Observation of Mutually Enhanced Collectivity in N=Z ^{76}Sr

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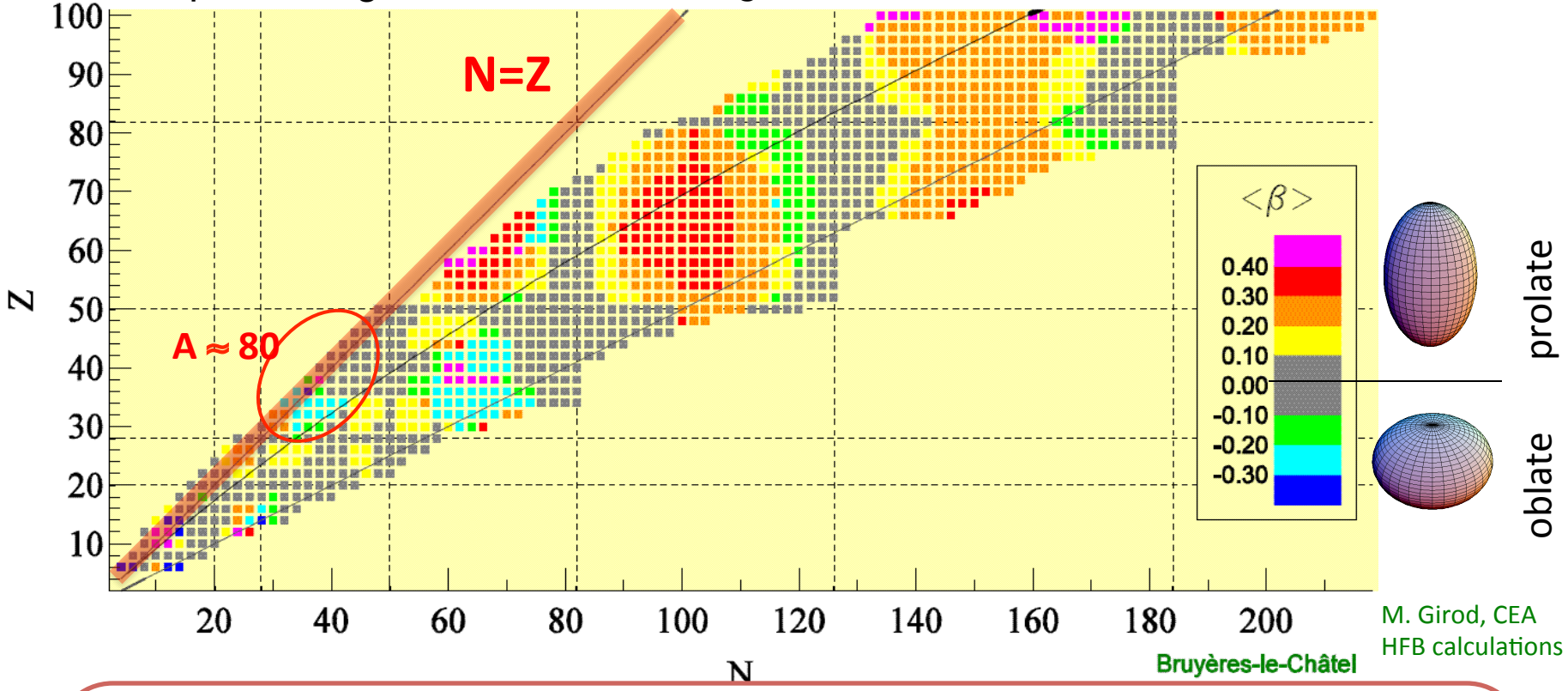
- **Collectivity** and **ground state deformation in N=Z nuclei** and new opportunities with **rare isotope beams**
- **Lifetime measurement of ^{76,78}Sr 2^+ state** at NSCL using **γ-ray peak lineshape method**
- Results for **ground state deformation and collectivity in ^{76}Sr**

Static nuclear deformation

Quadrupole elongation in the nuclear *ground states* from HFB calculations



- **Collectivity** of **many-body** and **finite size quantum system**
  - Delicate interplay between macroscopic and microscopic effects
  - Probing deformation driving mechanisms
- **Rare Isotope Beams : New phenomena away from stability**
  - Occurrence of very large ground-state deformation ($\beta > 0.4$)
  - Shape coexistence prolate / oblate

Self-Conjugate even-even Nuclei above ^{56}Ni

- Neutrons and Protons occupy same orbitals :
  shell effects acts coherently
- Rapid change of nuclei shape :
  - **Extreme sensitivity to small change in nucleon number**
  - Coexistence phenomenon between prolate and oblate shapes

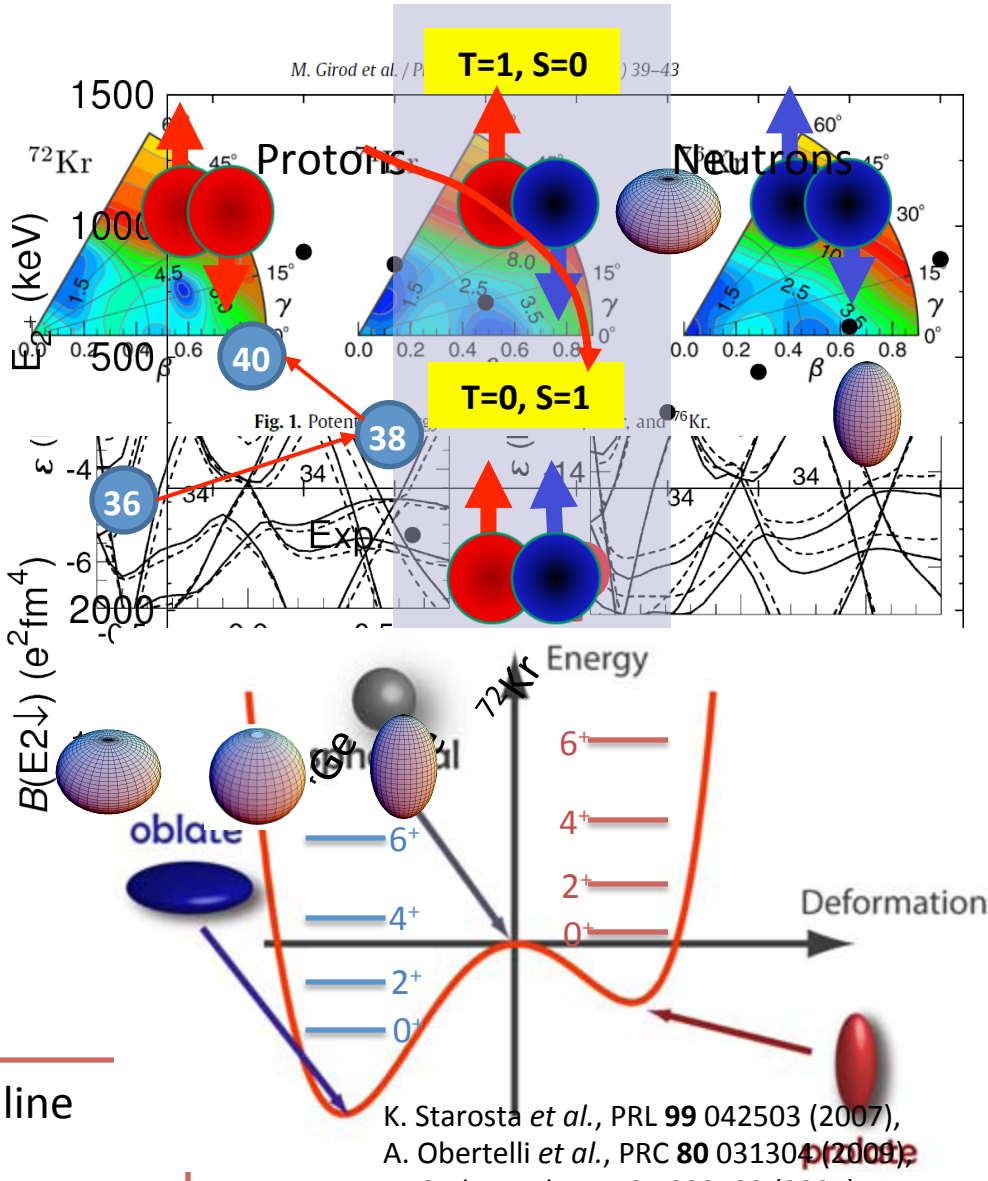
E. Bouchez *et al.*, PRL 90 082502 (2003)

- Possible role of T=0 *p-n* correlations in nuclear deformation

A. M. Macchiavelli *et al.*, PLB 480,1 (2000).

Still remain an open question …

- **Onset of collectivity in ^{72}Kr and rapid increase expected for N=Z>32**
  - Energy 2+ state
  - B(E2) measured from ^{64}Ge to ^{72}Kr



How does collectivity evolves along N=Z line beyond N=Z=36 ?

K. Starosta *et al.*, PRL **99** 042503 (2007),
A. Obertelli *et al.*, PRC **80** 031304(2009),
A. Gade *et al.*, PRL **95** 022502 (2005)

^{76}Sr (N=Z=38) : What is known so far ?

- Lowest E(2+) = 262.3 (2) keV along *N=Z* line in the A=70-80 region

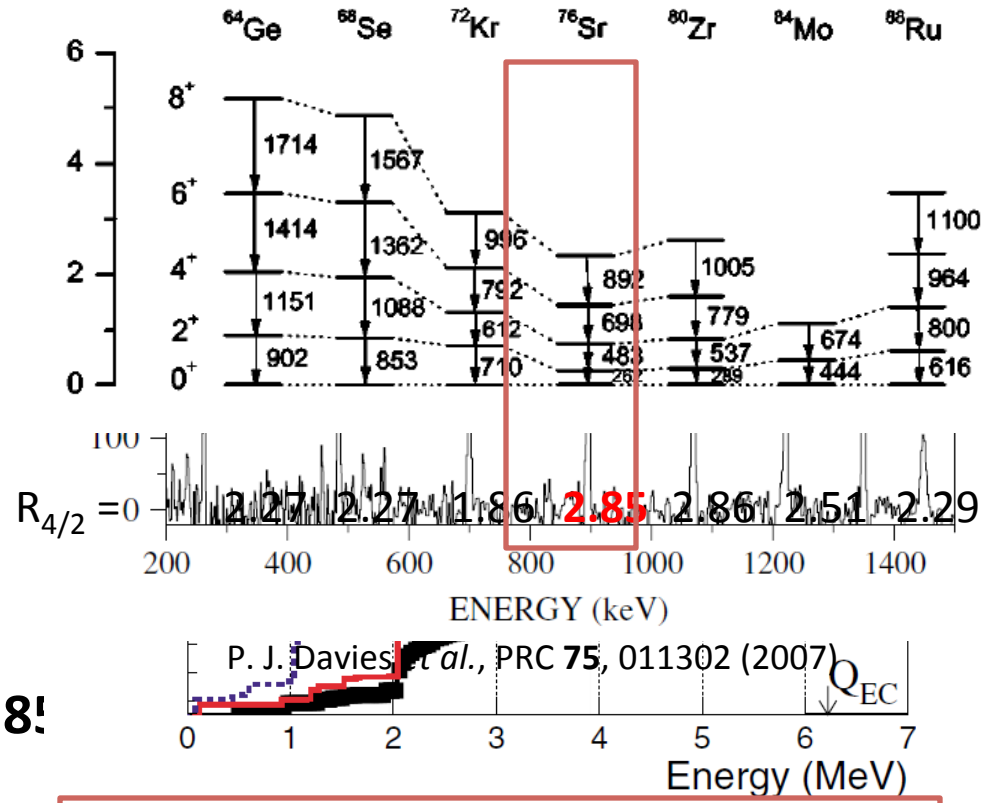
- *High spin studies up to 22ħ* : good rotational behavior

- β−decay : Gamov Teller strength distribution **suggests large prolate deformation** (comparison with QRPA)

- /!\ Relatively small $R_{4/2}=E_{4+}/E_{2+}$= 2.8

(compared to 3.3 for ideal rotor !)

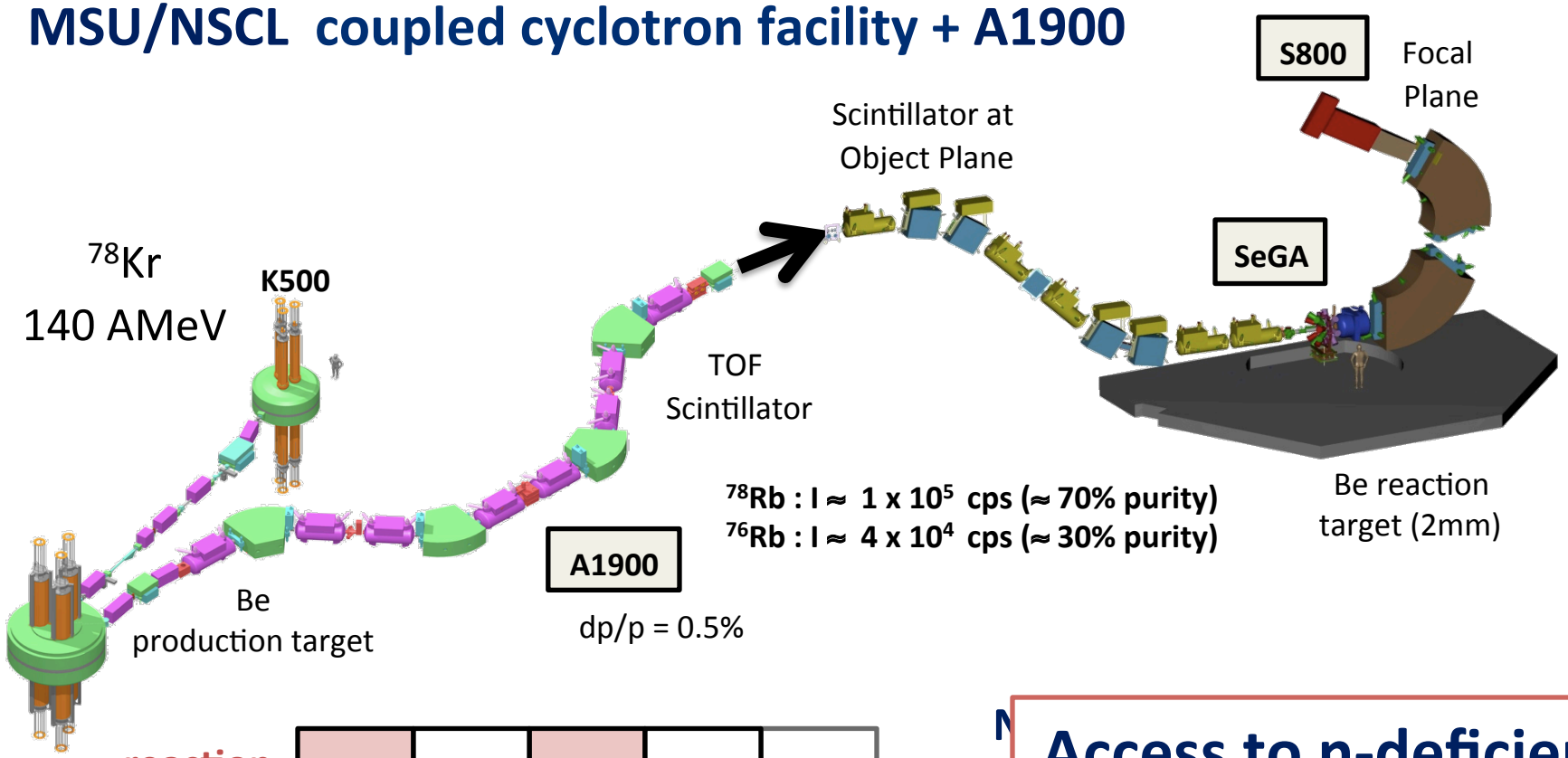
No direct quantitative information on quadrupole collectivity available

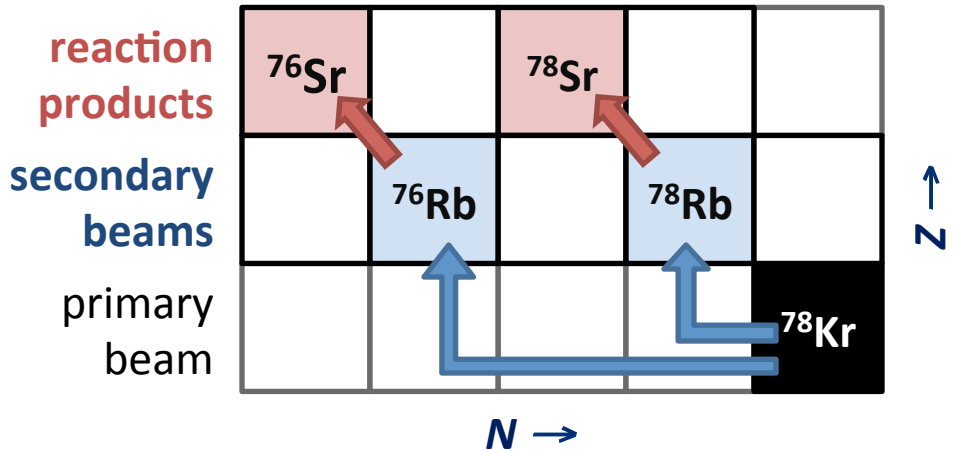


Characterization of the collectivity in ^{76}Sr by the measurement of 2^+ state lifetime

^{76,78}Sr (2^+) lifetime measurement at NSCL

MSU/NSCL coupled cyclotron facility + A1900

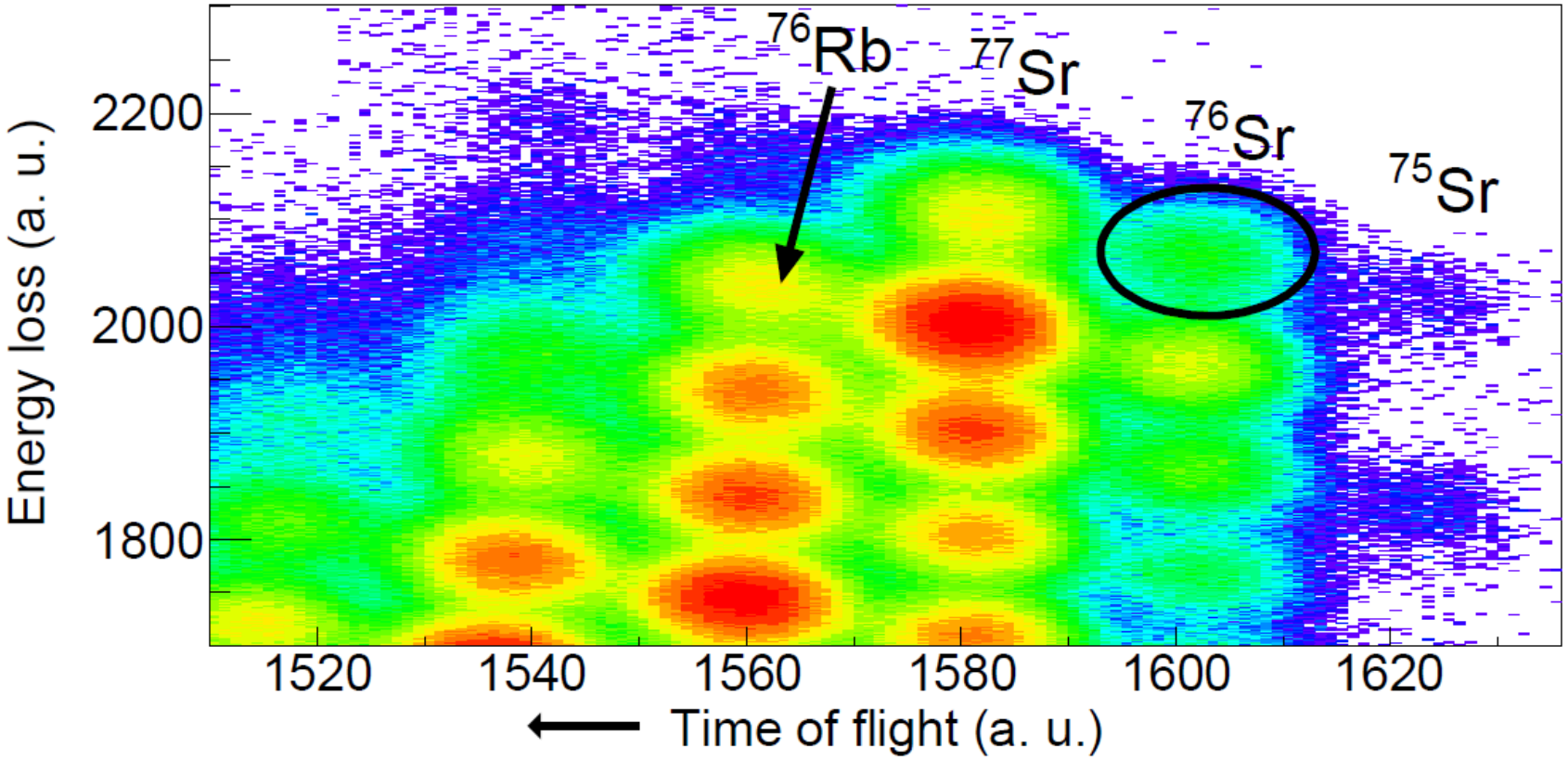




Access to n-deficient but higher *Z* nuclei than available primary beams

NSCL

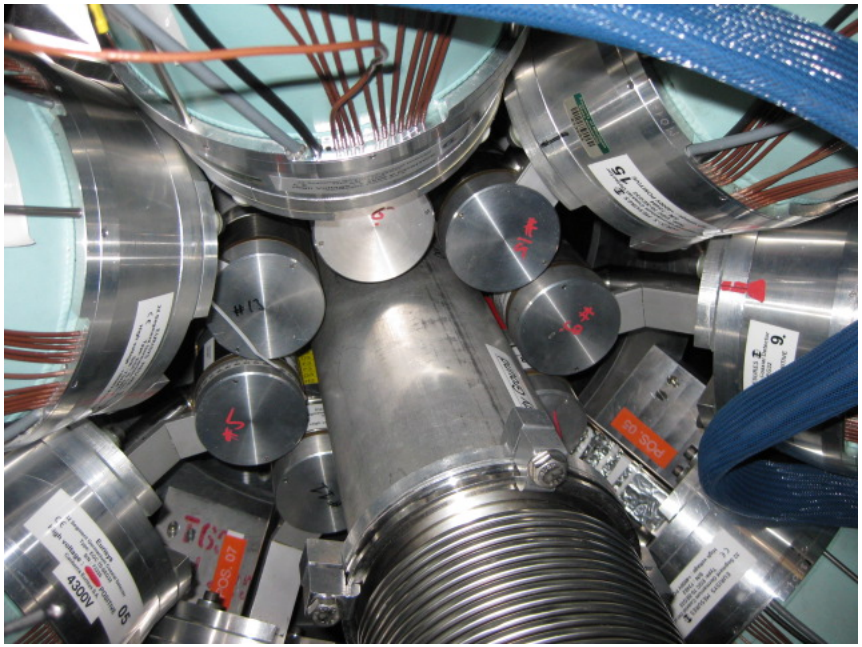
Particle identification of reaction products

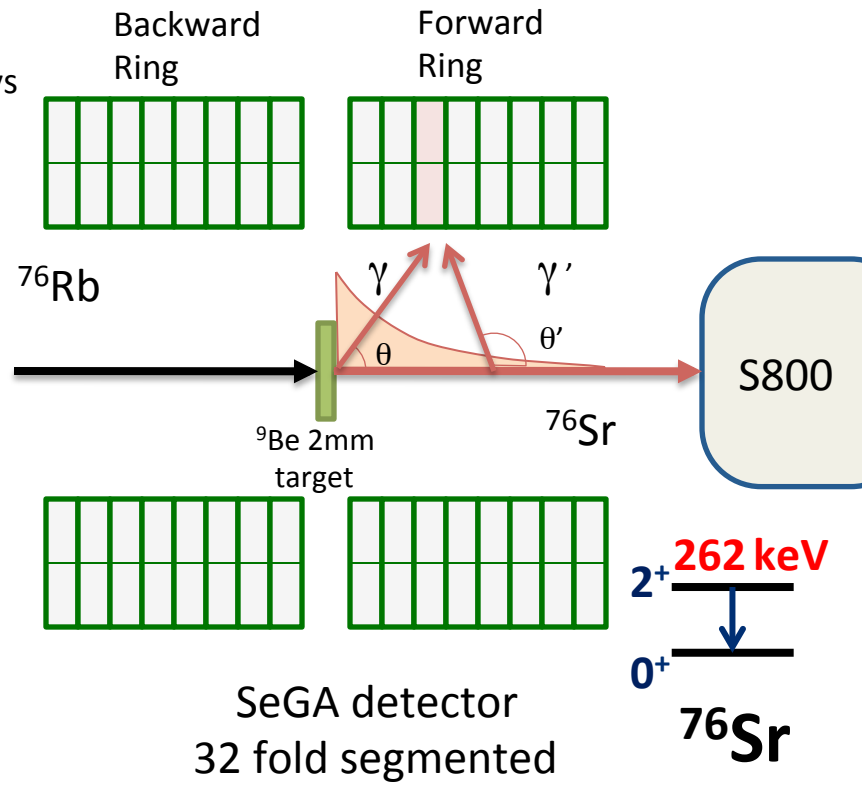


^{76}Rb setting

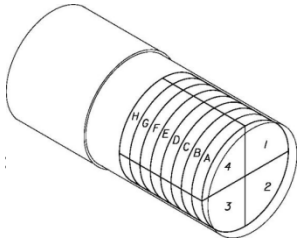
Line shape method

Optimized SeGA Barrel Configuration :
15 HpGe detectors : 17.5 % efficiency for 244-keV gamma rays





SeGA detector
32 fold segmented

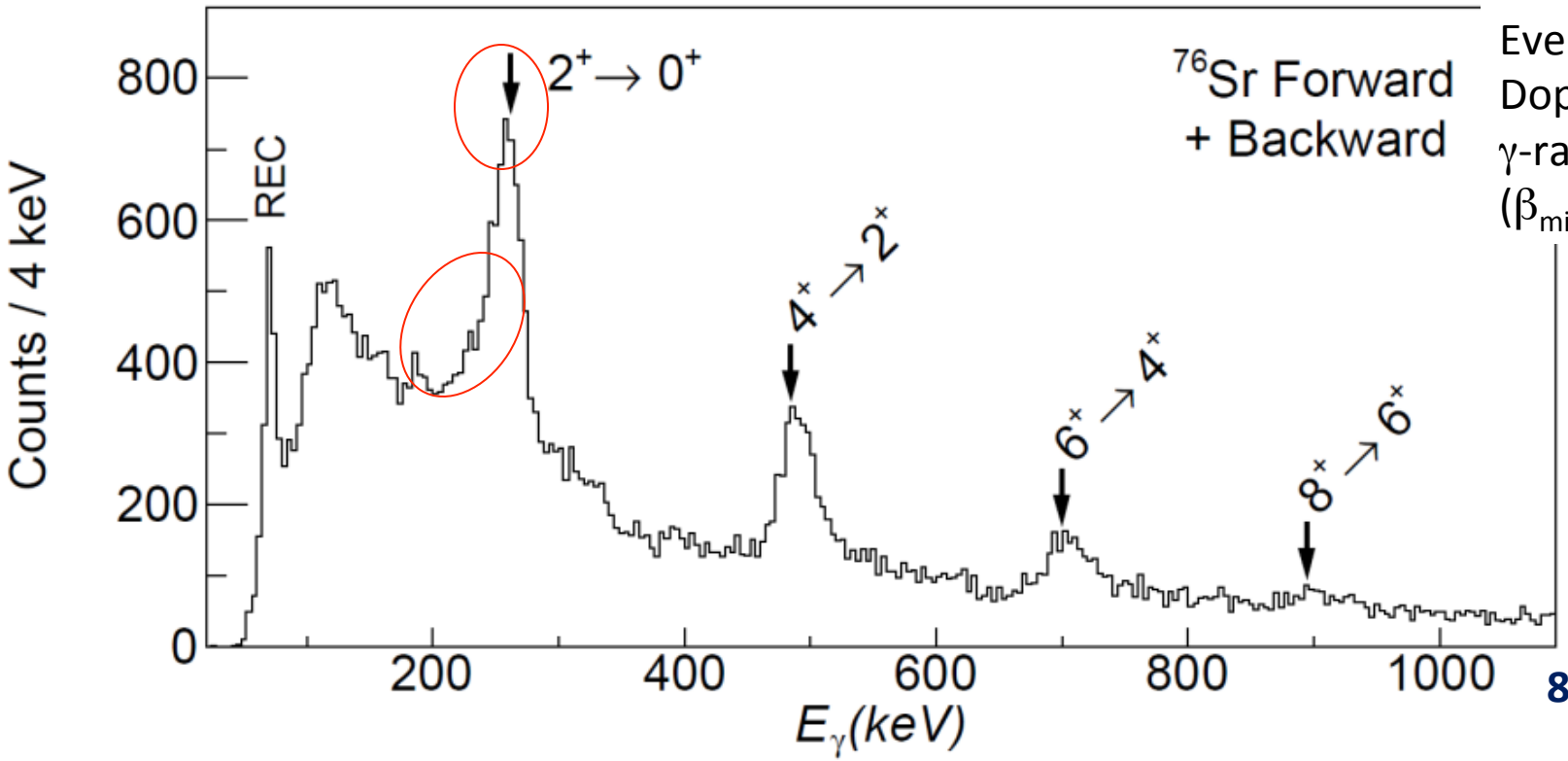


$$\gamma\ (1-\beta\cos(\theta))$$

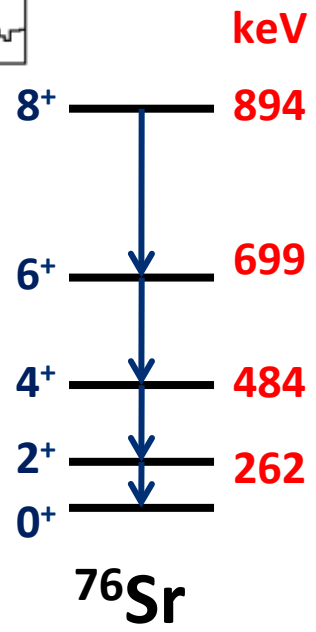
- In flight emission of Doppler shifted γ rays (β ≈ 0.3)
- Lifetime of τ =100 ps ⇔ Emission point shift : <δz>
- **Measurable effects in γ spectrum :**
  - *Asymmetric peak shape*
  - *Peak position shifted*

SeGA : J.R.Terry et al., PRC77, 014316 (2008)
RISING : P. Doornenbal et al., NIMA 613, 218 (2010)

Experimental γ-spectrum

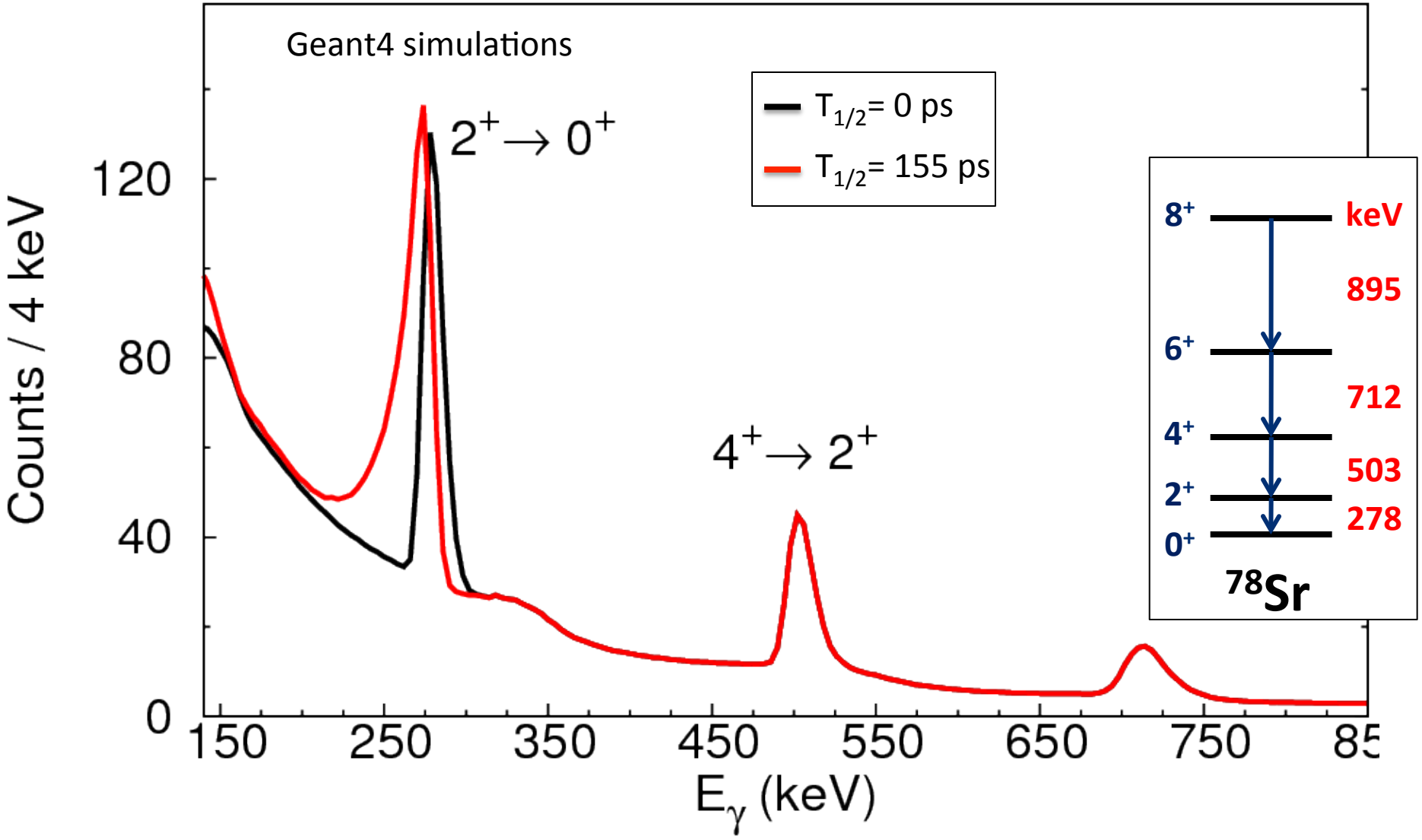


Event-by-event Doppler Corrected γ-ray spectra (β_{mid} = 0.396)



- Rotational band : Yrast states up to 8^+
- Inclusive 2^+ population : 45 (8) %
  (~70 % from 4^+ state)
- **Asymmetric peak** and **peak shift** for 2^+ state

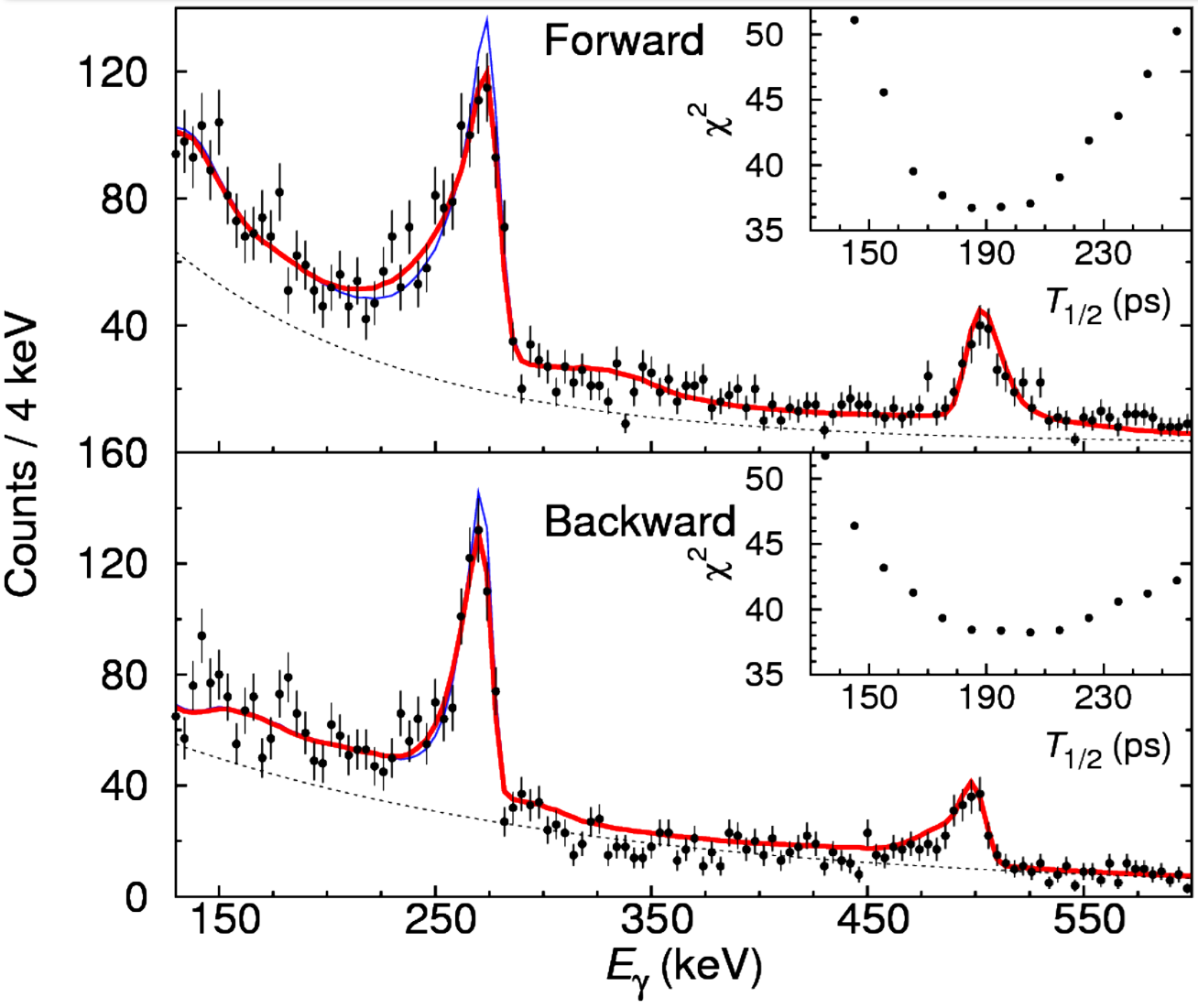
Line shape method : simulations



^{78}Sr : Reference case

C.J. Lister *et al.,* Phys. Rev. Lett. 49 (1982) 308

2^+ state lifetime in ^{78}Sr



Comparison with Geant4 simulations

^{78}Sr

$T_{1/2}$ = 191 (27) ps

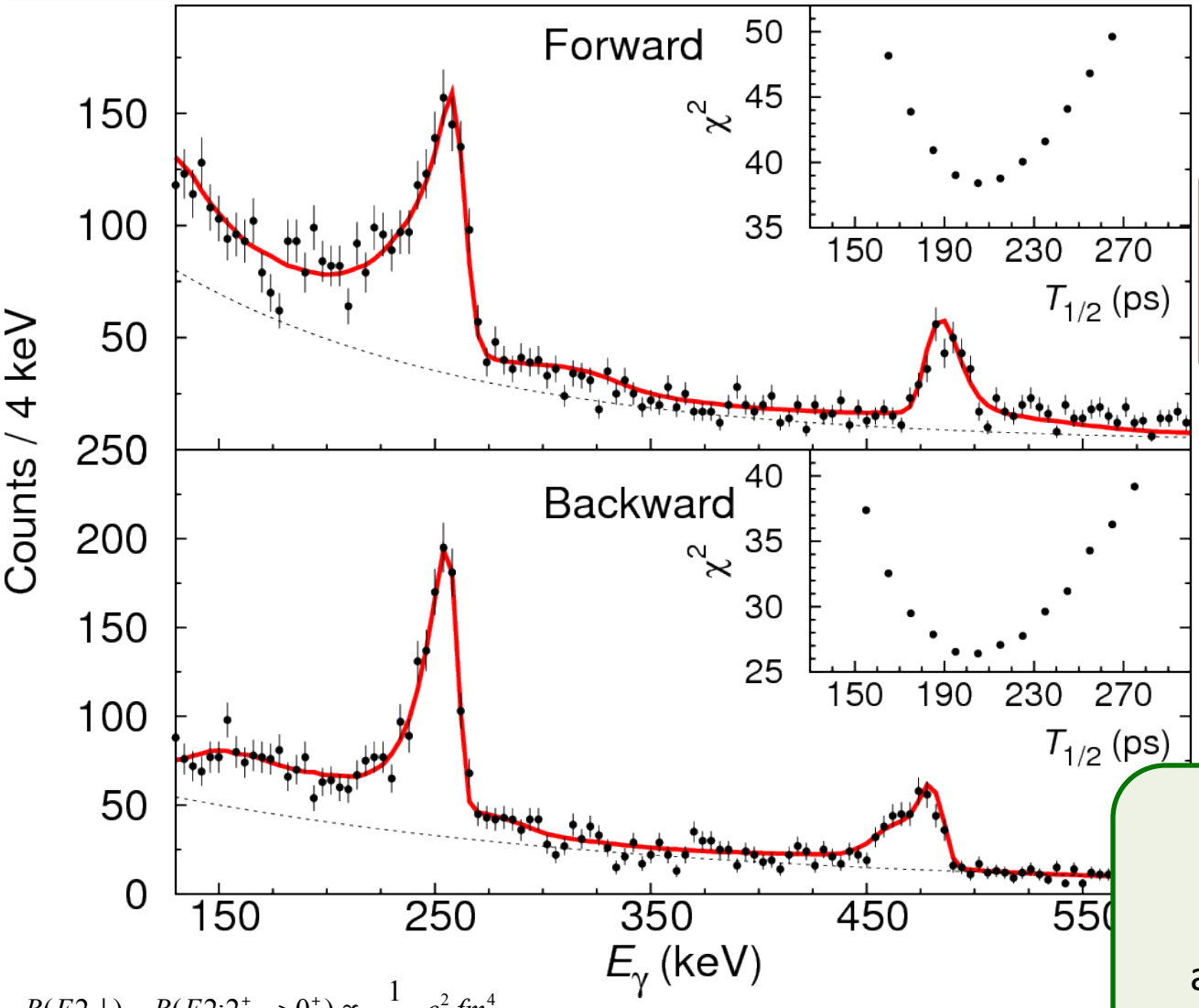
B(E2↓) = 1800 (250) e^2fm^4

Consistent with previous measurement

C.J. Lister *et al.*, PRL **49**, 308 (1982)

$T_{1/2}$ = 155 (19) ps

2^+ state lifetime in ^{76}Sr



^{76}Sr

$T_{1/2}$ = 205 (25) ps

B(E2) = 2200 (270) e^2fm^4

β_2 = 0.45 (3)
among largest ground state deformation in the nuclei chart

$$B(E2\downarrow) = B(E2;2^+ \rightarrow 0^+) \propto \frac{1}{\tau E^5} e^2 fm^4$$

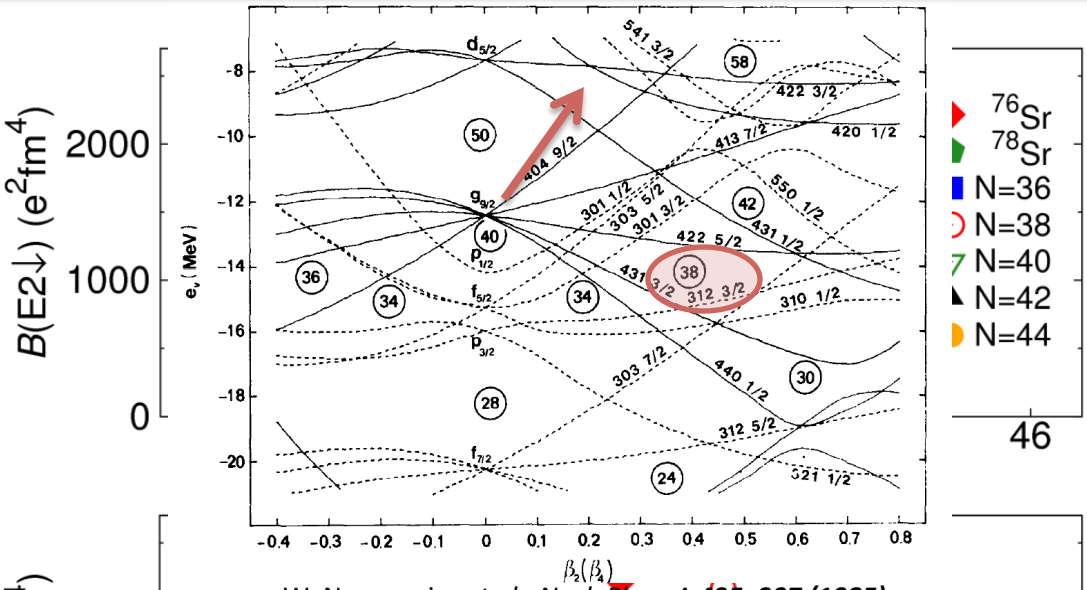
$$\beta_2 = \frac{4\pi}{3ZR_0^2}\sqrt{\frac{B(E2\downarrow)}{5}};\ R_0 = 1.2A^{1/3} fm$$

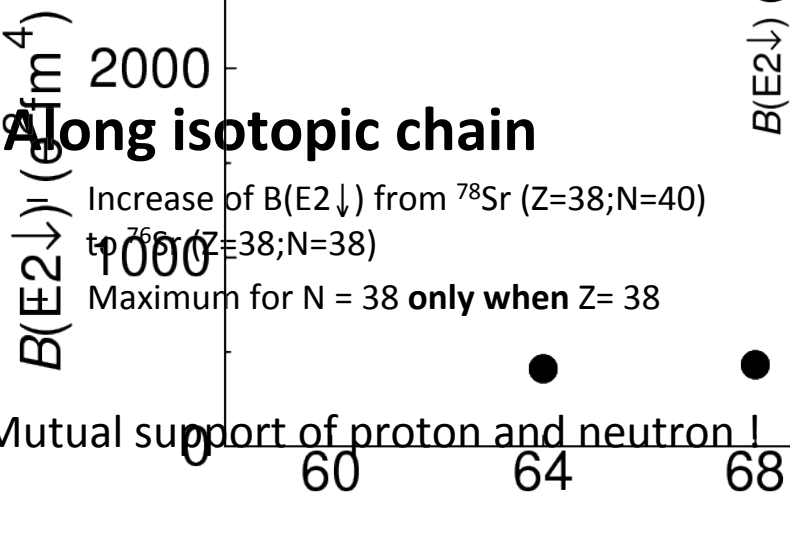
A. Lemasson *et al.*
Phys. Rev. C **85**, 041303(R) (2012)

Mutually Enhanced Collectivity at N=Z=38

- **Along N = Z Line**
  - **Rapid increase** of collectivity for N=Z>36
  - Driven by deformed $g_{9/2}$ Nilsson orbitals at N=Z=38
  - Beyond Nilsson scheme
- **Along isotonic chain**
  - Increase of B(E2↓) towards Z = 38
  - **Steeper for N = 38**
- **Along isotopic chain**
  - Increase of B(E2↓) from ^{78}Sr (Z=38;N=40) to ^{76}Sr (Z=38;N=38)
  - Maximum for N = 38 **only when** Z= 38

Mutual support of proton and neutron !





Mutually enhanced collectivity for ^{76}Sr at N=Z=38

Comparison with theoretical predictions

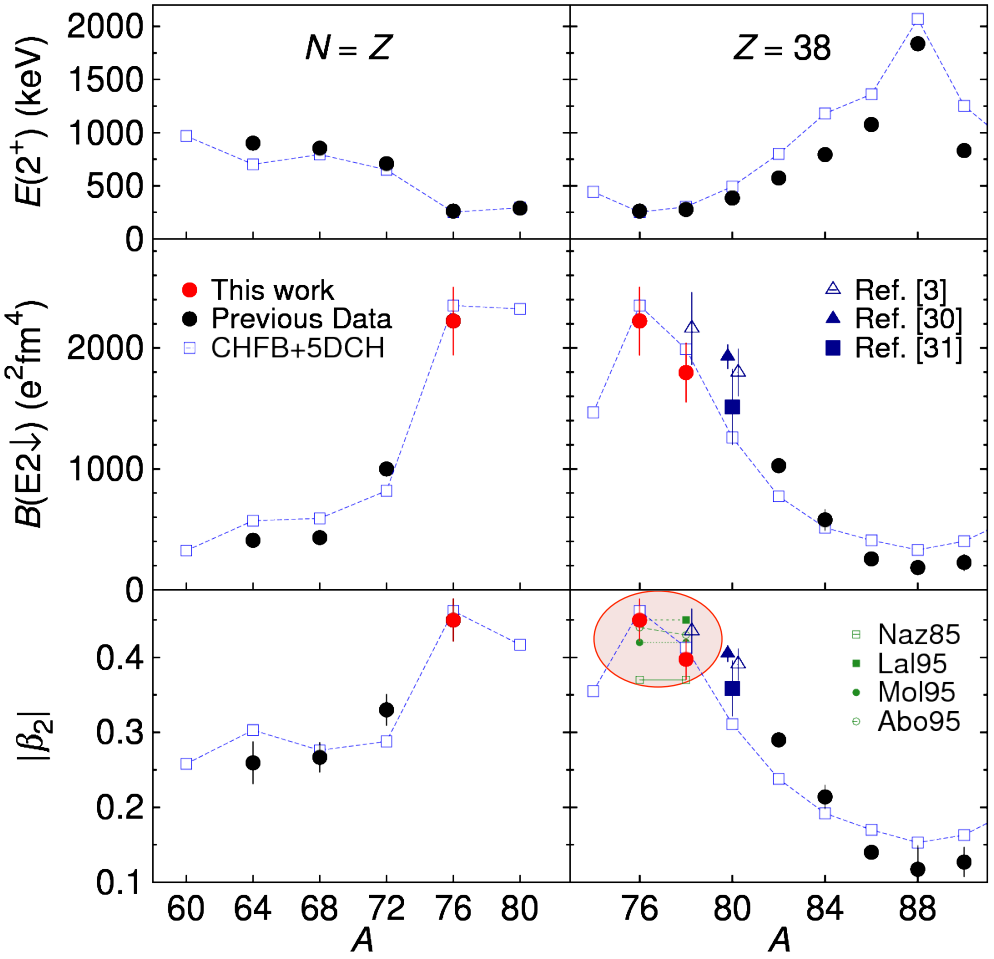
Various calculations predict large deformation ($\beta \approx 0.4$)

- W. Nazarewitcz et al. NPA 435,397(1985)
- P. Bonche et al., NPA 443,39 (1985)
- A. Petrovici, NPA 708, 190 (2002)
- CHFB + 5DCH : J.-P. *Delaroche et al., PRC* 81, 014303 (*2010)*
- RMF : G.A Lalazissis et al, NPA 586,201 (1995)
- FRDM : P. Moller et al. At. Data Nucl. Data Tables 59, 185 (1995)
- ETF-SI : Y. Aboussir et al. At. Data Nucl. Data Tables 61, 127 (1995)
- ….

Most suggest similar amplitude for ^{78}Sr and ^{76}Sr …

Excellent agreement of **CHFB + 5DCH** beyond-mean-field approach using the Gogny D1S interaction

J.-P. *Delaroche et al., PRC* 81, 014303 (*2010)*



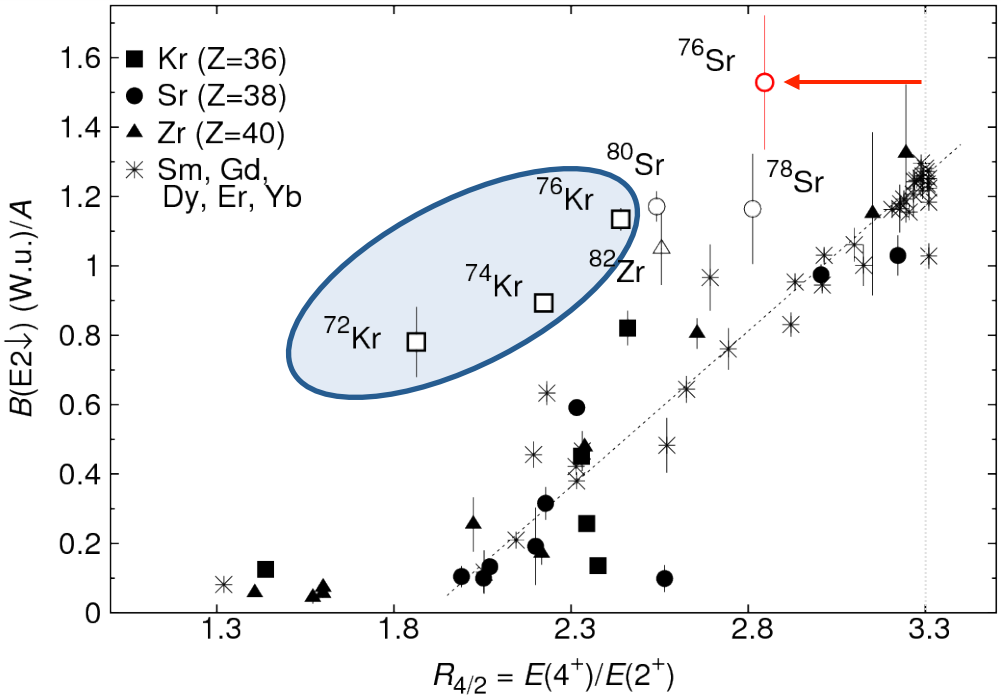
Advanced features :
- Quadrupole Correlations
- Mixing of configurations including triaxial degree of freedom

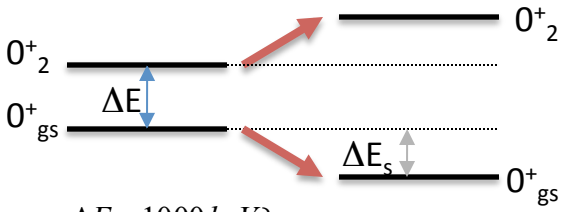
^{76}Sr lies in the center of the deformation island around A ≈ 80
with extremely large collectivity associated with β_2 = 0.45 (3)

Large deformation, but $R_{4/2}$ = 2.85 !

- **B(E2)[W.u.] / A** *vs* **$R_{4/2} = E_{4+}/E_{2+}$**
  - R. F. Casten and N.V. Zamfir, PRL **70**, 402 (1995)
  - Correlation from vibrational to rotational nuclei
- ^{76}Sr deviates from systematic trend (expecting $R_{4/2} \approx 3.3$)
- Oblate-prolate shape coexistence phenomena for nuclei ^{72,74,76}Kr
- Possible fine signature of coexistence phenomena in ^{76}Sr
  - Small perturbation of ground-state energy
  - (Very) Weak mixing, but high sensitivity due to small E(2^+) = 262.3 keV

Further emphasizes the importance of B(E2) measurement to assess collective properties compared to energy information





$$\left.\begin{array}{l}\Delta E = 1000\,keV \\ |V| = 200 keV\end{array}\right\} \Rightarrow \Delta Es \approx 40\,keV$$

W. Korten, Act. Phys. Pol. B **32**, 729 (2001)

Weak mixing (amplitude ≈ 3.5 %)

$R_{4/2}$ = 2.85 => $R_{4/2} \approx 3.2$

Summary and outlook

- First lifetime measurement 2+ state in self-conjugate **^{76}Sr** using
  - **γ-ray peak line-shape method**
  - in conjunction with two step **charge exchange reactions**

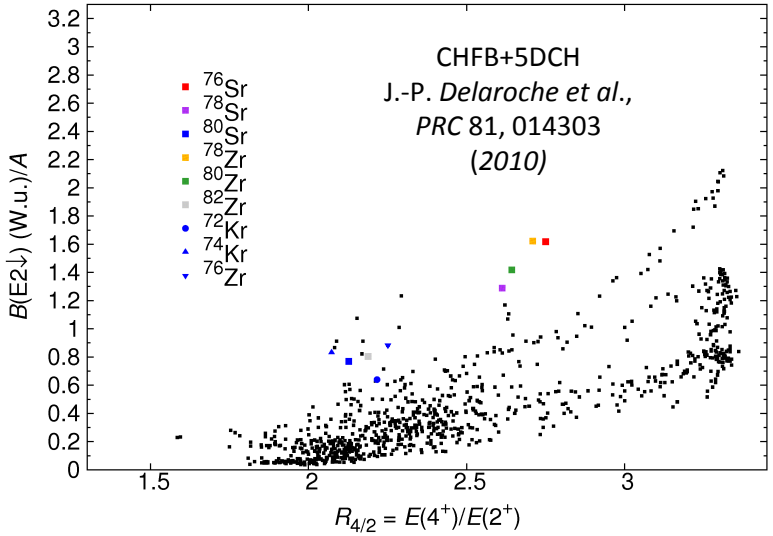
    → allow to study nuclei that are **more n-deficient *but* higher Z** than available beams.

- Direct confirmation of **very large deformation of ^{76}Sr** with $\beta_2 = 0.45\ (3)$
  - Set ^{76}Sr as **one of the most deformed nuclei** of the nuclear chart.
  - Rapid increase of collectivity along N=Z line.
  - Observation of **mutually enhanced collectivity** at N=Z=38.

- Possible signature of **weak shape coexistence** phenomenon

As an outlook …

- Need of advanced beyond mean-field theories for rigorous description of well-deformed nuclei in the A ≈ 80 and N=Z region.
- Very challenging experiments to quantify collectivity of ^{80}Zr, ^{78}Zr, ^{74}Sr …



NSCL/Michigan State University

D. Bazin, T. Baugher, J. Berryman, A. Gade, H. Iwasaki
S. McDaniel, C. Morse, A. Ratkiewicz, S. Stroberg, P. Voss,
D. Weisshaar, K. Wimmer and R. Winkler

Univ. of Cologne

A. Dewald and C. Fransen

Univ. of York

A. Nichols and R. Wadsworth

Thank you for your attention

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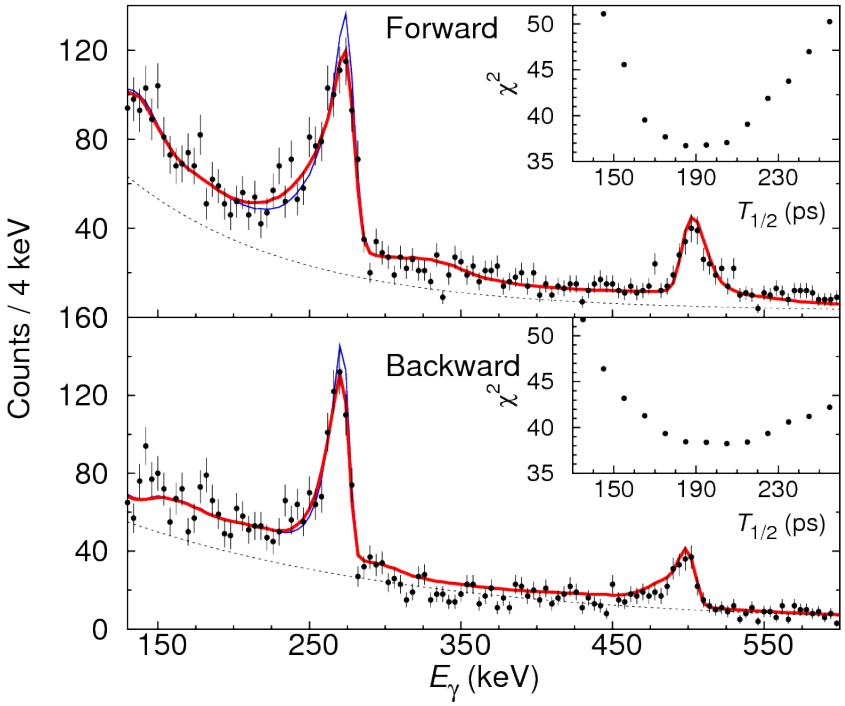
2^+ state lifetime in ^{78}Sr



Reference Data

Comparison with Geant4 simulations

- including 2^+ to 8^+ states
- Exponentional background
  (slope fixed as similar to other reaction products)
- Measured outgoing ion velocity
- Independent fit of backward and forward rings
- χ^2 analysis

Main systematic errors

- Detector/Target Geometry (3%)
- Background shape (3%)
- γ-ray anisotropy due to nuclei alignment in reaction (1.5%)
- 4^+ state feeding (1%)

=> Overall : 4.6 %

^{78}Sr

Forward : $T_{1/2} = 188 \pm {}^{17}_{15}$ (stat) ps

Backward : $T_{1/2} = 194 \pm {}^{21}_{19}$ (stat) ps

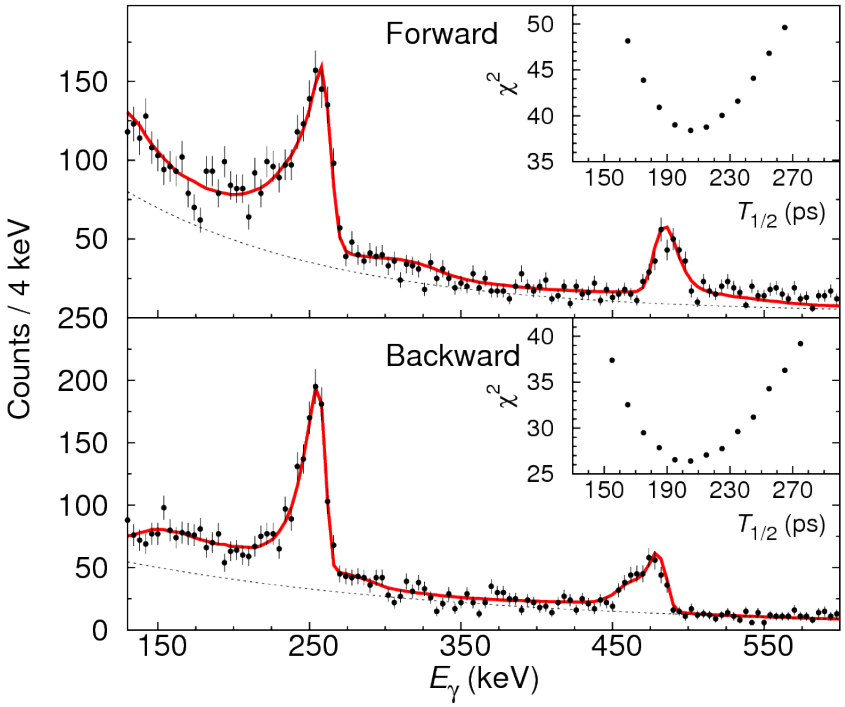
Adopted : $T_{1/2}$ = 191 (27) ps

Consistent with previous measurement

C.J. Lister *et al.*, PRL 49, 308(1982)

$T_{1/2}$ = 155 (19) ps

2^+ state lifetime in ^{76}Sr



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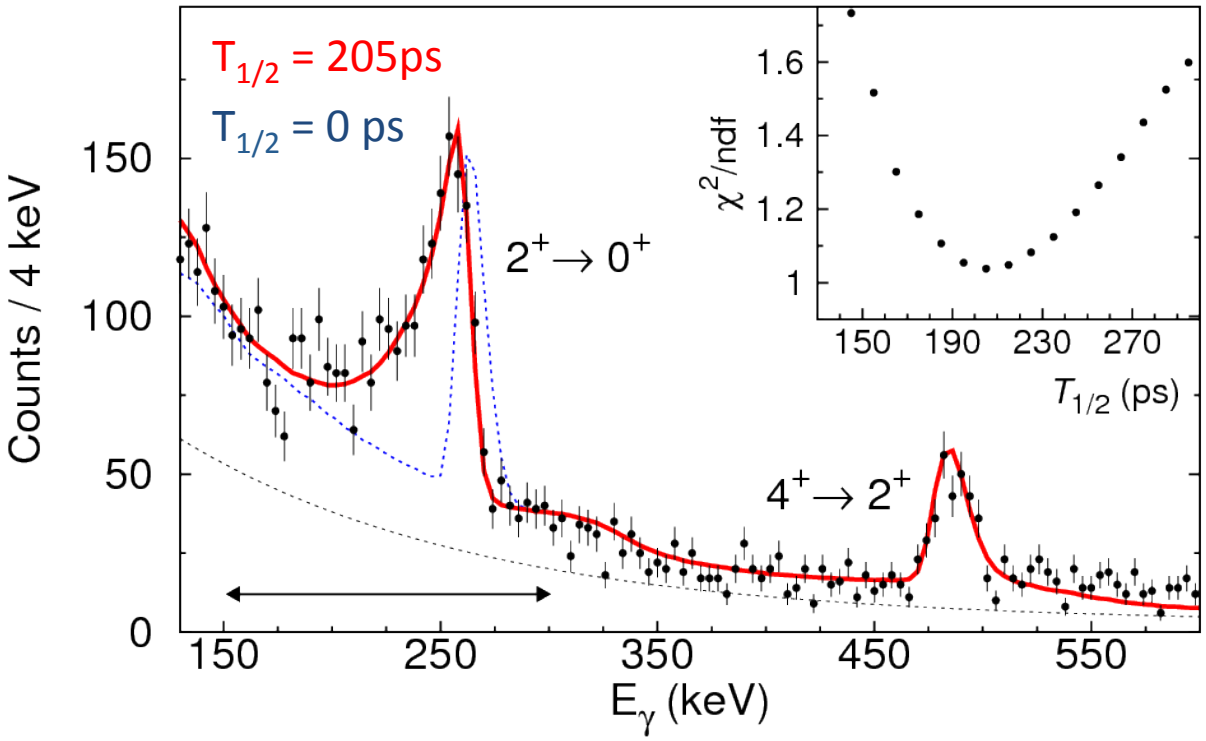
^{76}Sr

Forward : $T_{1/2} = 207 \pm {}^{16}_{14}$ (stat) ps

Backward : $T_{1/2} = 203 \pm {}^{18}_{16}$ (stat) ps

Adopted : $T_{1/2}$ = 205 (25) ps

Lifetime of 2^+ state in ^{76}Sr



$E(2^+)$ = 262.3 keV

^{76}Sr

$T_{1/2}$ = 205 (25) ps

Comparison with Geant4 simulations

$$B(E2\downarrow) = B(E2;2^+ \rightarrow 0^+) \propto \frac{1}{\tau E^5} e^2 fm^4$$

$$\beta_2 = \frac{4\pi}{3ZR_0^2}\sqrt{\frac{B(E2\downarrow)}{5}};\quad R_0 = 1.2A^{1/3} fm$$

B(E2) = 2200 (270) e^2fm^4

β_2 = 0.45 (3)

among largest ground state deformation in the nuclei chart …

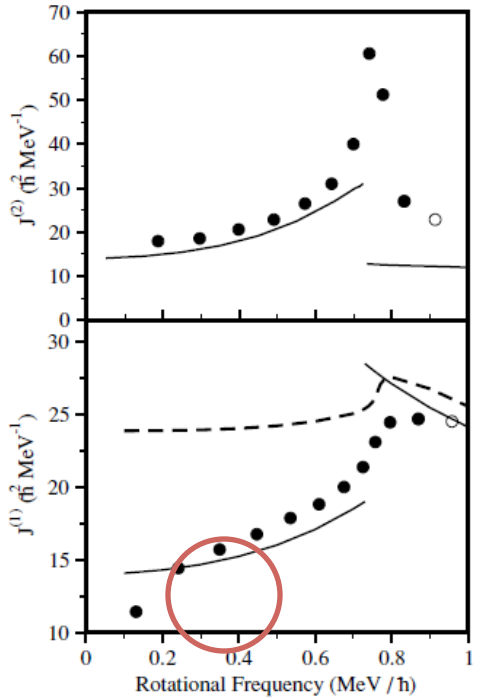


FIG. 2. The upper (lower) panels show the dynamic $J^{(2)}$ (kinematic $J^{(1)}$) moments of inertia, respectively. Circles are used for the ^{76}Sr data (solid for firmly established transitions and open circle for the point incorporating the tentative 1953 keV transition). The solid and dashed lines show theoretical values obtained in the CRHB+LN and CRMF calculations, respectively, which are taken from Ref. [9].

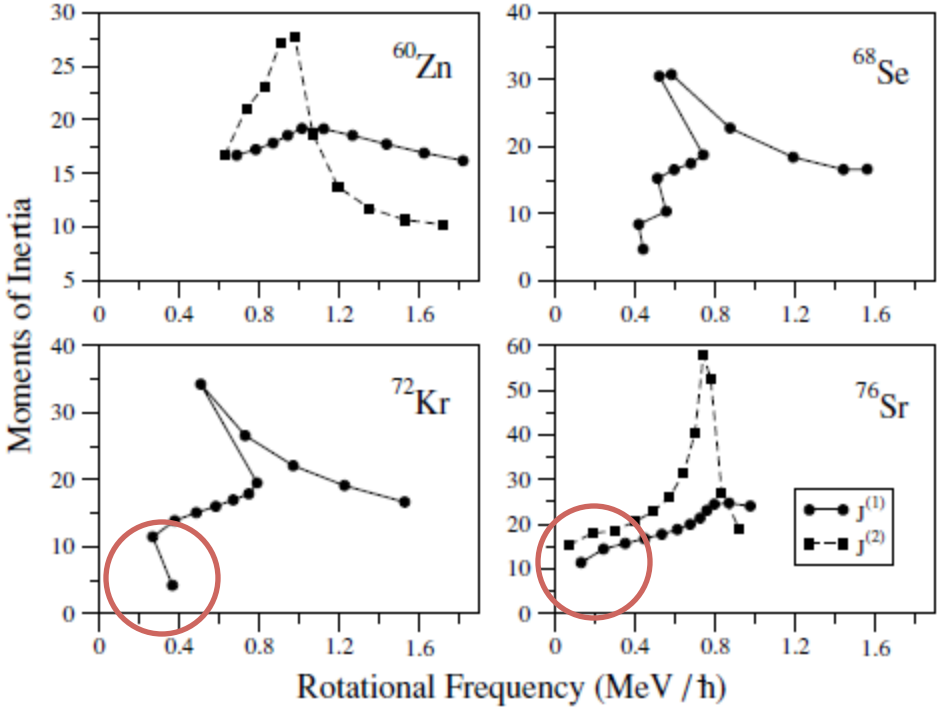


FIG. 3. Kinematic (solid lines) moments of inertia [and dynamic (dashed lines) moments of inertia for ^{60}Zn, ^{76}Sr] as a function of rotational frequency for a superdeformed band in ^{60}Zn and the yrast bands in ^{68}Se, ^{72}Kr, and ^{76}Sr.

P. J. Davies *et al.*, PRC 75, 011302 (2007)

Extra slides

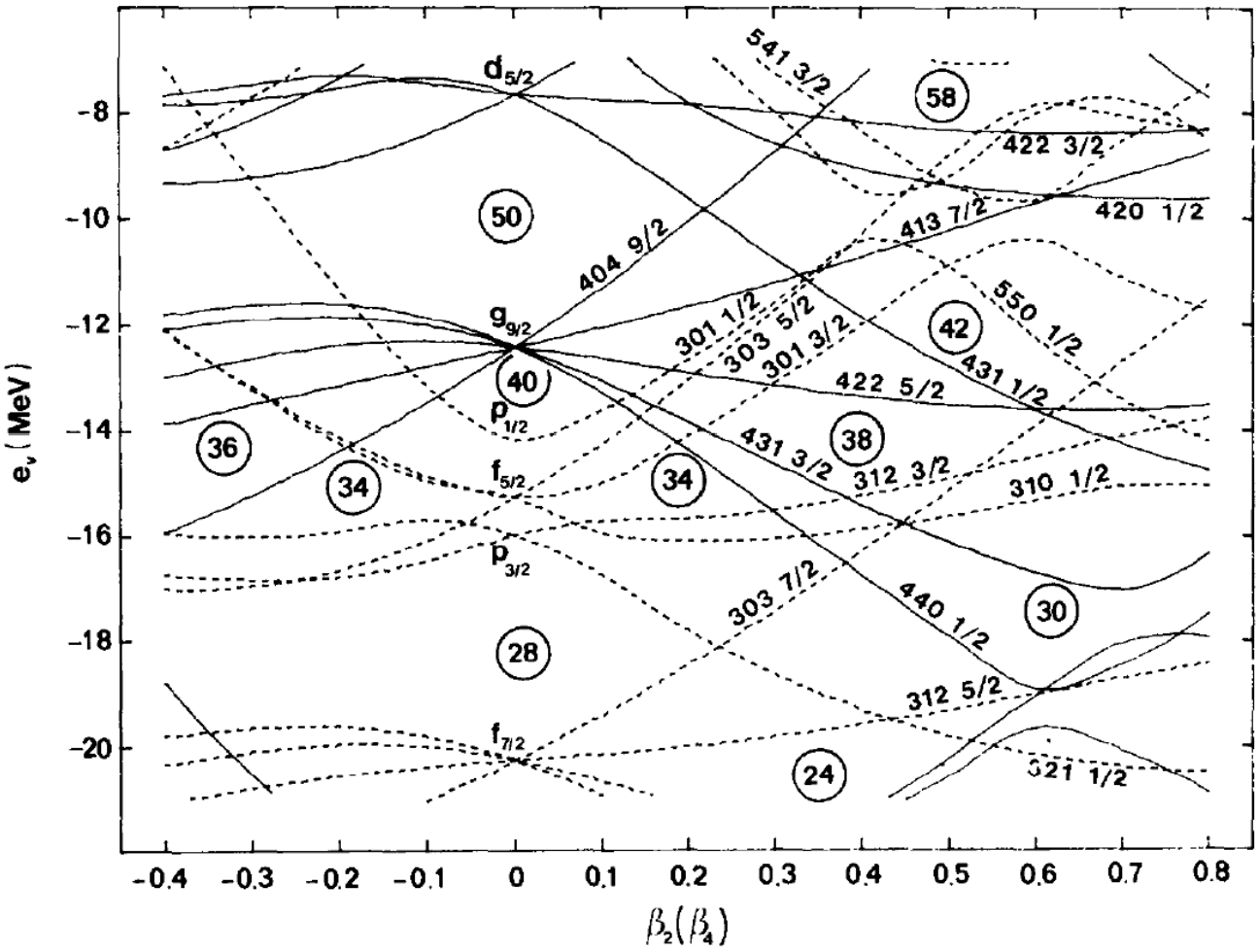
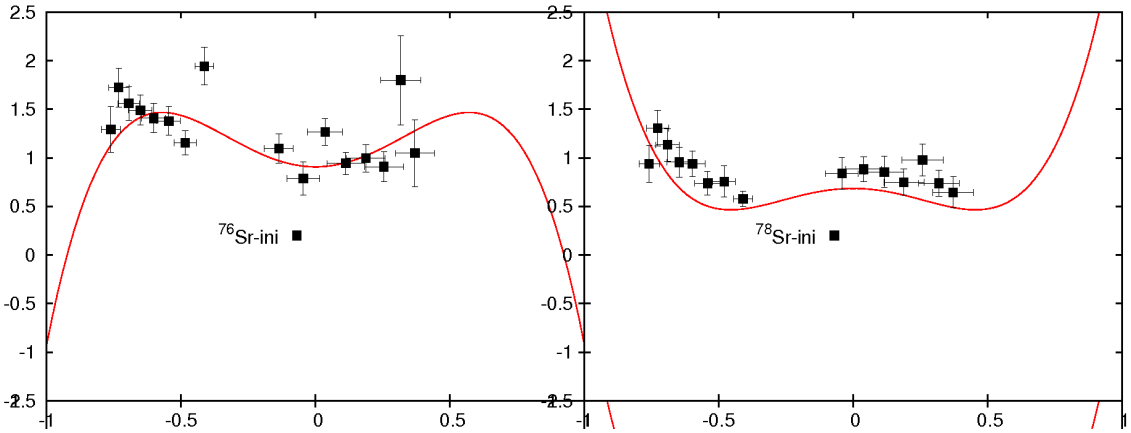


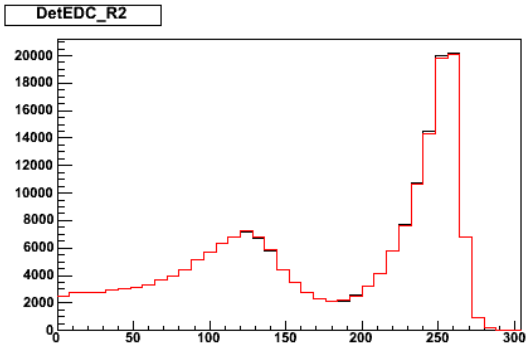
Fig. 1. Neutron single-particle levels in ^{80}Sr as functions of the quadrupole deformation β_2, calculated using the Woods–Saxon potential. At each value of β_2 the liquid-drop-model energy has been minimized

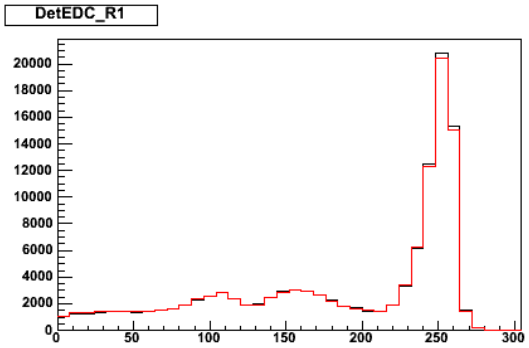
W. Nazarewicz *et al., Nucl. Phys. A* ***435, 397 (1985)***

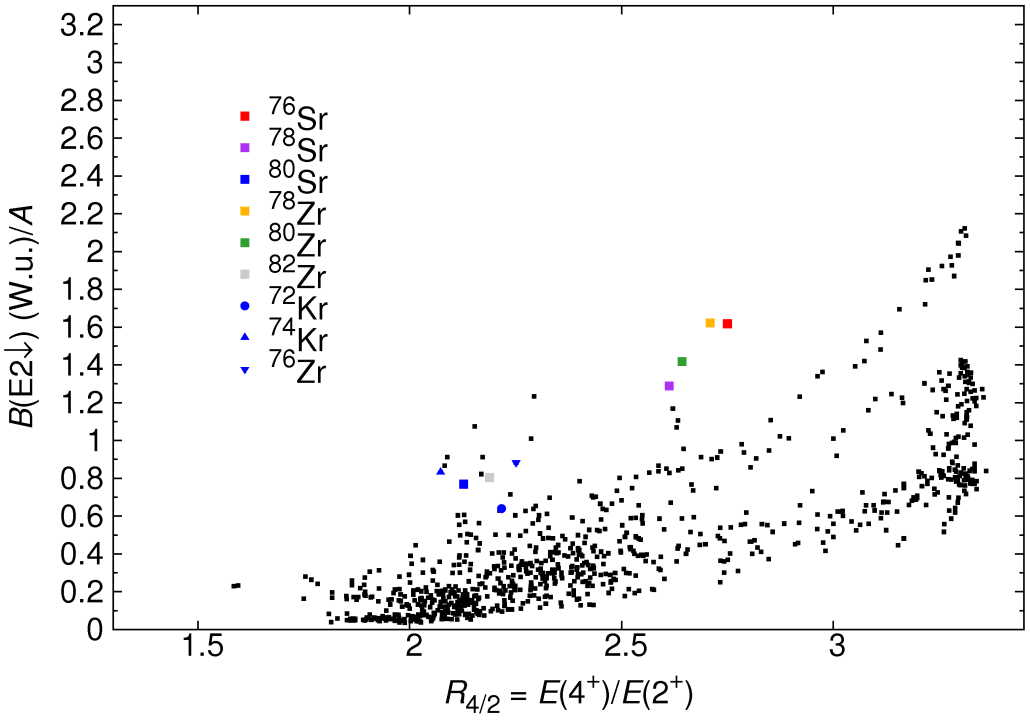
γ – Angular Correlations

- Alignment of reaction product








3.2
3
2.8
2.6
2.4
2.2
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
1.5
2
2.5
3
B(E2↓) (W.u.)/A
R4/2 = E(4+)/E(2+)
76Sr
78Sr
80Sr
78Zr
80Zr
82Zr
72Kr
74Kr
76Zr