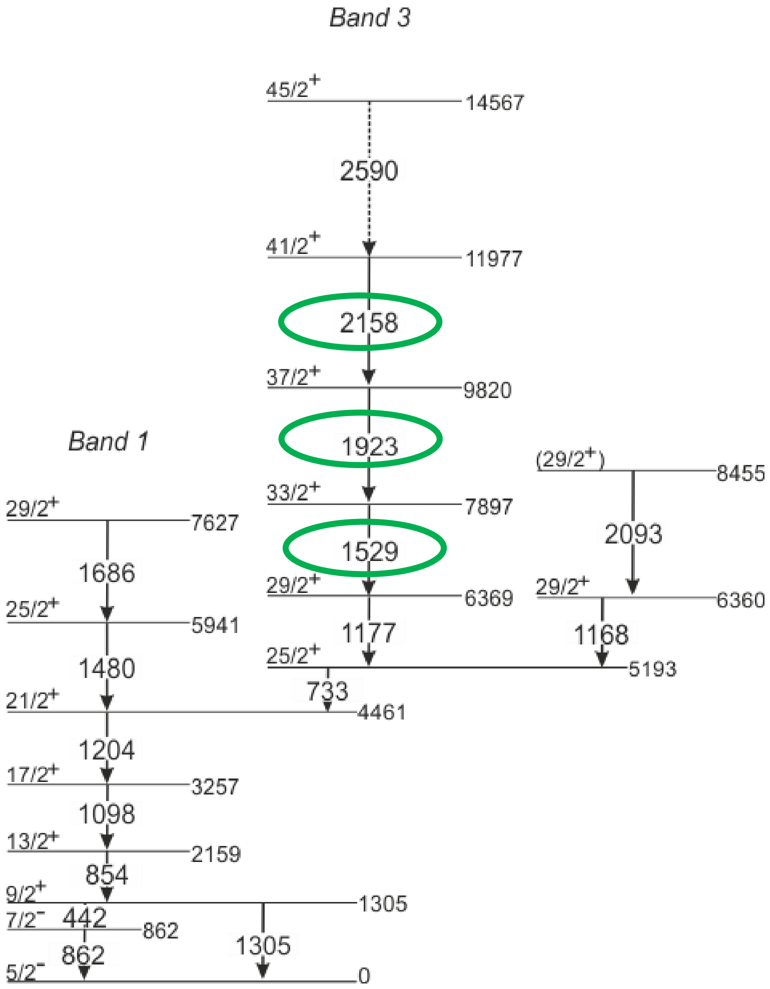

M. Matejska-Minda et. al, PRC 100, 054330 (2019)

Theoretical			Experimental		
ħω [MeV]	(β_2, γ)	Q_t [eb]	ħω [MeV]	E_γ [MeV]	$\lvert Q_t$ (K=3/2)$\rvert$ [eb]
0.7	(0.315, 48)	-1.96			
0.8	(0.316, 48)	-1.96	0.76	1528.5	1.99 (-0.43, +0.68)
0.9	(0.268, 20)	1.42	0.96	1923.0	> 1.03
1.0	(0.267, 20)	1.40			

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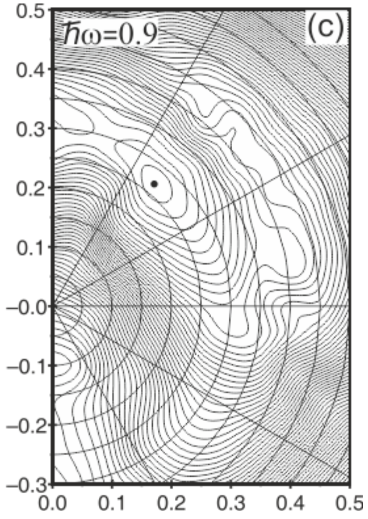

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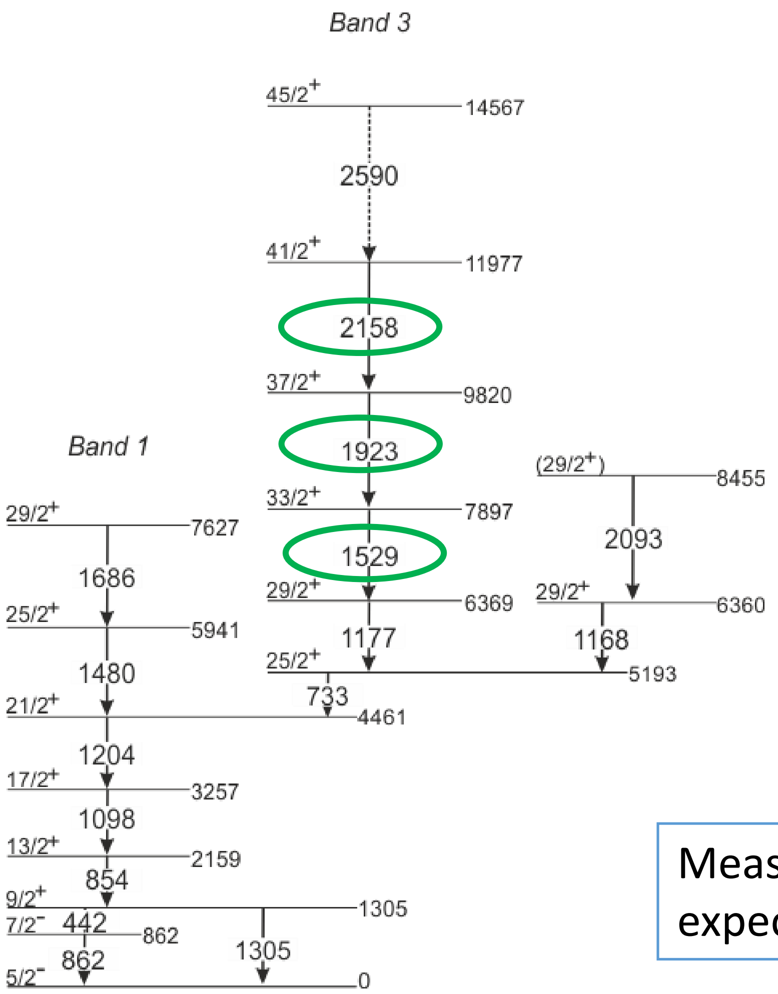

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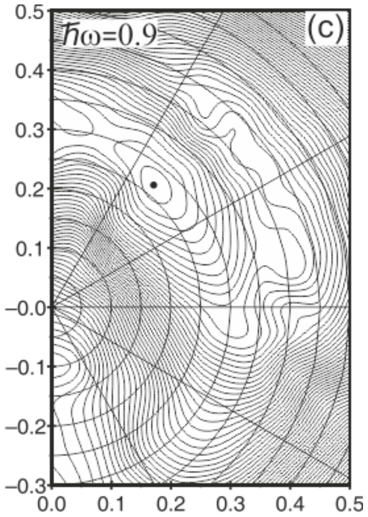
Theoretical			**Experimental**		
ħω [MeV]	(β_2, γ)	Q_t [eb]	ħω [MeV]	E_γ [MeV]	$\lvert Q_t\ (K=3/2)\rvert$ [eb]
0.7	(0.315, 48)	-1.96			
0.8	(0.316, 48)	-1.96	0.76	1528.5	1.99 (-0.43, +0.68)
0.9	(0.268, 20)	1.42	0.96	1923.0	> 1.03
1.0	(0.267, 20)	1.40			

τ = 72 (-32, +45) fs

E = 1528.5 (-0.5, +0.4) keV

τ < 85 fs

E = 1923.0 (-1.0, +1.1) keV



Measurement of very short lifetimes (in fs range) which are expected at high spins might be additional advantage.

Partial level scheme of ^{69}As obtained in the GASP+RFD.

SUMMARY

High spin studies in A~40 mass region via discrete and continuum γ spectroscopy….

- Application of modern γ-ray instruments: AGATA+PARIS, and particle detectors RFD, EUCLIDES is necessary
- Re-examine ^{42}Ca and ^{44}Ti at high spins, in order to extend the known and unknown structures up to or beyond the terminating states
- Deformed „cluster states" are favored at high spin
- Open question whether the Jacobi shape transition is a general phenomenon in light mass nuclei
- Link between deformed states (resonances) in a hot CN and yrast SD in a cold ER
- Complementary COULEX experiments (structure near SD band heads)
- Results will be helpful in evaluation and confrontation of nuclear theories as: Large-Scale Shell Model, cluster model or the EDF approach to nuclear excitation
- Advantage of such measurement will be also a possibility to estimate the lifetimes of the high spin states of interest, for both nuclei

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and the **PARIS** and **AGATA** Collaborations

Thank you for your kind attention