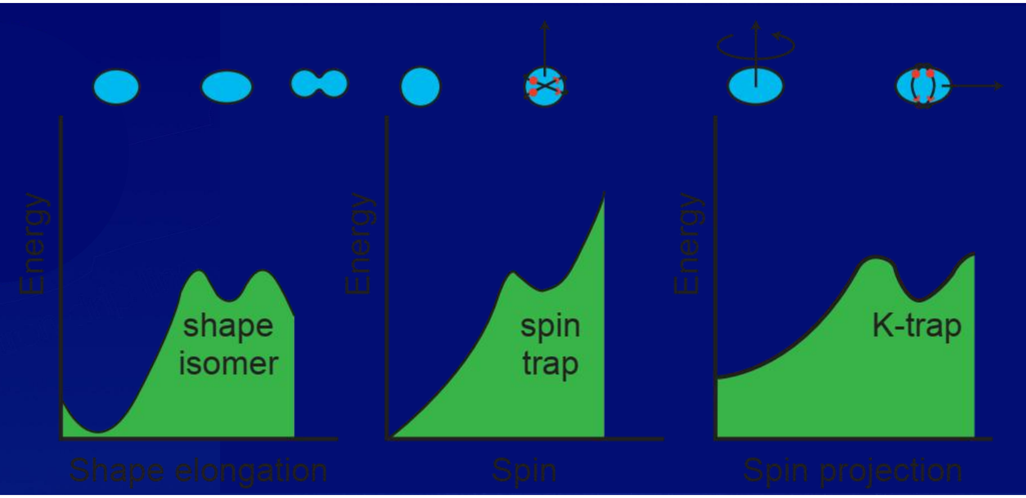
Metastable States of ^{92,94}Se: Identification of an Oblate K Isomer of ^{94}Se and the Ground State Shape Transition between N = 58 and 60

C. Lizarazo *et.al.*,



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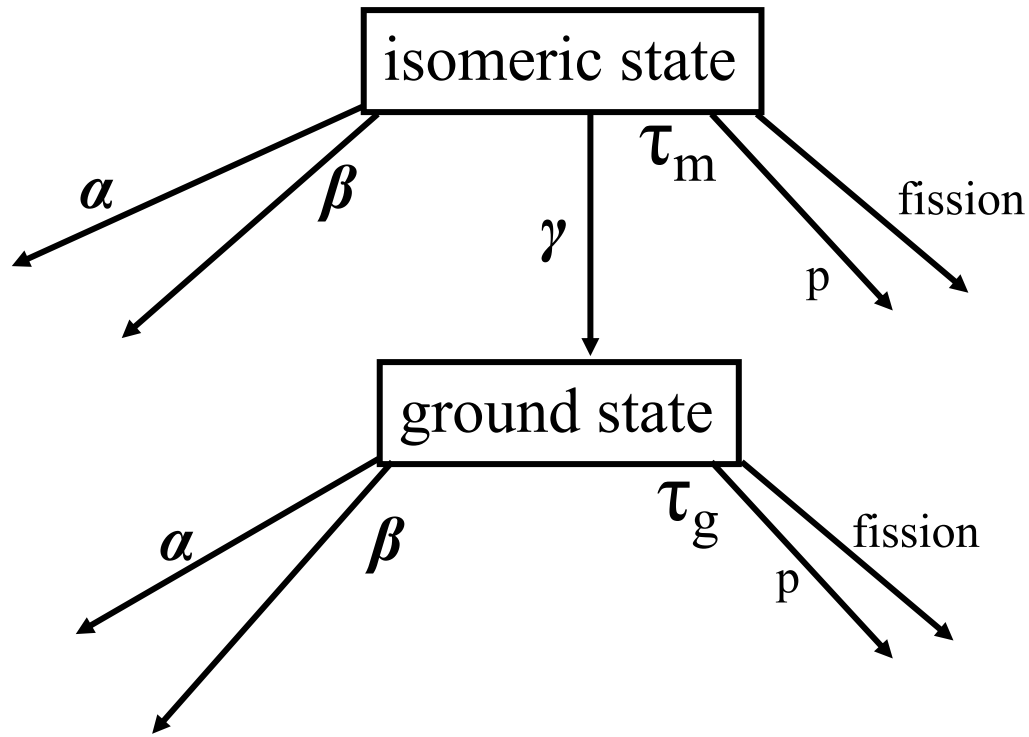
Journal Club, October 31st @ Zhuhai, Guangdong

Nuclear isomers

"The existence of isotopic isobars (same-Z, same-A), with clearly distinguishable properties such as different radioactive half-periods, was anticipated in 1917 when Soddy proposed that such nuclei be called isomers if and when found." Evans, 1955

"An excited nuclear state which endures long enough to have a directly measurable lifetime is called an isomeric state." Bethe, 1956

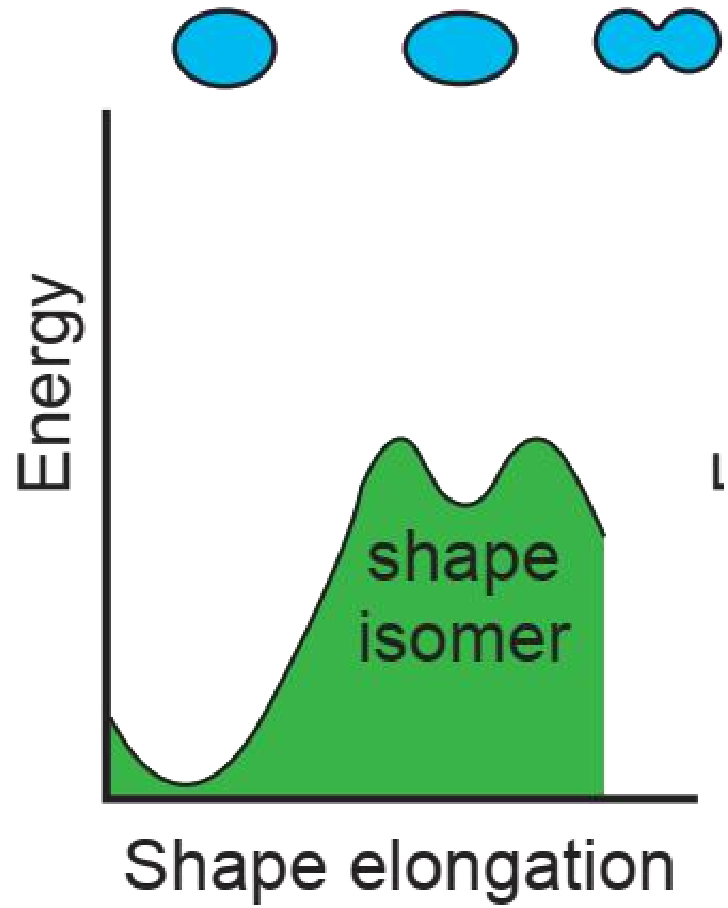
Rule of thumb:
$\tau > 1$ ns



Types of isomers

Shape isomers

- A secondary energy minimum at large elongation.
- Fission isomers in heavy nuclei, such as ^{242}Am.
- Elongated such that its major-to-minor axis ratio is about 2:1
- Decay back to the ground state competes with fission.



Types of isomers

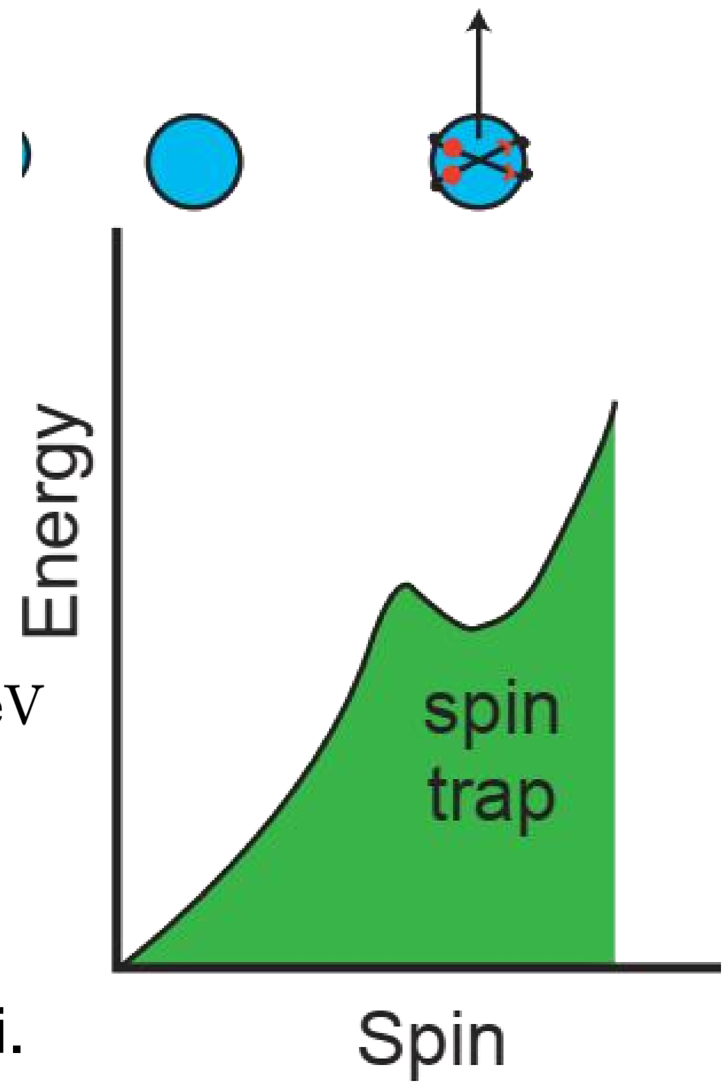
Spin trap

- The decay path to lower energy states requires a large change in nuclear spin, and therefore the emission of radiation with a high multipolarity $\lambda = \Delta I$

- ^{180m}Ta case:
  g.s.: 1^+, isomer: 9^-, $\lambda = 8, E_x = 77.2\ \mathrm{keV}$

$$T_{1/2}\,(\mathrm{g.s.}) = 8.154\ \mathrm{h}$$
$$T_{1/2}\,(9^-) > 7.1 \times 10^{15}\ \mathrm{a}$$

- In spherical or near-spherical nuclei.



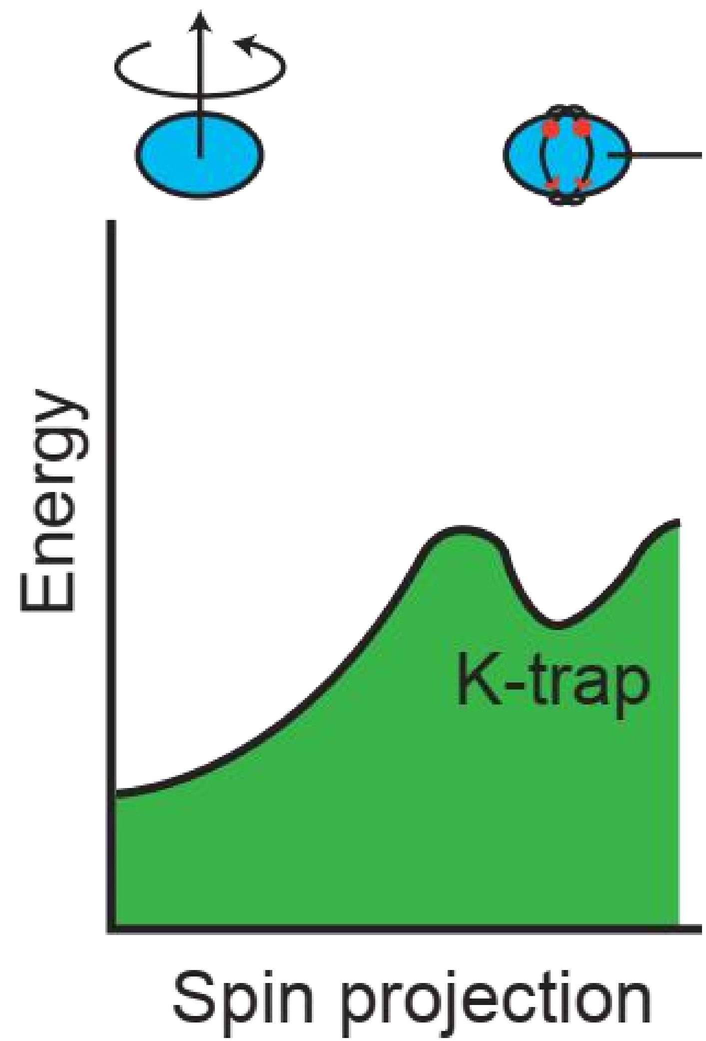
Types of isomers

K traps (K isomers)

- A special spin trap depends on spin's orientation.
- K represents the projection of the total nuclear spin along the symmetric axis of the nucleus.
- ^{180m}Hf case:
  isomer: I = 8, K = 8, at 1.1 MeV
  probable decay to I = 8, K = 0 state

$$\Delta K = 8, \lambda = 0, f = \Delta K - \lambda = 8$$

$$\Rightarrow T_{1/2}\left(8^{-}\right) = 5.5 \text{ h}$$



- In axially deformed (mainly prolate) nuclei.

Motivation

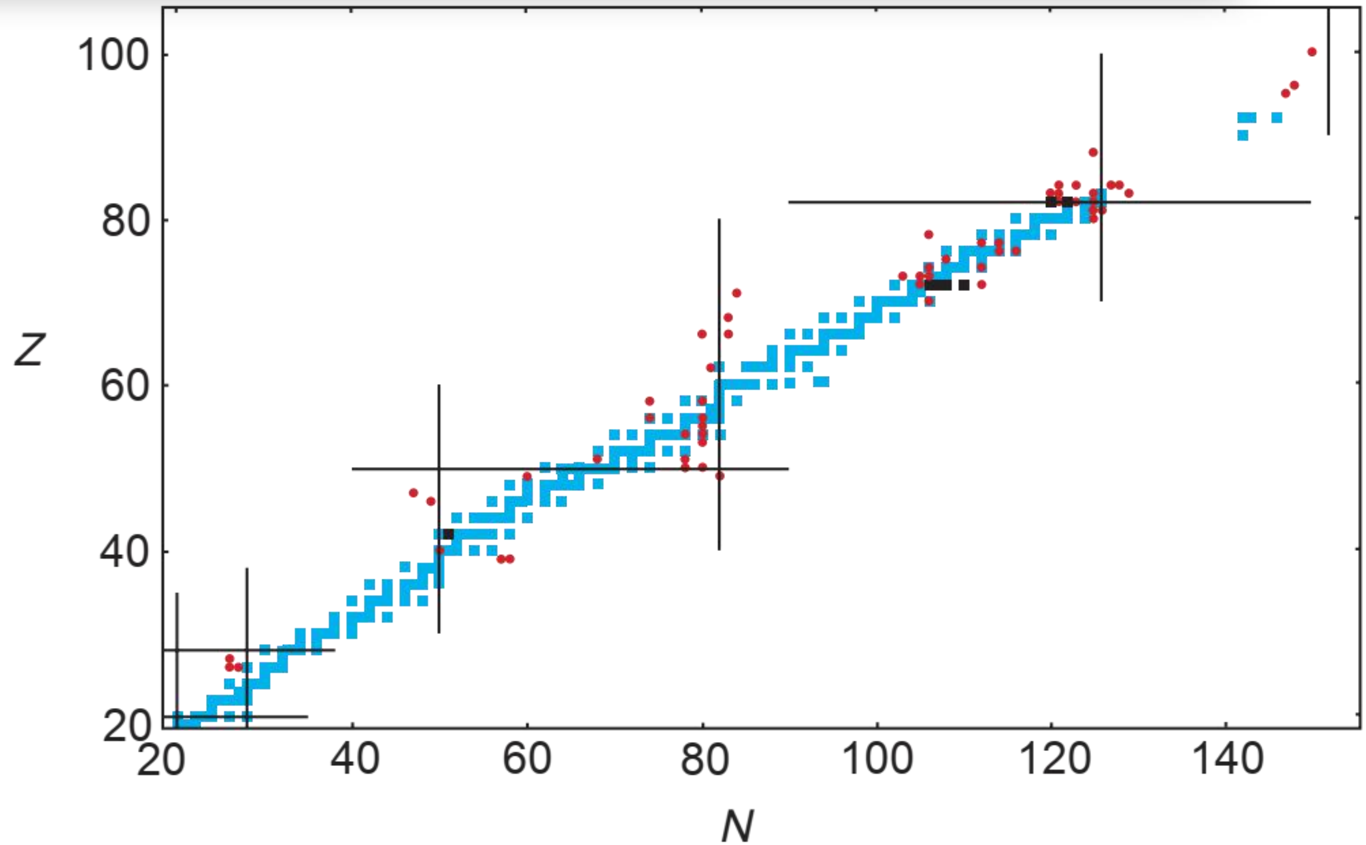


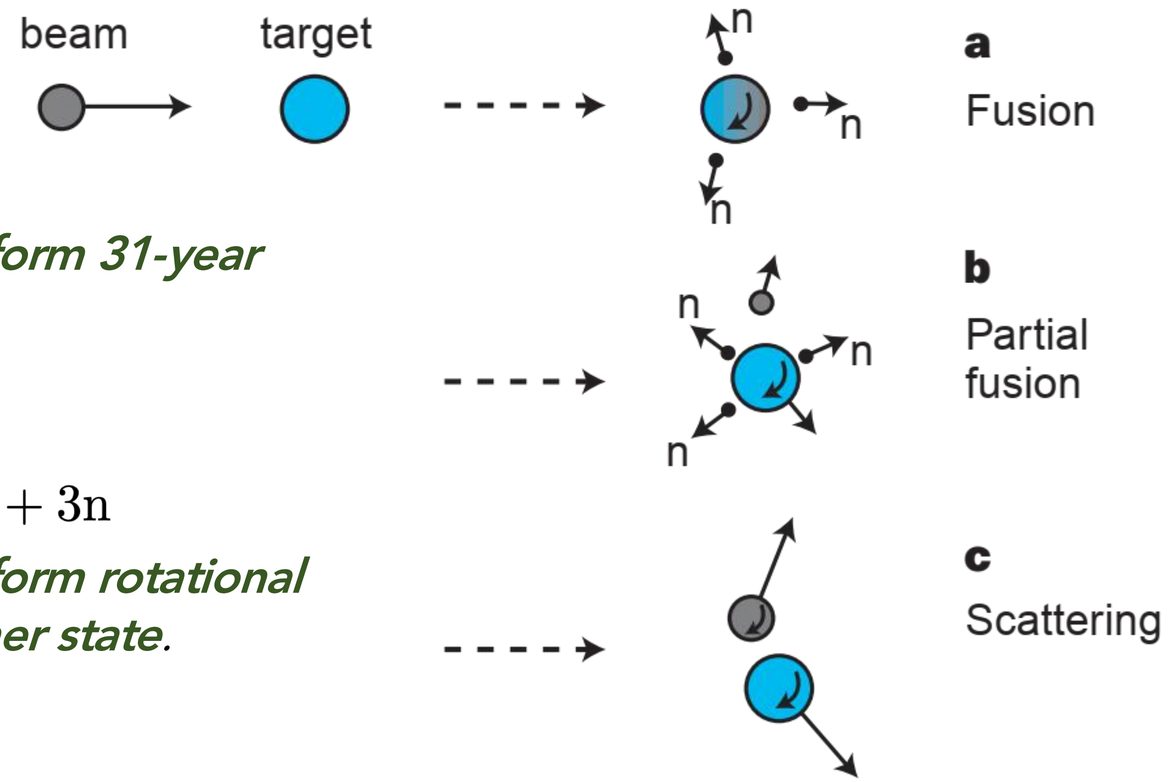
Figure 2 Chart of atomic nucleic, as a function of neutron number (*N*) and proton number (*Z*). Naturally occurring isotopes are represented by blue squares. The straight lines are drawn for the 'magic numbers' that correspond to closed shells (and spherical shapes). The other symbols indicate isomers with excitation energies greater than 1 MeV and long half-lives: red circles for >1 ms, and black squares for >1 hour. The data are taken from refs. 4, 10, 11.

Making spin traps

Fusion: Colliding ^{4}He into ^{176}Yb, and evaporates two neutrons.

$$^4\mathrm{He} + ^{176}\mathrm{Yb} \rightarrow ^{178m}\mathrm{Hf} + 2\mathrm{n}$$

bring up to 16 hbar spins and form 31-year 16^+ isomer state.



Partial fusion:

$$^9\mathrm{Be} + ^{176}\mathrm{Yb} \rightarrow ^{178m}\mathrm{Hf} + ^4\mathrm{He} + 3\mathrm{n}$$

bring up to 23 hbar spins and form rotational band built on 31-year 16^+ isomer state.

Scattering reaction:

Bombarding heavy, deformed, target nuclei, such as ^{180}Hf with heavy, deformed, projectile nuclei, such as ^{238}U

Nucleons can also be exchanged, so that states in adjacent nuclei may also be reached.

Motivation

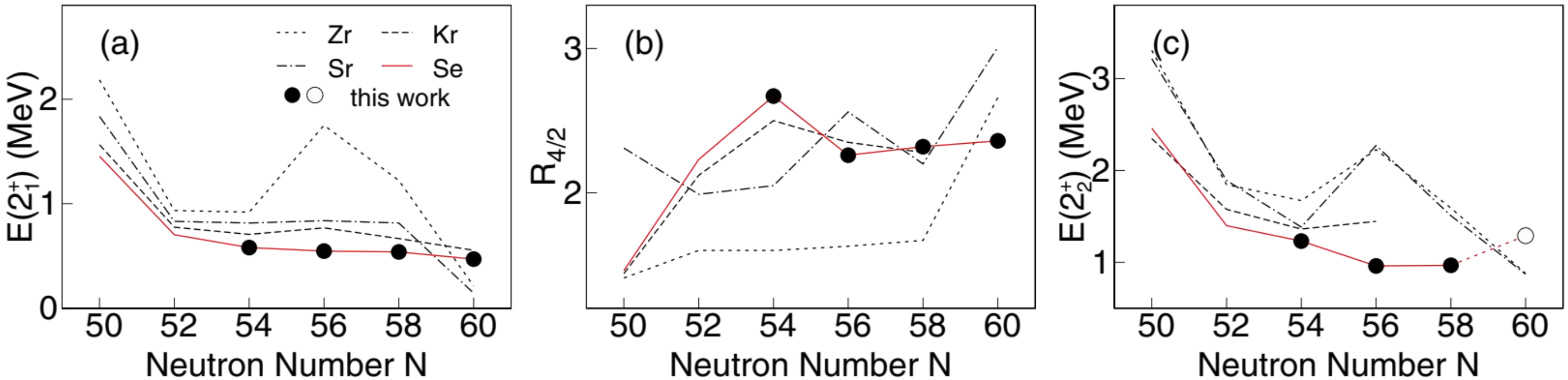
The purpose of this Paper: presents new information on the shape evolution of the very neutron-rich $^{92,94}Se$ nuclei from an isomer-decay spectroscopy experiment.

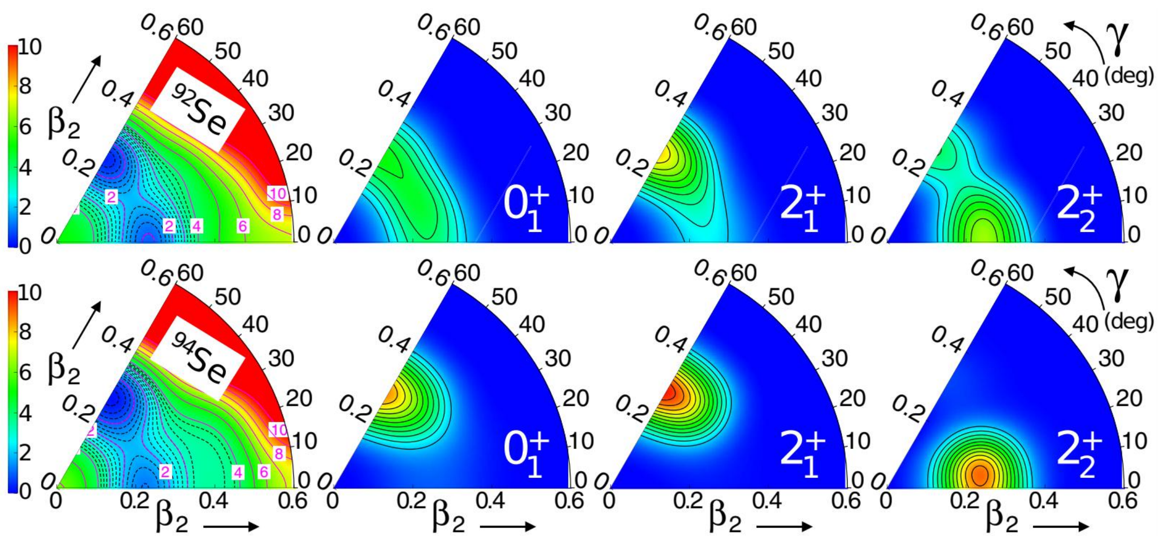
Highlights:

- The isomeric levels are interpreted as originating from high-*K* quasineutron states with an oblate deformation of $\beta \sim 0.25$.
- ^{94}Se is the **lowest-mass** neutron-rich nucleus known to date with such a substantial *K* hindrance.
- The first observation of an ***oblate K*** isomer in a deformed nucleus.

Motivation

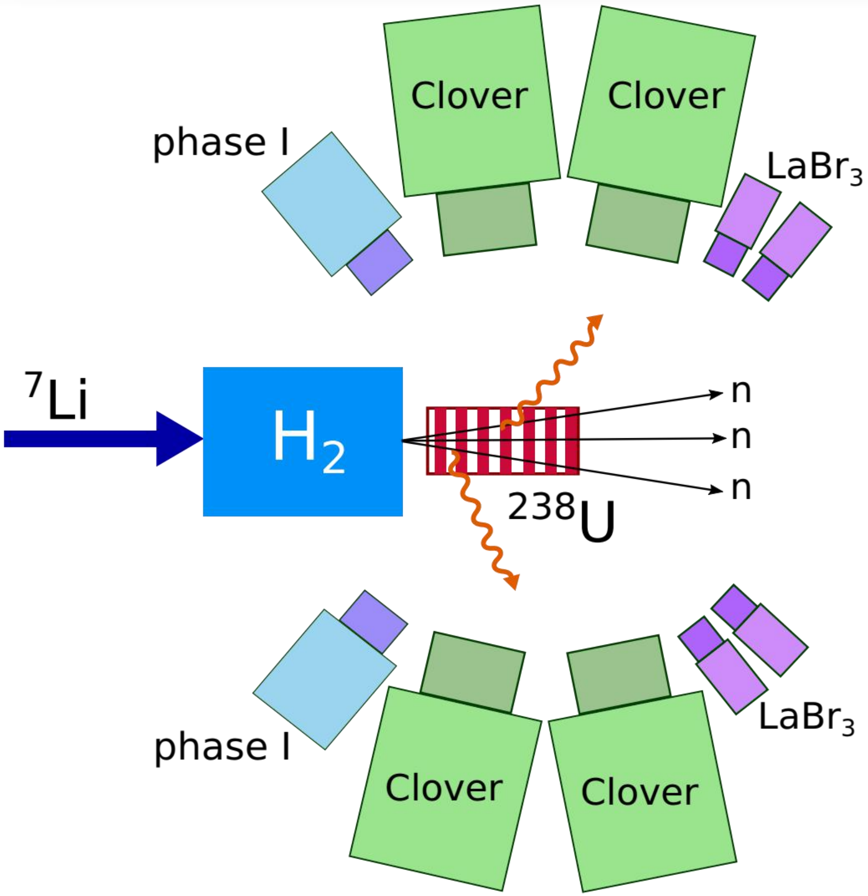
Another thing: both triaxial degree of freedom and shape coexistence playing important roles in the description of intrinsic deformations in neutron-rich Se isotopes.

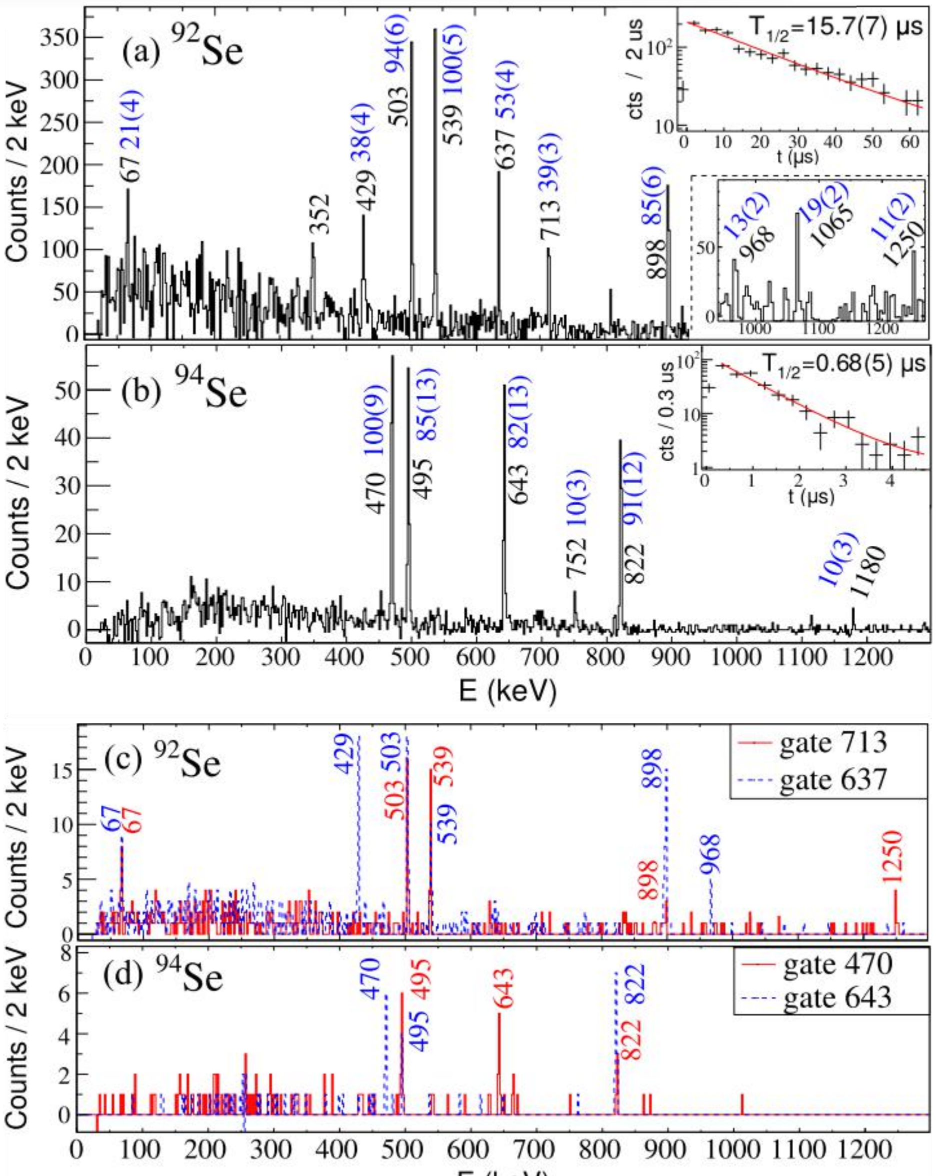




S. Chen et. al., PRC 95, 041302(R) (2017).

Experiment


phase I
Clover
Clover
LaBr3
7Li
H2
n
n
n
238U
phase I
Clover
Clover
LaBr3

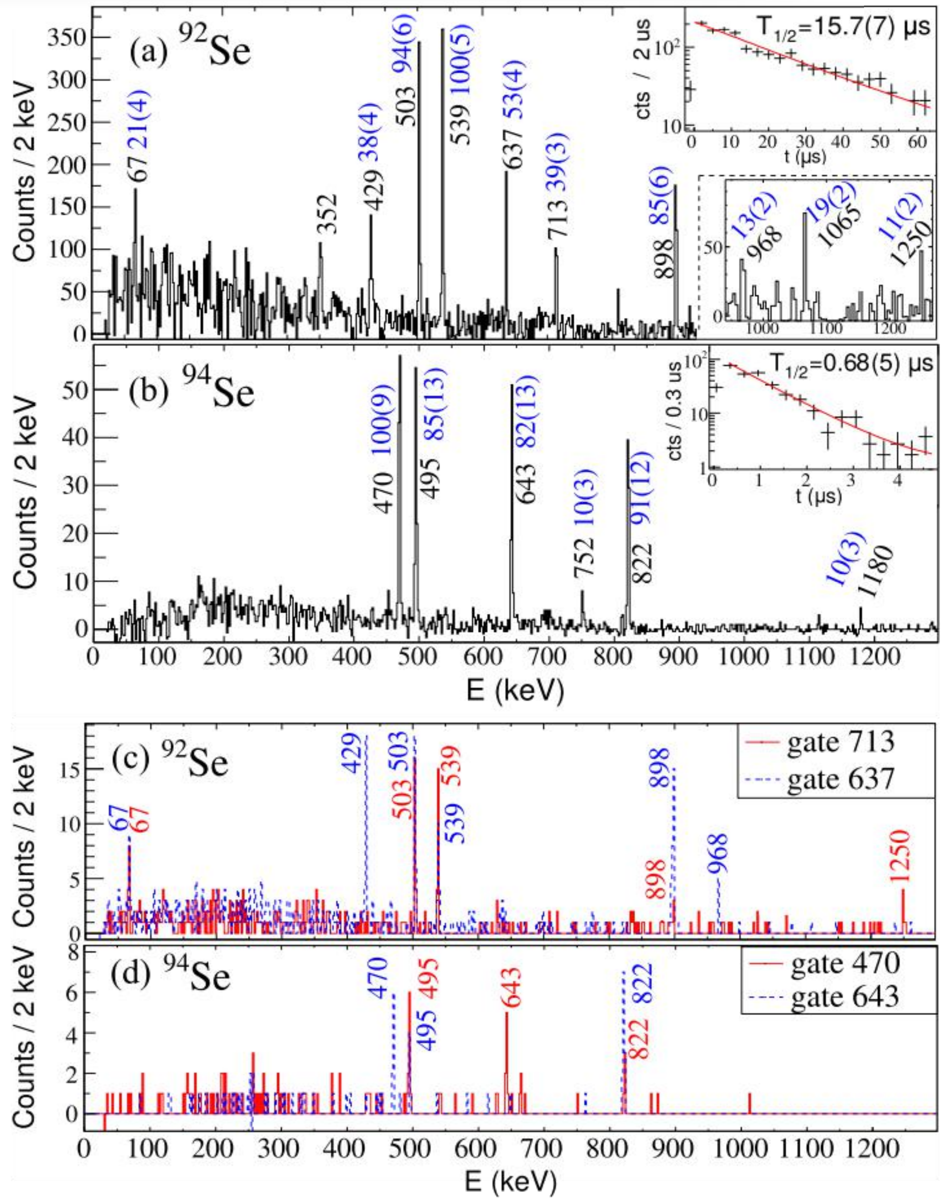

(a) 92Se
T1/2=15.7(7) μs
(b) 94Se
T1/2=0.68(5) μs
(c) 92Se
gate 713
gate 637
(d) 94Se
gate 470
gate 643
Counts / 2 keV
E (keV)

Data analysis

For ^{92}Se, γ rays detected within $0.19 \leq t_\gamma \leq 70$ μs were used.

A spectrum of events with $t_\gamma \geq 70$ μs was scaled and subtracted to further reduce the environmental background component.

The half-life was determined using an exponential decay curve plus a constant baseline.



The half-life of $K^\pi = 7^-$ isomers:

$$T_{1/2} = 15.7(7)\ \mu\text{s in } ^{92}\text{Se}$$

$$T_{1/2} = 0.68(5)\ \mu\text{s in } ^{94}\text{Se}$$

Data analysis

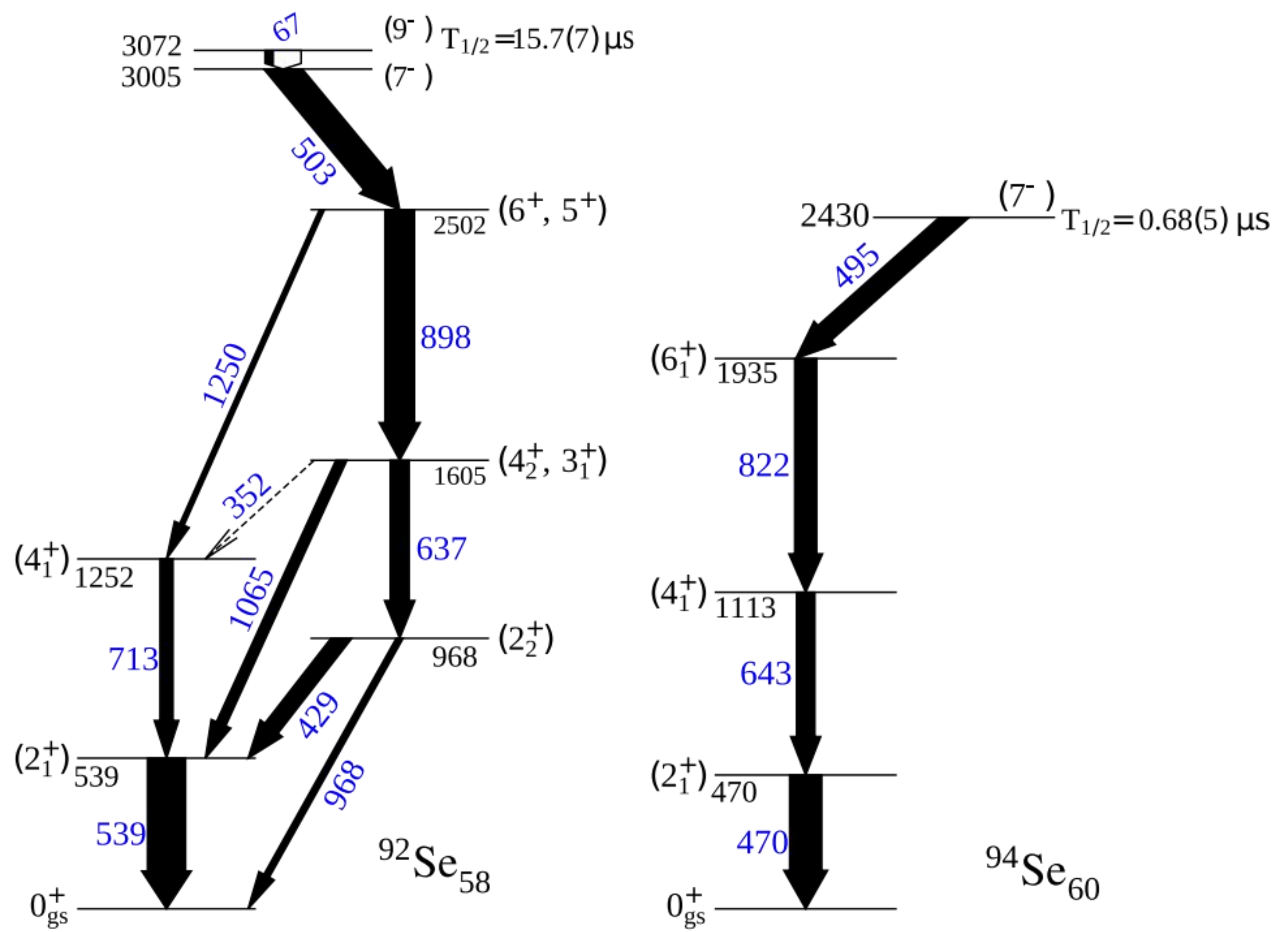
Level schemes constructed for ^{92,94}Se

Deduced from energy-sum checks, $\gamma\gamma$ coincidences, and sums of efficiency-corrected intensities.

The average internal conversion coefficient of the 67-keV transition is α = 3.4(6)

favors *E*2 transition

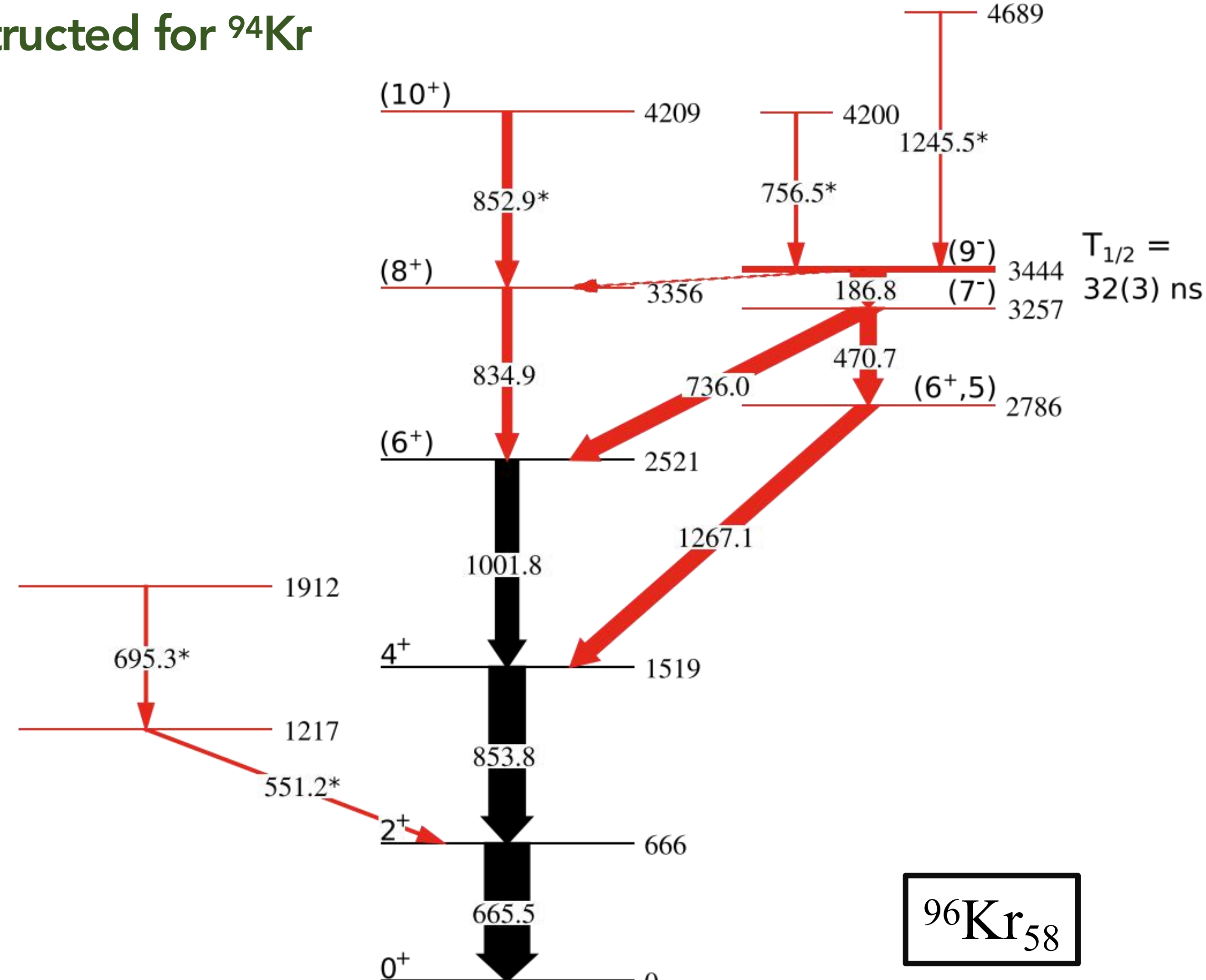
The 3005- and 3072-keV levels have same parity and ΔJ = 2



Data analysis

R. -B. Gerst et. al., PRC 102, 064323 (2020).

Level schemes constructed for ^{94}Kr



Why *K* isomers are usually prolate

Example: the configuration of high-K isomers in ^{178}W.

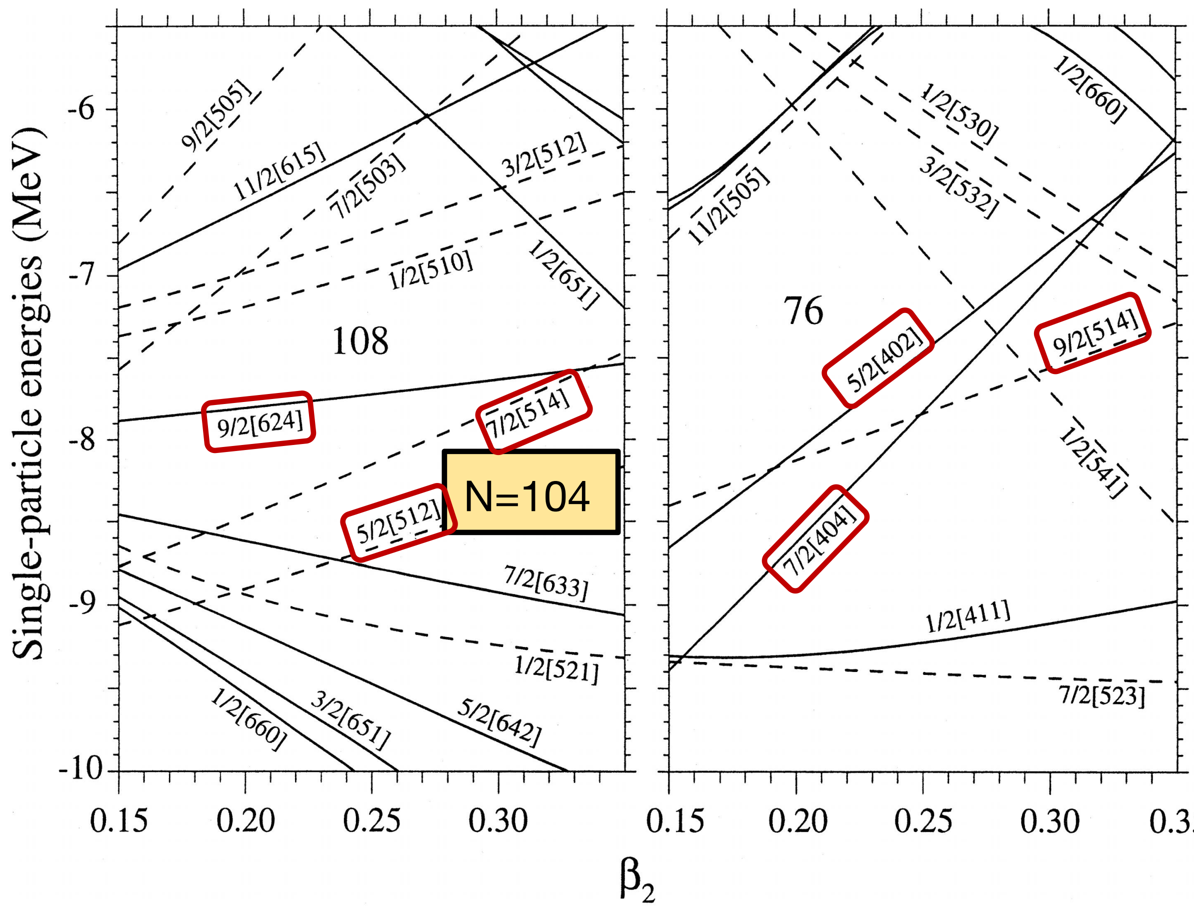
$$K = \Omega_1 + \Omega_2$$

Sum of the projection of angular momentum of the broken-pair nucleons

Large *K* → *K* forbidden → metastable isomers

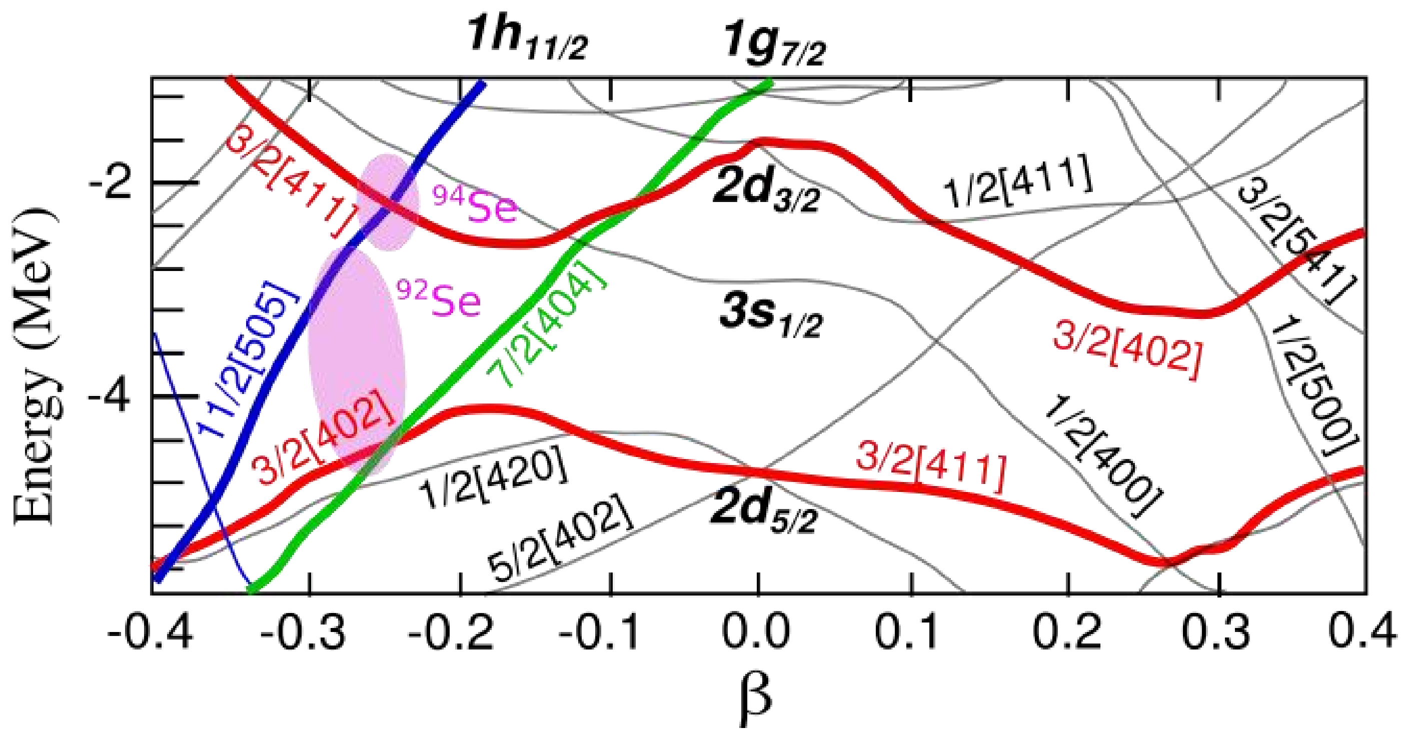
$$K^\pi = 6^+: \ \nu\frac{7}{2}[514] \otimes \nu\frac{5}{2}[512]$$

$$K^\pi = 8^-: \ \nu\frac{9}{2}[624] \otimes \nu\frac{7}{2}[514]$$



Discussions

The Nilsson diagrams obtained by Gogny HFB calculations



$$K^{\pi} = 7^{-}(\nu 11/2^{-}[505] \otimes \nu 3/2^{+}[402])$$

$$K^{\pi} = 9^{-}(\nu 11/2^{-}[505] \otimes \nu 7/2^{+}[404])$$

at oblate deformations of $\beta \sim -0.24$

Discussions

Configuration-constrained PES calculations for high-*K* states

Solve the Shrödinger equation $H_{\mathrm{WS}}\Psi = E_{\mathrm{WS}}\Psi,$

with the Woods-Saxon potential,

$$H_{\mathrm{WS}} = T + V(r,\hat{\beta}) + V_{l\cdot s}(r,\hat{\beta}) + \frac{1}{2}(1+\tau_3)V_{\mathrm{c}}(r,\hat{\beta}),$$

where

$$V(r,\hat{\beta}) = \frac{-V_{00}\left[1 \pm \kappa\frac{N-Z}{N+Z}\right]}{1+\mathrm{e}^{\frac{r-R}{a}}}$$

Central force

$$V_{l\cdot s}(r,\hat{\beta}) = \lambda\left(\frac{\hbar}{2Mc}\right)^2[\nabla V(r,\hat{\beta})\times p]\cdot\sigma,$$

Spin-orbit term

$$V_{\mathrm{c}}(r,\hat{\beta}) = \frac{Z-1}{\frac{4}{3}\pi R^3}\int\frac{1}{|r'-r|}\mathrm{d}^3r'$$

Coloumb term

Discussions

Configuration-constrained PES calculations for high-*K* states

Pairing treatment: **Lipkin-Nogami method**

Add a residual pairing interaction to the Hamiltonian

$$H = H_{sp} - G \sum_{k,k'>0} a_k^\dagger a_{\bar{k}}^\dagger a_{k'} a_{\bar{k}'}$$

And the BCS wave function is

$$|\mathrm{BCS}\rangle = \prod_{k>0} \left(u_k + v_k a_k^\dagger a_{\bar{k}}^\dagger \right) |0\rangle$$

The v_k^2 and u_k^2 represent the probability that a certain pair state is or is not occupied, which has to be determined in such a way that the corresponding energy has a minimum (variational principle).

The should fulfill $2\sum_k v_k^2 = N$

The variational Hamiltonian is $H' = H - \lambda N$

Discussions

But BCS method would collapse if the pairing is too weak. Now we add high order particle-number constraint

$$\hat{H}_{LN} = \hat{H} - \lambda \hat{N} - \lambda_2 \hat{N}^2$$

And solve equations iteratively:

$$N = 2\sum_k v_k^2$$

$$\frac{2}{G} = \sum_k \frac{1}{\sqrt{(\epsilon_k - \lambda)^2 + \Delta^2}}$$

$$\epsilon_k = e_k + (4\lambda_2 - G)\, v_k^2$$

$$v_k^2 = \frac{1}{2}\left[1 - \frac{\epsilon_k - \lambda}{\sqrt{(\epsilon_k - \lambda)^2 + \Delta^2}}\right]$$

$$\lambda_2 = \frac{G}{4}\left[\frac{(\Sigma_k u_k^3 v_k)(\Sigma_k u_k v_k^3) - \Sigma_k u_k^4 v_k^4}{(\Sigma_k u_k^2 v_k^2)^2 - \Sigma_k u_k^4 v_k^4}\right]$$

Discussions

The expectation value of the total Hamiltonian becomes

$$E_{LN} = \sum_k 2v_k^2 e_k - \frac{\Delta^2}{G} - G\sum_k V_k^4 - 4\lambda_2 \sum_k (u_k v_k)^2$$

If we want to create a broken pair, block the i- and j-th single-particle orbitals, make sure that in every iteration the $v_i = 1$, $v_j = 1$. And the *LN* energy is

$$E_{LN} = \sum_{j=1}^{S} e_{k_j} + \sum_{k\neq k_j} 2v_k^2 e_k - \frac{\Delta^2}{G} - G\sum_{k\neq k_j} v_k^4 + G\frac{N-S}{2} - 4\lambda_2 \sum_{k\neq k_j} (u_k v_k)^2 。$$

Using macroscopic-microsopic method, i.e.,

$$E_{\mathrm{tot}} = E_{\mathrm{LDM}} + E_{\mathrm{LN}} - \tilde{E}_{strut}.$$

Calculate the energies with different β_2, β_4, and γ to get the configuration-constrained PES.

Discussions

Results given by Configuration-constrained PES

For ^{92}Se: g.s. deformation is **prolate**

$$K^\pi = 7^-(\nu 11/2^-[505] \otimes \nu 3/2^+[402])$$

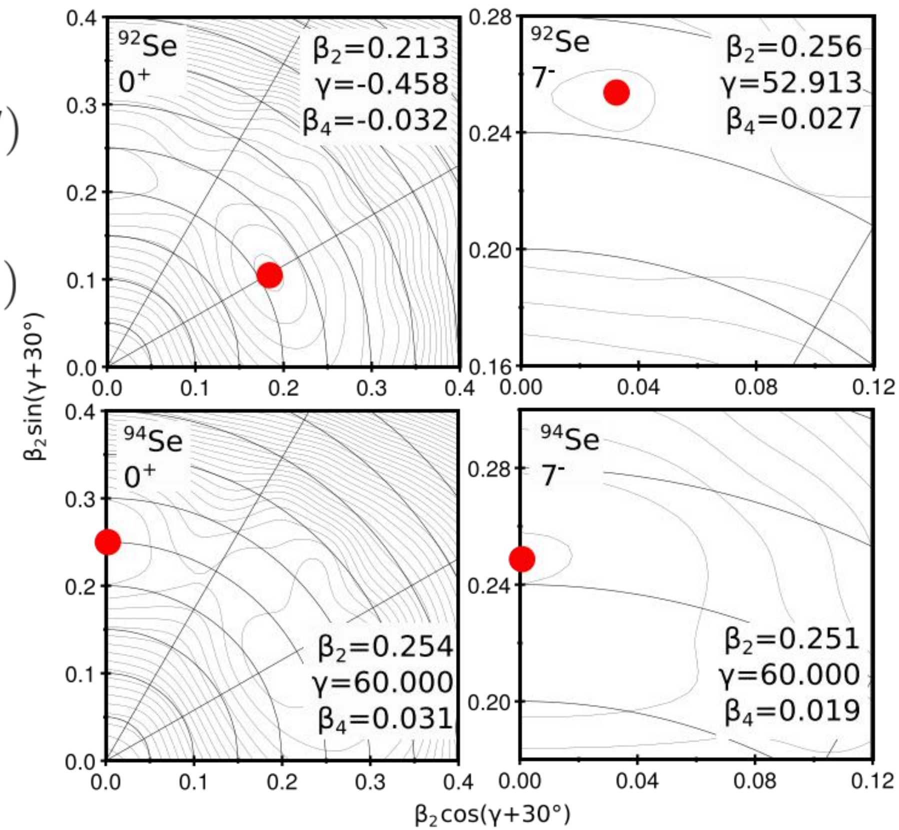
deformation: $(\beta_2, \gamma, \beta_4) = (0.256, 52.9, 0.027)$

$$K^\pi = 9^-(\nu 11/2^-[505] \otimes \nu 7/2^+[404])$$

deformation: $(\beta_2, \gamma, \beta_4) = (0.254, 54.1, 0.021)$

表 1　N=58 同中子链中 $K^\pi = 9^-$ 态激发能与形变参数的计算结果*

核素	β_2(基态)	β_2(激发态)	γ(基态) /(°)	γ(激发态) /(°)	E_{cal} /keV	E_{exp} /keV
^{88}Zn	0.182	0.183	0	45	6 026	
^{90}Ge	0.198	0.196	1	58	3 286	
^{92}Se	0.208	0.209	0	60	3 255	3 072
^{94}Kr	0.253	0.238	0	58	3 322	3 444
^{96}Sr	0.315	0.206	0	60	3 853	3 524
^{98}Zr	0.309	0.199	0	57	3 522	
^{100}Mo	0.202	0.195	35	54	3 362	
^{102}Ru	0.195	0.180	24	0	3 353	
^{104}Pd	0.140	0.164	0	20	4 987	
^{106}Cd	0.127	0.127	0	15	5 809	



Discussions

Results given by Configuration-constrained PES

For ^{94}Se: g.s. deformation is **oblate**

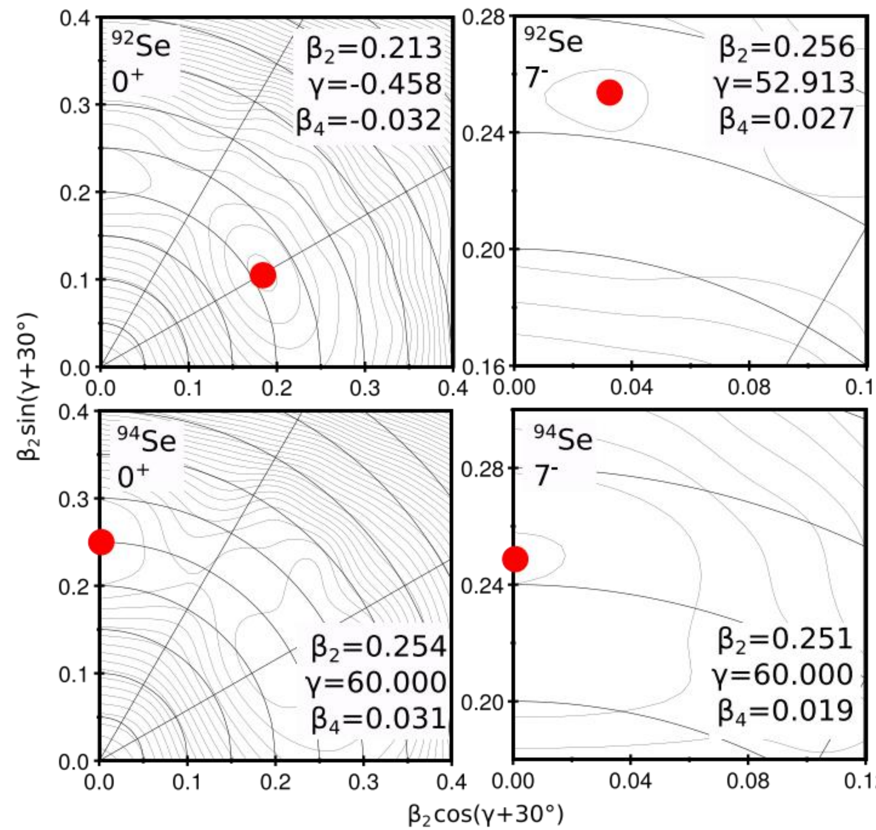
$$K^{\pi} = 7^{-}(\nu 11/2^{-}[505] \otimes \nu 3/2^{+}[402])$$

deformation:

$$(\beta_2, \gamma, \beta_4) = (0.251, 60.0, 0.019)$$

表 2 N=60 同中子链中 $K^{\pi}=7^{-}$ 态激发能与形变参数的计算结果*

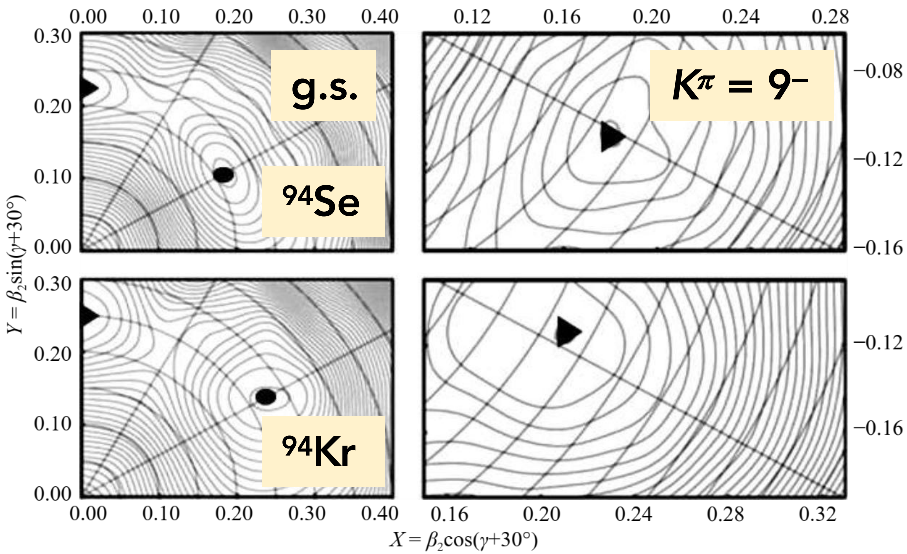
核素	β_2 (基态)	β_2 (激发态)	γ (基态) /(°)	γ (激发态) /(°)	E_{cal} /keV	E_{exp} /keV
^{90}Zn	0.195	0.207	56	47	2 259	
^{92}Ge	0.210	0.219	1	41	2 353	
^{94}Se	0.239	0.236	58	58	2 431	2 400
^{96}Kr	0.309	0.254	0	59	2 837	
^{98}Sr	0.334	0.221	0	57	3 791	
^{100}Zr	0.340	0.213	1	50	3 511	
^{102}Mo	0.262	0.262	21	15	2 578	
^{104}Ru	0.226	0.233	31	20	2 621	
^{106}Pd	0.174	0.188	0	2	1 786	
^{108}Cd	0.134	0.159	0	1	2 043	



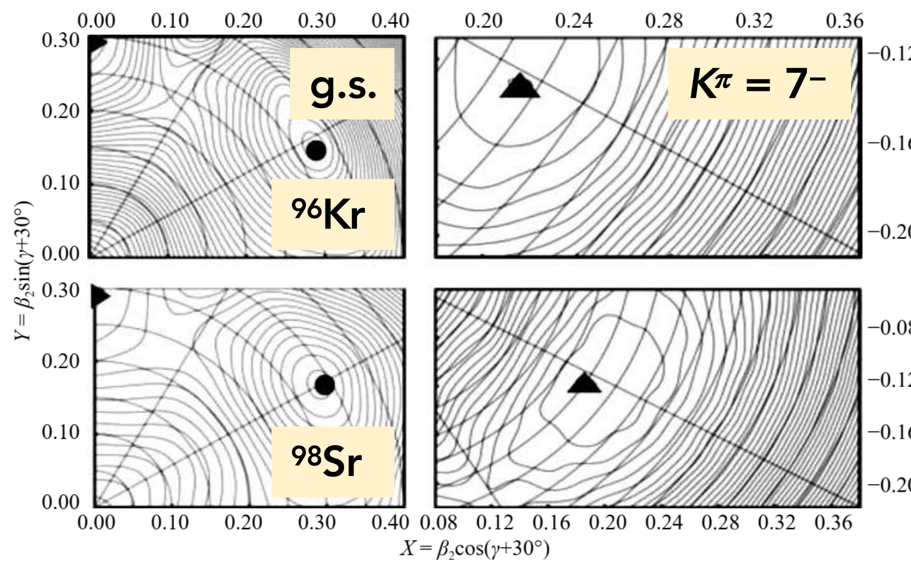
The rather soft potential energy surface implying that K is a less well-defined quantum number.

Discussions

More results given by Configuration-constrained PES



Shape + *K* isomer?

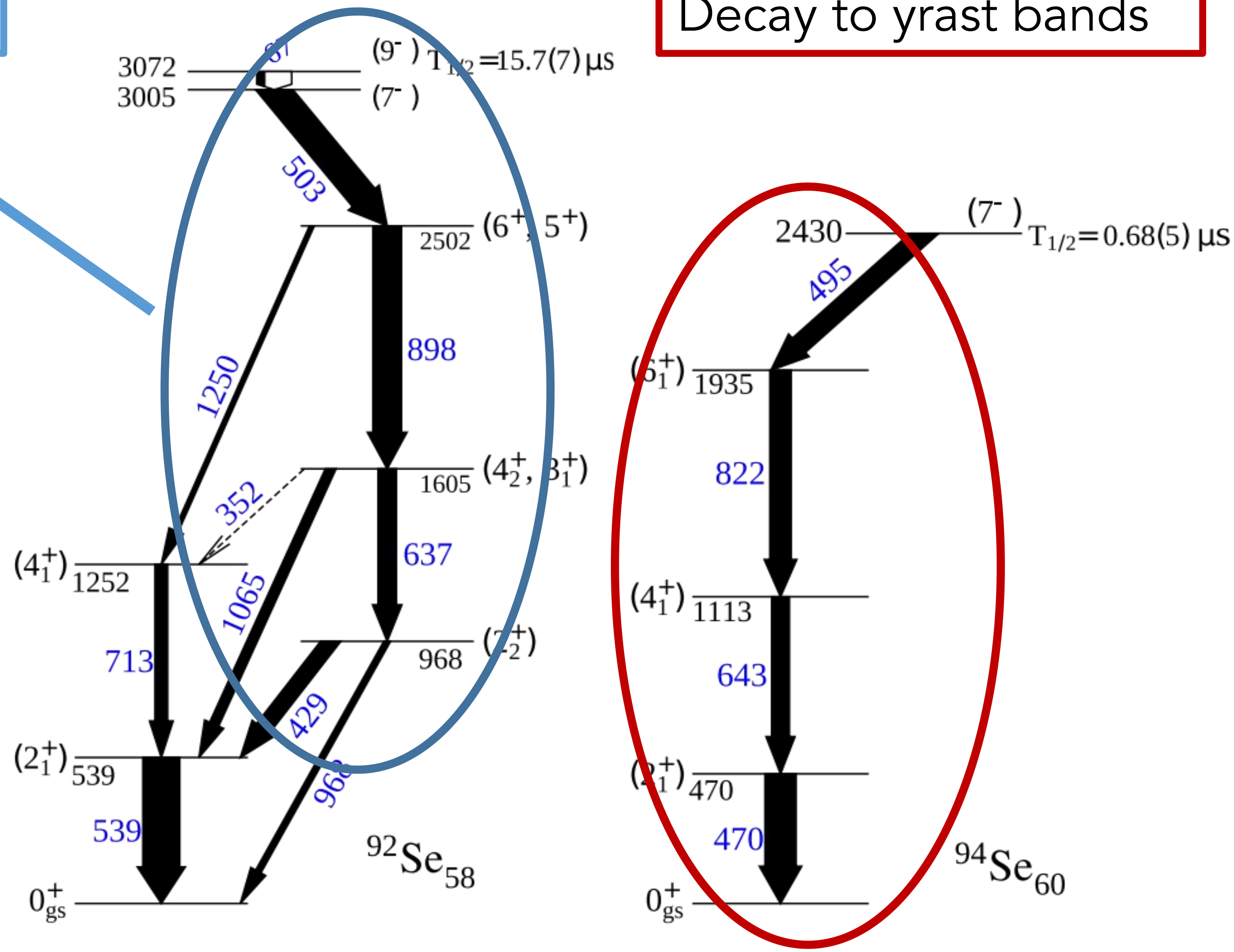


Discussions

A question that hasn't been answered

Decay to yrare bands

Decay to yrast bands



Shape + *K* isomer?