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# Investigating shape coexistence in $^{80,82}$Sr with $\beta^+$/*EC* decay spectroscopy

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ISOLDE INTC Meeting

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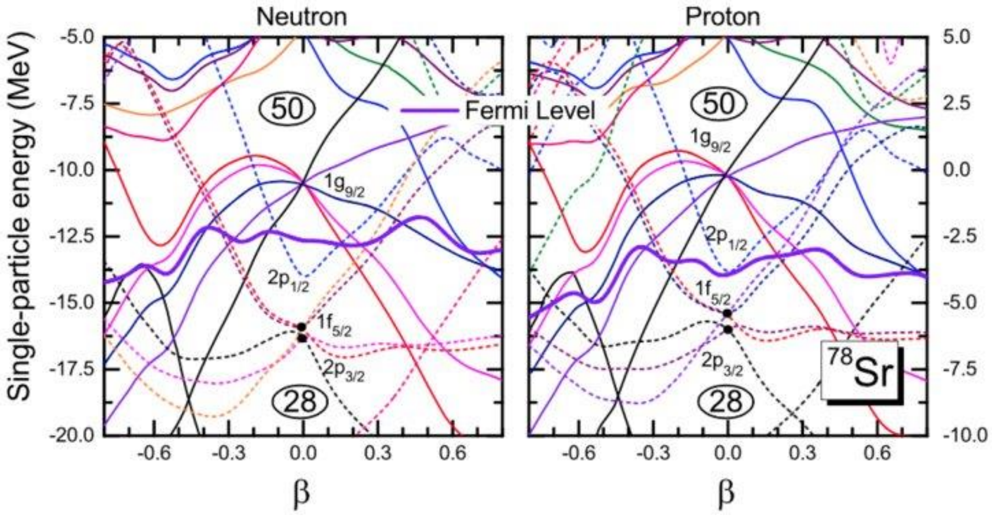
# Nuclear Shape Coexistence



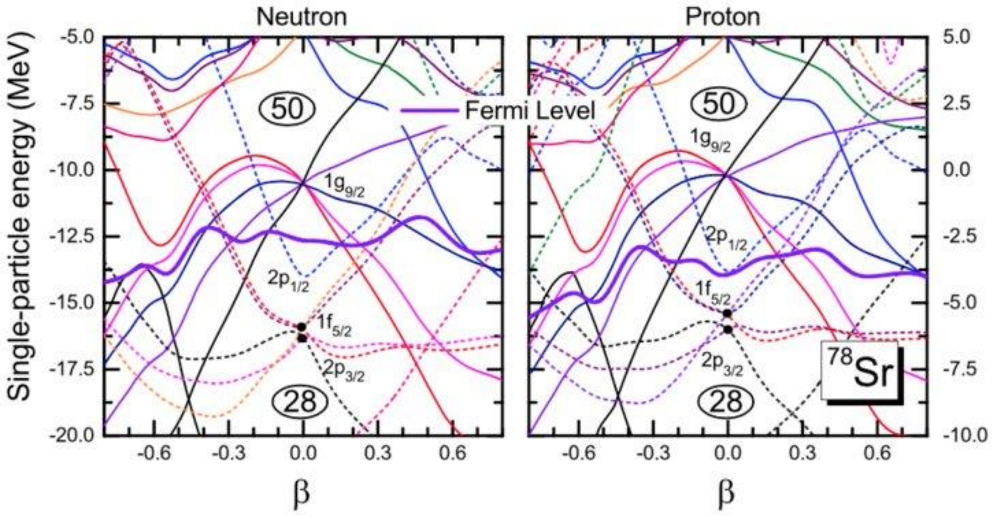
- The Sr isotopes lie in a region where a variety of subshell gaps may give rise to sudden changes in **deformation**.

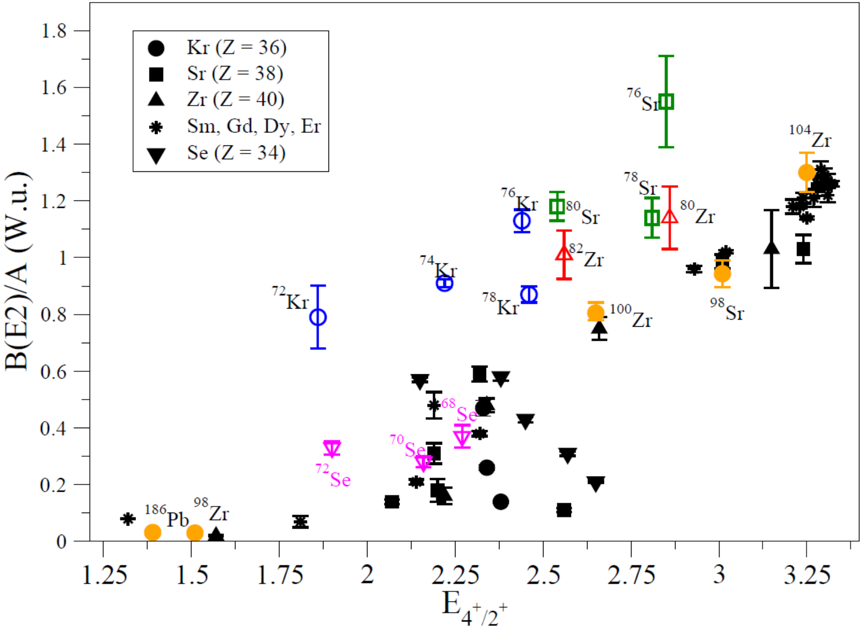


# Nuclear Shape Coexistence

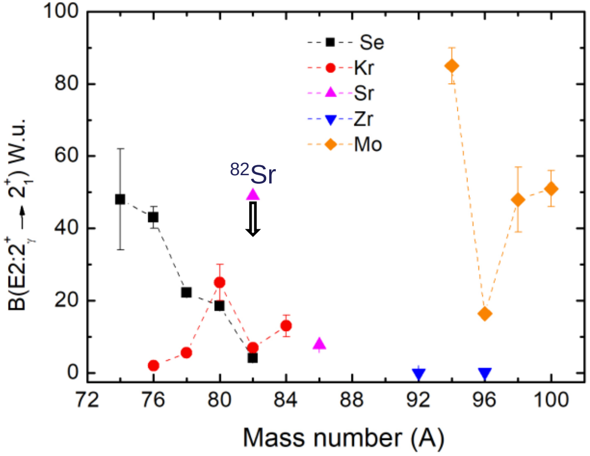


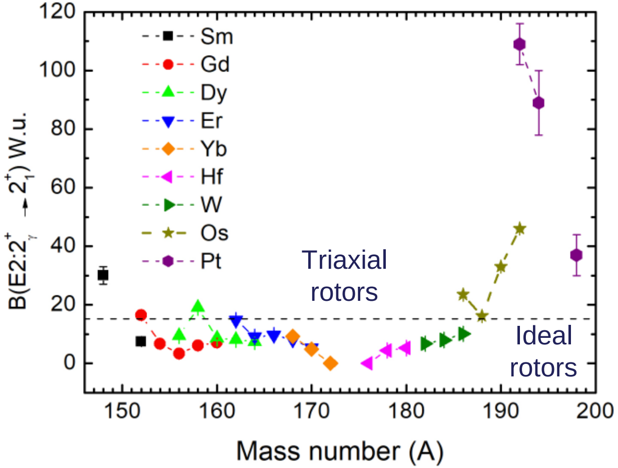
- The Sr isotopes lie in a region where a variety of subshell gaps may give rise to sudden changes in **deformation**.
- The neutron-deficient *A* ~ 72-82 isotopes show extreme prolate deformation and large *E2* strengths, comparable to **axially symmetric rotors** in the *A* ~ 180 region.
- This behaviour might be explained by softness of the potential energy surface or by shape mixing (Korten, 2001; Bouchez *et al.*, 2003).

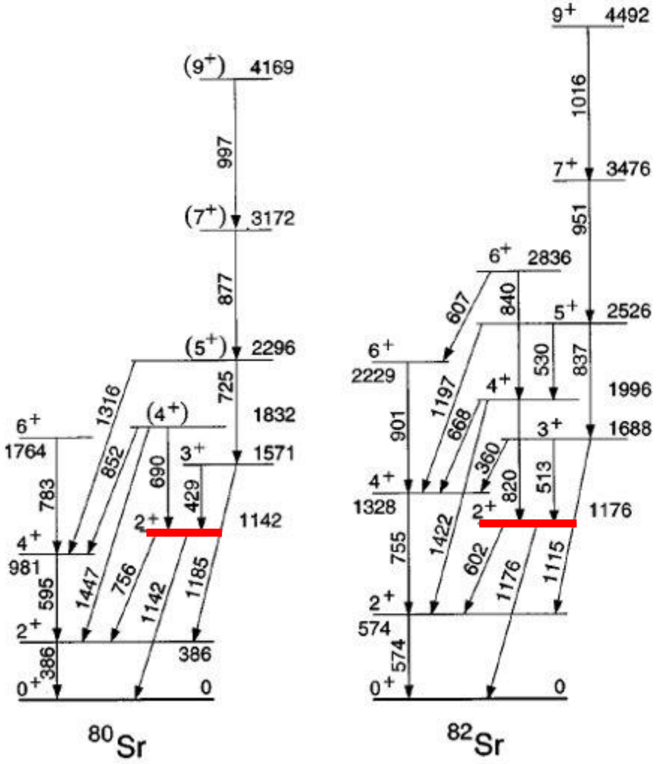


- Low-energy γ-vibrational bands ($K$ = 2) are a signature of triaxiality.
- Axially-symmetric rotors between $A$ ~ 150-190 present a systematic behaviour with $B(E2;2^+_\gamma \rightarrow 2^+_1)$ values, while triaxial rotors Os and Pt show a clear enhancement (Wu *et al.*, 1996).



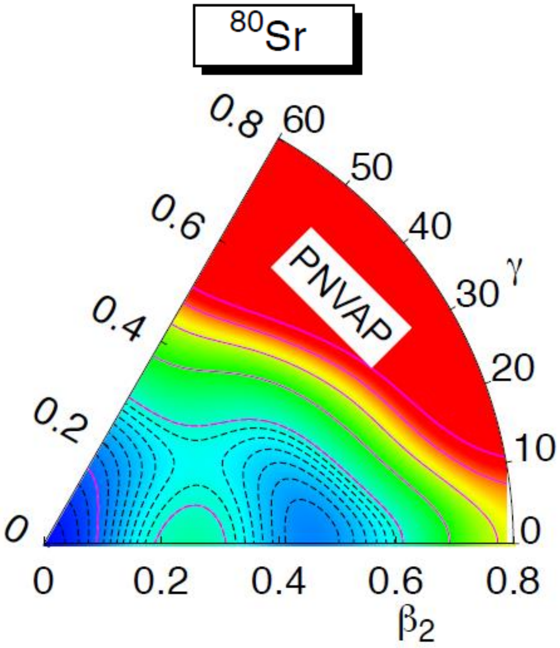



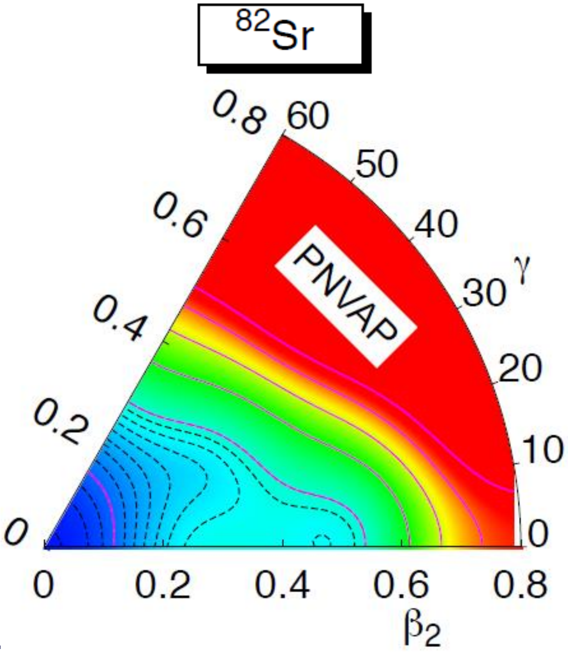

Adapted by J. Doring *et al.*, Phys. Rev. **C 59** 1 (1999) from R. F. Davie *et al.*, Nucl. Phys. **A 463** 683 (1987), and S. L. Tabor *et al.*, Phys. Rev. **C 49** 2 (1994).

# Potential Energy Surface



- Particle Number Variation After Projection (PN-VAP) beyond mean-field calculations iteratively vary the shape and minimize the energy to obtain the collective behaviour of a given nucleus (PES).
- A barrier of 4-5 MeV between prolate and oblate shape minima is predicted in $^{80}$Sr with a $0^+_2$ state at 1.19 MeV, whereas $^{82}$Sr is more γ-soft.



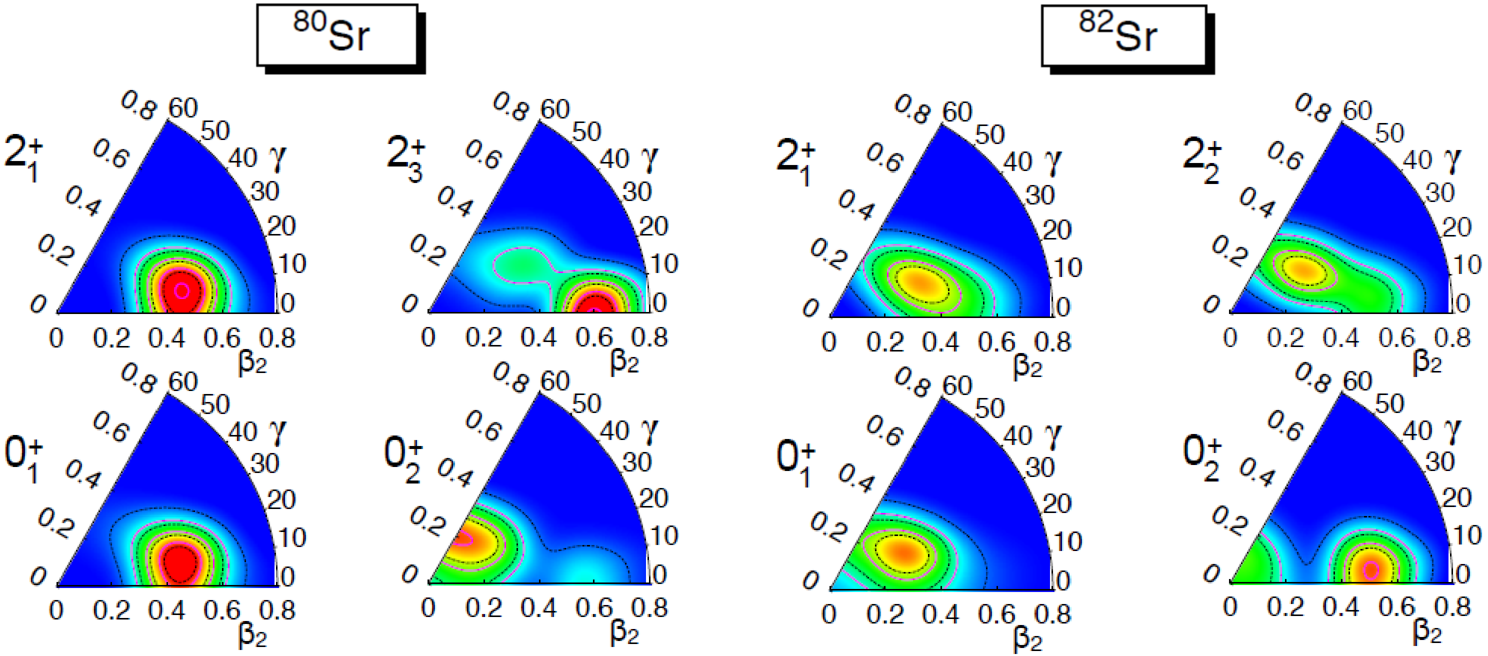




T. Rodriguez (2020).

# Shape Mixing



- After projection onto angular momentum and configuration mixing, the energy and collective wavefunctions for different states are obtained by solving the Schrödinger equation.
- The $0^+_2$, $2^+_2$ and $2^+_3$ states show **mixed configurations** with components of different shapes.




T. Rodriguez (2020).

# Electric Monopole Strength

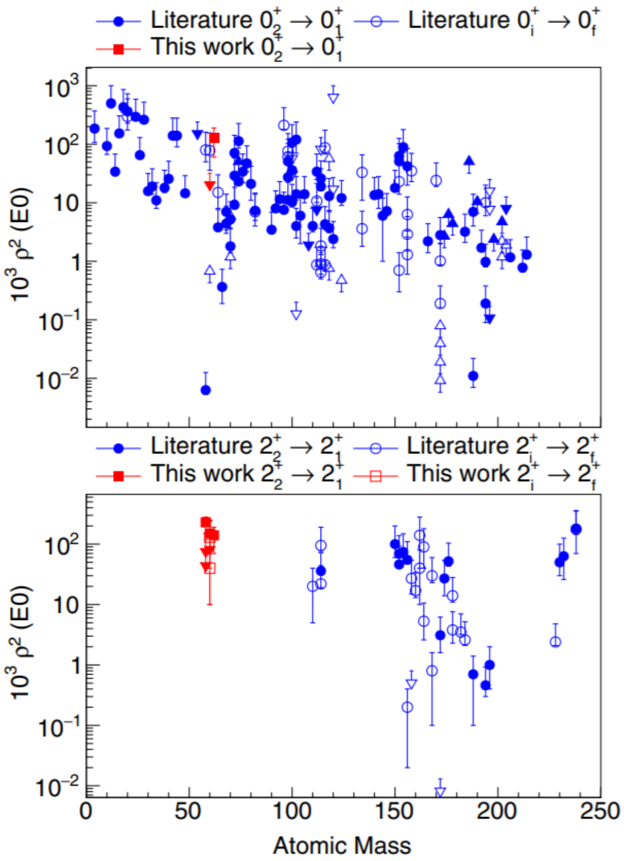


- The strength of an *E0* transition, $\rho^2(E0)$, can be directly related to the difference in the mean-squared charge radii $< r^2 >$ and mixing of configurations:

$$\hat{M}(E0) = \frac{3Z}{4\pi}\left(\frac{4\pi}{5} + \beta^2 + \frac{5\sqrt{5}}{21\sqrt{\pi}}\beta^3 \cos\gamma\right)$$

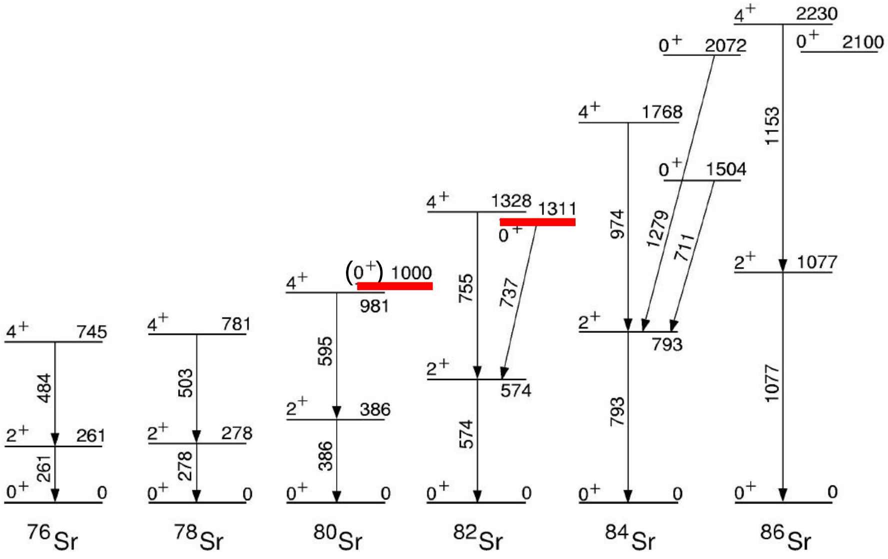
$$\rho^2(E0) = \left(\frac{3Z}{4\pi}\right)^2 a^2\left(1 - a^2\right)\left(\beta_1^2 - \beta_2^2\right)^2$$

- Large $\rho^2(E0)$ values have already been observed in $^{72,74,76,78}$Kr isotopes, however nothing is known in the light Sr isotopes.

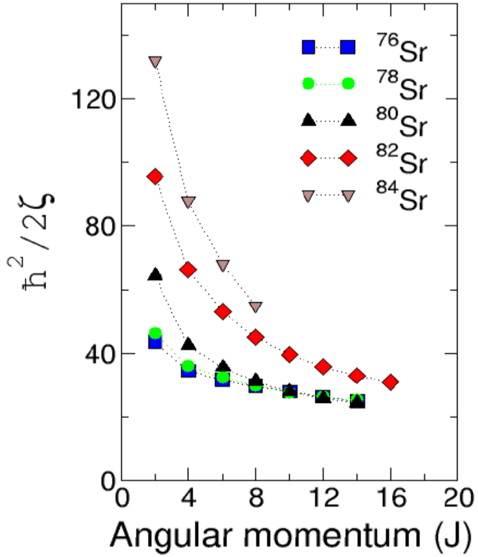



L. J. Evitts *et al.*, Phys. Rev. **C** 99, 024306 (2019).

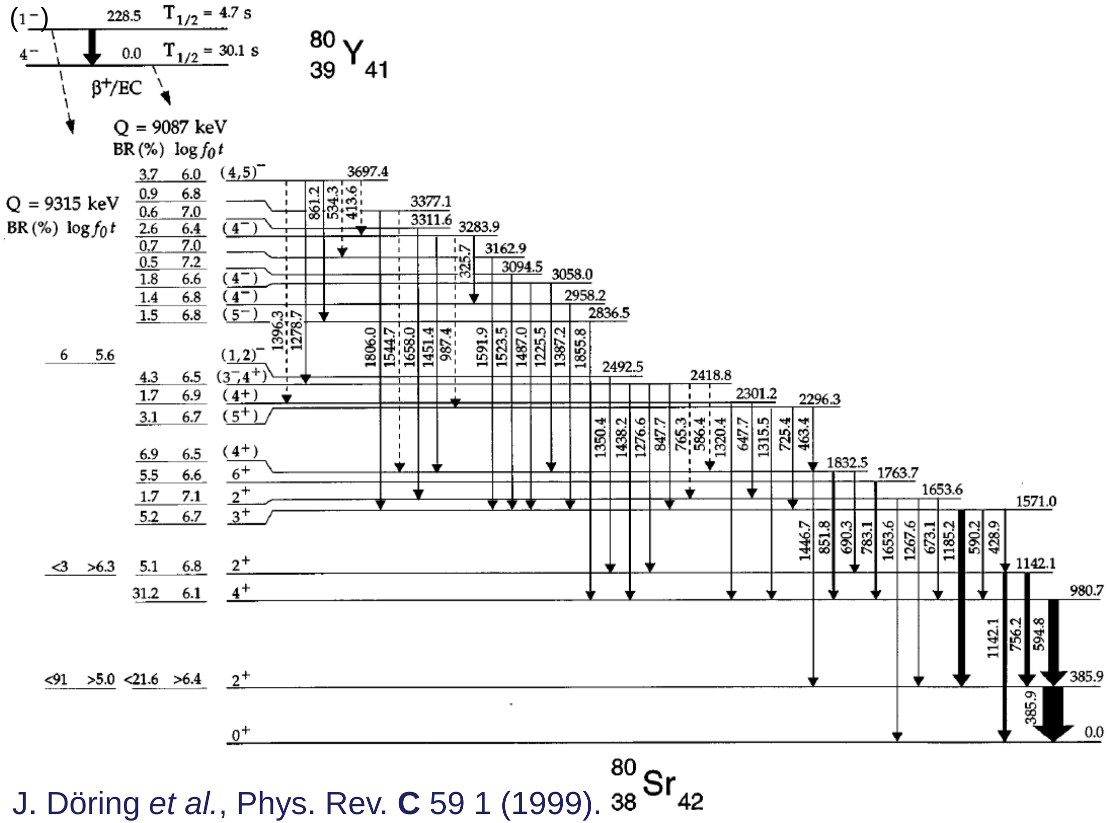
- The existence of low-lying excited $0^+$ states has been associated with shape coexistence and is predicted to manifest in the light Sr isotopes.
- Mixing of $0^+$ states could explain the anomalously high rotational parameter of the $2^+_1$ state in $^{80,82,84}$Sr.
- The identification of these states and the determination of ***ρ*²(*E0*)** will be used to investigate shape mixing at low spins.



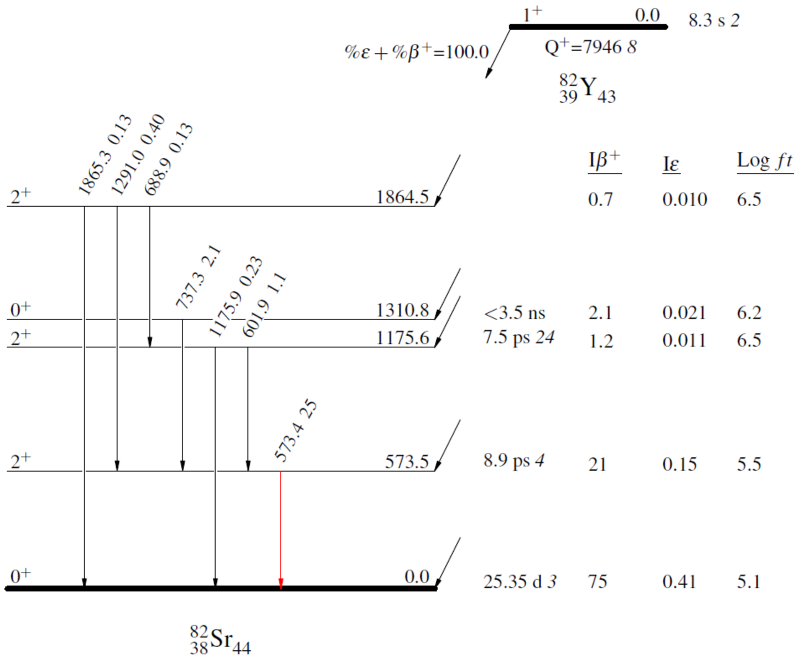

J. Döring *et. al.*, Res. Natl. Inst. Stand. Technol. **105**, 43 (2000).



- The $0^+_2$ state in $^{82}Sr$ is populated by the $1^+$ ground state of $^{82}Y$.
- For $^{80}Sr$, it is expected to be populated by the **(1⁻) isomer** in $^{80}Y$ which has a 19(2)% branch.

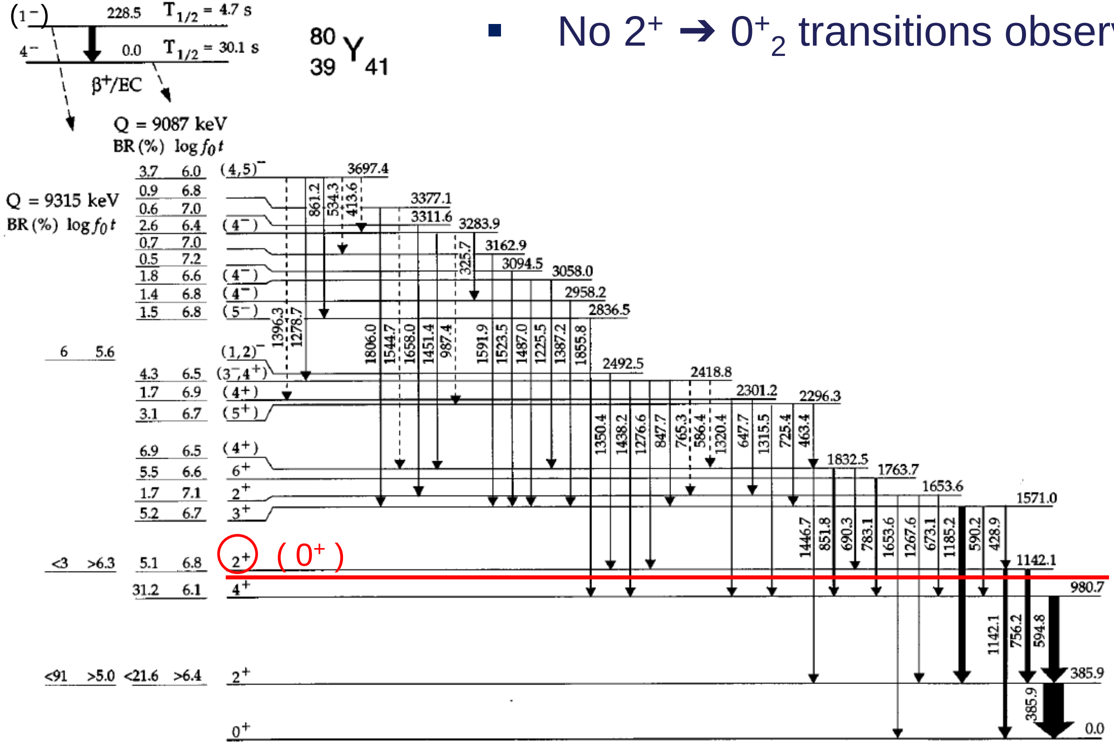



J. Döring *et al.*, Phys. Rev. **C** 59 1 (1999).

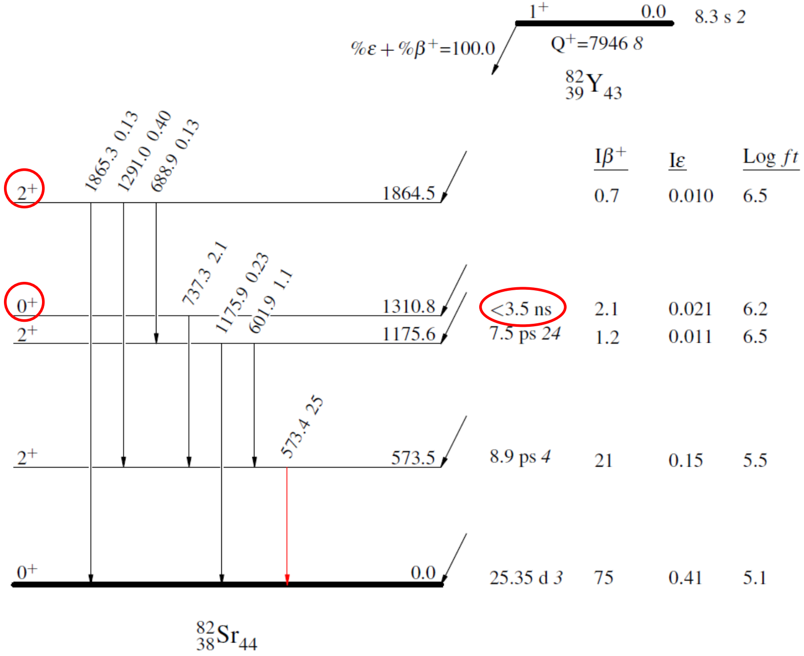



Adapted from M. Oinonen *et al.*,
Nucl. Instr. and Meth. In Phys. Res. **A416** 485 (1998).

- The $0^+_2$ state in $^{82}Sr$ is populated by the $1^+$ ground state of $^{82}Y$.
- For $^{80}Sr$, it is expected to be populated by the **($1^-$) isomer** in $^{80}Y$ which has a 19(2)% branch.
  - No $2^+ \rightarrow 0^+_2$ transitions observed (Chakraborty *et al.*, $^{94}Zr$ PRL 2013).




J. Döring *et al.*, Phys. Rev. **C** 59 1 (1999).



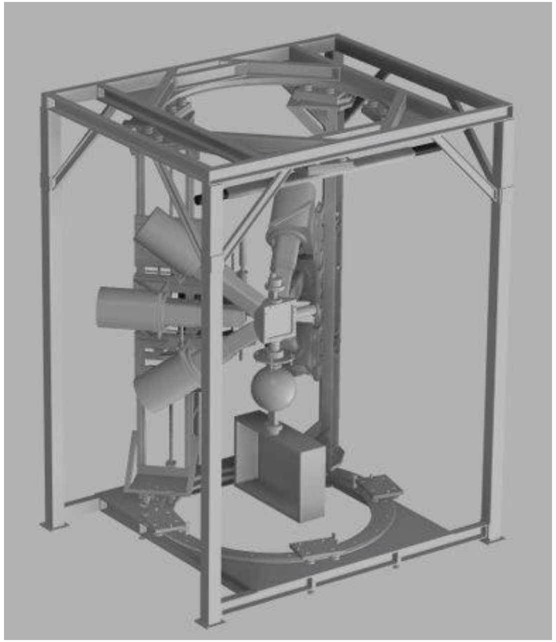

Adapted from M. Oinonen *et al.*,
Nucl. Instr. and Meth. In Phys. Res. **A416** 485 (1998).

# Decay Spectroscopy of $^{80,82}$Y at ISOLDE



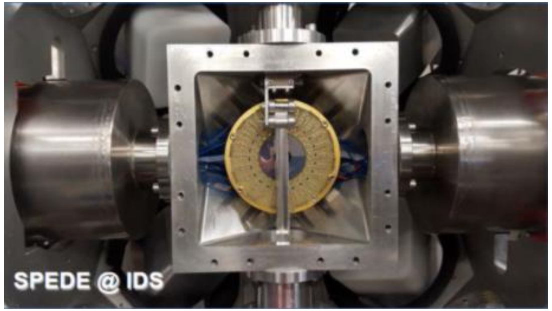
- To populate non-yrast low-lying states in $^{80,82}$Sr via $\beta^+/EC$ decay of $^{80,82}$Y using the enhanced efficiency of the new Isolde Decay Station (IDS) with two measurement positions:

  - The **implantation** position with 4 clovers and SPEDE, the conversion electron spectrometer, to measure the *E0* electrons, K-shell ratio and *E0* strengths.
  - The **decay** position with another 4 clovers and $LaBr_3$(Ce) fast-timing detectors to measure ps lifetimes using $\beta$-$\gamma_{Ge}$-$\gamma_{LaBr}$ coincidences.



- $q_k^2(E0/E2)$ is the K-shell ratio of the $0^+_2 \rightarrow 0^+_1$ and $0^+_2 \rightarrow 2^+_1$ competing transitions:

$$q_k^2(E0/E2) = \frac{I_k(E0)}{I_k(E2)} = \rho^2(E0)e^2r_0^4 \cdot \frac{\Omega_k(E0)}{\alpha_k(E2)} \cdot \frac{T_{1/2}}{\ln(2)}$$

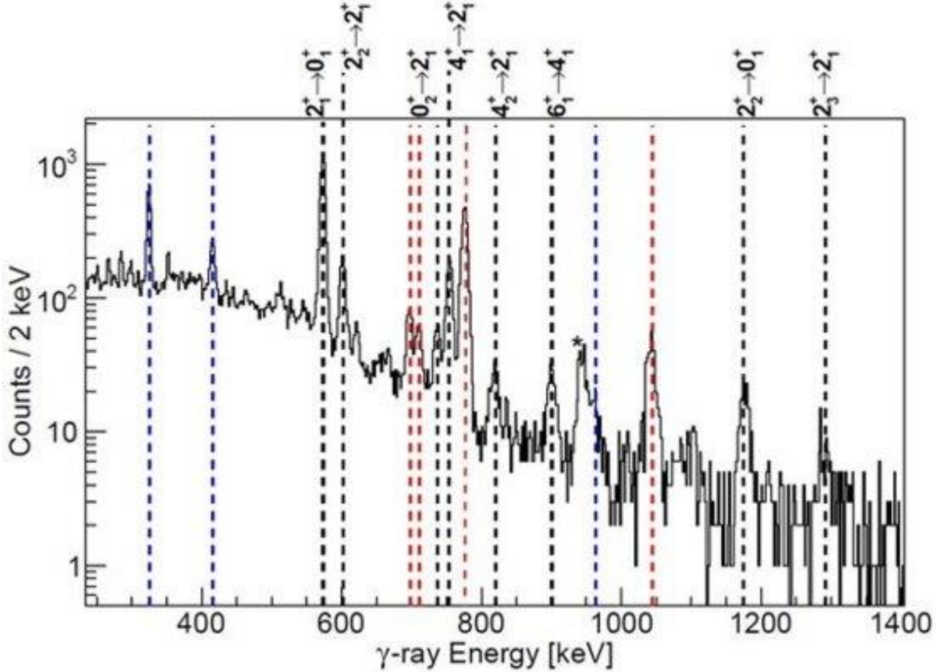


# Complementary Measurements



- $\rho^2(E0)$ will also be determined using the ***B*(*E2*) values** obtained from the complimentary multistep Coulomb excitation of $^{80,82}$Sr at safe energies approved with high priority and ran at TRIUMF with the TIGRESS array.

$$q_k^2(E0/E2) = \frac{I_k(E0)}{I_k(E2)} = \rho^2(E0)e^2r_0^4 \cdot \frac{\Omega_k(E0)}{\alpha_k(E2)} \cdot \frac{1}{2.54\text{x}10^9\ E_\gamma^5\ B(E2)}$$



# Beam Request



| Isotope | Half-life | Yield [ions/s] | $\beta$-$\gamma_{Ge}$-$\gamma_{Ge}$ [counts/shift] | $\beta$-$\gamma_{Ge}$-$\gamma_{LaBr}$ [counts/shift] | $0_2^+ \to 0_1^+$ K $E0$ $e^-$ [counts/shift] | $2_\gamma^+ \to 2_1^+$ K $E0$ $e^-$ [counts/shift] | # of shifts |
|---|---|---|---|---|---|---|---|
| $^{80}$Y | 4.8(3) s | 1 x $10^4$ | ~ 2 x $10^2$ | ~ 1 x $10^2$ | 40 | 3 x $10^3$ | 9 |
| $^{82}$Y | 8.3(2) s | 1 x $10^5$ | 4 x $10^4$ | 1 x $10^4$ | 140 | 9 x $10^4$ | 6 |

- **Pure** $YF_2^+$ molecular beams will be produced from a Nb foil target with a W surface ionizer and a $CF_4$ leak.
- Yields from the SC were published, however a yield for the isomer of the $^{80}$Y is not quoted. We request a run of **3 shifts** for yield confirmation from the PSB.

- An uncertainty of 6% on $q_K^2(E0/E2)$ will be obtained with **9 shifts** of $^{80}$Sr and 4%, in **6 shifts** of $^{82}$Sr.
- Total of 18 shifts + 1 shift of beam tunning

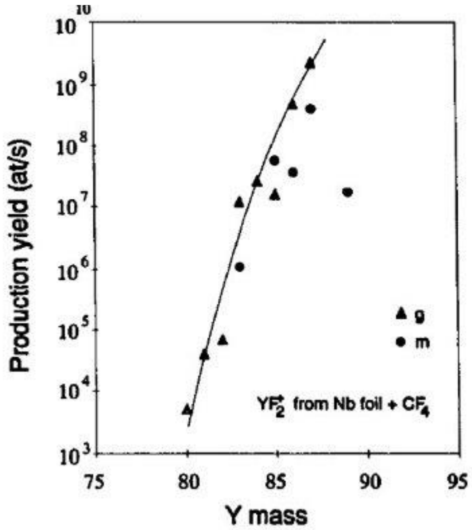



Fig. 3. Production yields of $YF_2^+$ ions from a 47 g/cm² Nb foil target equipped with a W surface ionizer and a $CF_4$ leak (g = ground state, m = isomer). Irradiation: 600 MeV protons.

R. Eder et al., Nucl. Instr. and Meth. in Phys. Res. B **62** 4 535-540 (1992).

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RESPICE PROSPICE

# Thanks to collaborators!


N. Bernier[1,2], T. D. Bucher[1,2], J. N. Orce[1], L. J. Evitts[3], T. Kibédi[4], P. E. Garrett[5,1], T. R. Rodriguez[6], K. J. Abrahams[1], E. H. Akakpo[1], A. Algora[7], A. Andreyev[8], H. Bidaman[5], V. Bildstein[5], M. J. G. Borge[9], S. Buck[5], A. Briscoe[10], J. A. Briz[9], K. Chrysalidis[15], J. Cubiss[6], L. M. Fraile[11], J. Henderson[12], A. Illana[10,13], D. G. Jenkins[8,1], A. Korgul[14], R. Lica[15], C. V. Mehl[1], K. Miernik[14], A. I. Morales[5], E. Nácher[5], C. Ngwetsheni[1], S. S. Ntshangase[2], J. Ojala[10], B. Olaizola[15], S. Orrigo[5], R. Page[16], J. Pakarinen[10], M. Piersa[14], A. Radich[5], S. Rothe[15], B. Rubio[7], J. Smallcombe[16], M. Stryjczyk[17], S. Triambak[1], S. Valbuena[5], R. Wadsworth[8]

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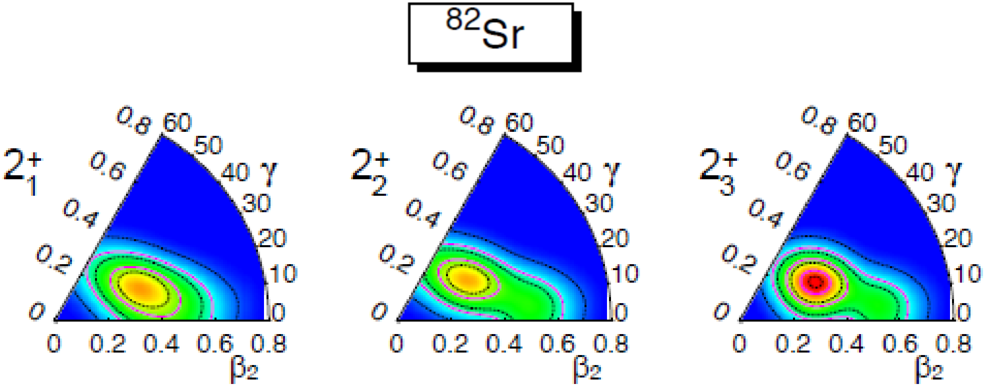
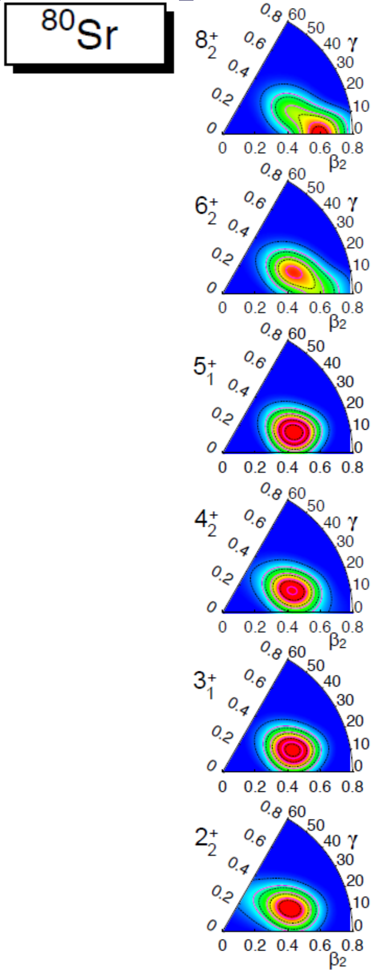
# $2^+_\gamma \rightarrow 2^+_1$

- $B(E2;2^+_\gamma \rightarrow 2^+_1)$ values can also give the *E2*/*M1* mixing ratio $\delta^2$ ($\delta^2 = +1.2(14)$ for $^{82}$Sr, NNDC), which is crucial to explain the deviation from rotor patterns.
- As *E0* processes have a $\Delta K = 0$ selection rule, mixing between $\Delta K = 2$ bands can be established from large *E0* strengths between $2^+$ states (Heyde & Wood, 2011).




T. Rodriguez (2020).