Collective Excitations in ^{166}Re and ^{162}W by Means of γ-ray Spectroscopy and Lifetime Measurements

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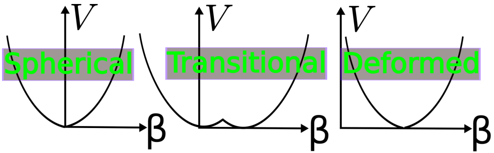
Contents

Transitional Nuclei

Collectivity and Deformation



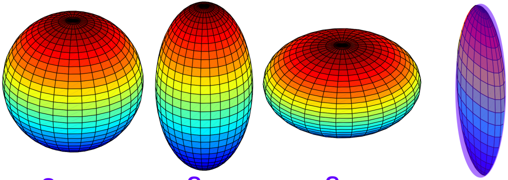
$$R = R_0[1 + \sum \alpha_\mu Y_{2\mu}(\theta, \phi)]$$

$$\alpha_0 = \beta\cos\gamma,\ \alpha_{-2} = \alpha_2 = \beta\sin\gamma$$

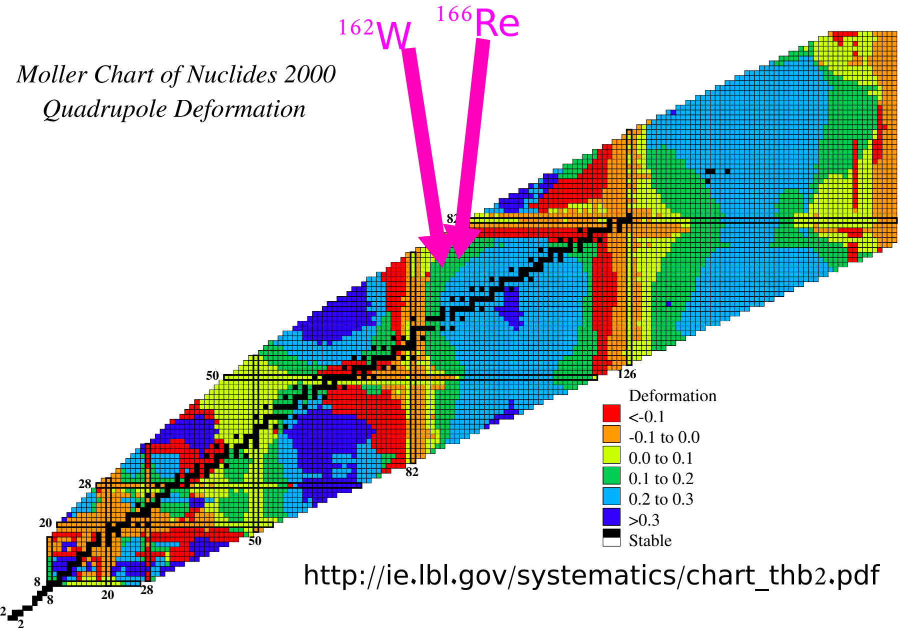
$$\delta R_x = \sqrt{\frac{5}{4\pi}} R_0 \beta \cos[\gamma - \frac{2}{3}\pi]$$

$$\delta R_y = \sqrt{\frac{5}{4\pi}} R_0 \beta \cos[\gamma - \frac{4}{3}\pi]$$

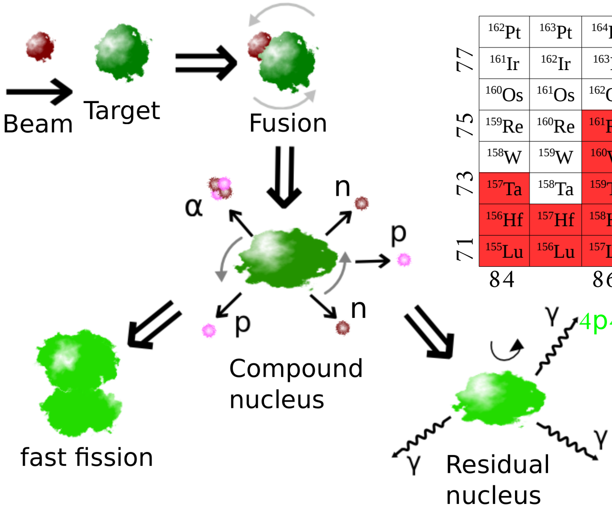
$$\delta R_z = \sqrt{\frac{5}{4\pi}} R_0 \beta \cos\gamma$$

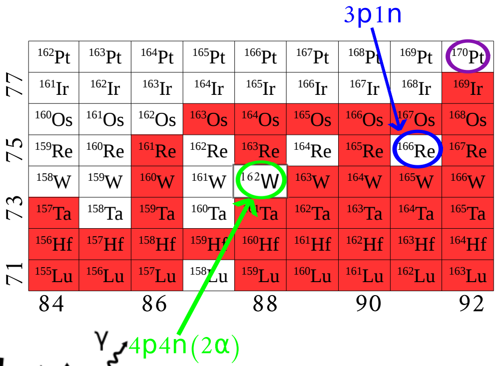


$\beta=0$ spherical | $\beta>0$ prolate | $\beta<0$ oblate | γ triaxial



http://ie.lbl.gov/systematics/chart_thb2.pdf



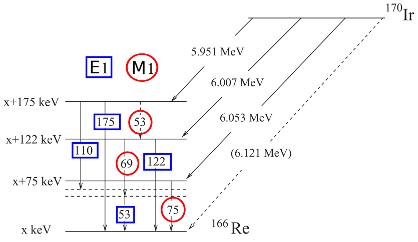


^{92}Mo(^{78}Kr, 3pn)^{166}Re

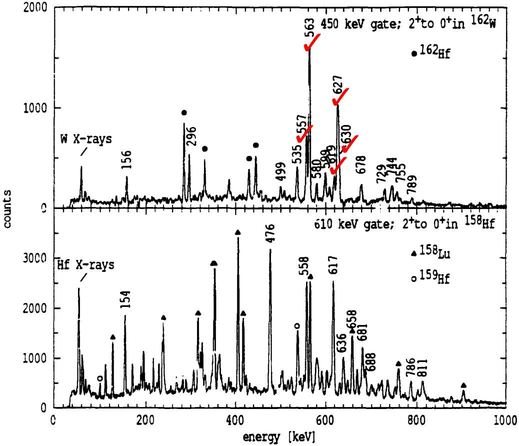
^{92}Mo(^{78}Kr, 2α)^{162}W

Prior knowledge of excited states in ^{166}Re and ^{162}W

α-decay of ^{170}Ir



B. Hadinia *et al.*, PRC76, 044312 (2007)

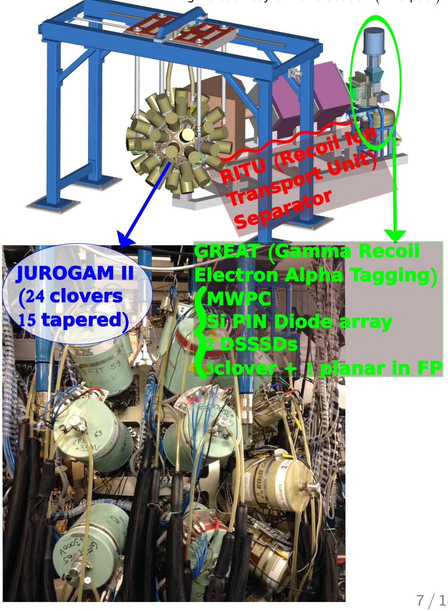


G.D. Dracoulis *et al.*, Proc. Int. Conf. Nuclear Structure at High Angular Momentum, Ottawa 2, 94 (1992)

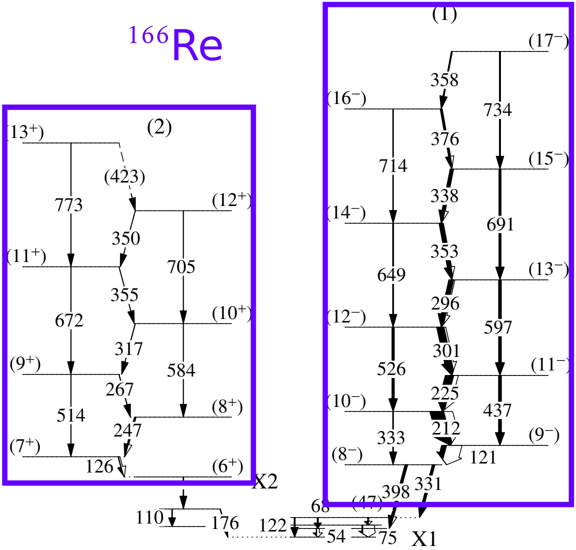
Experimental Details

- Reactions: ^{92}Mo(^{78}Kr, 3*pn*)^{166}Re
  ^{92}Mo(^{78}Kr, 2α)^{162}W
- E_{beam}=380 MeV
- Accelerator: K-130 cyclotron
- Target: 0.6-mg/cm^2 ^{92}Mo
- DPUNS Plunger: 1-mg/cm^2 Mg degrader with the distances of 5, 100, 200, 500, 1000, 2000, 3000, 5000, 8000 μm
- JUROGAM II + RITU + GREAT
- Beam time: $\sim$7 days

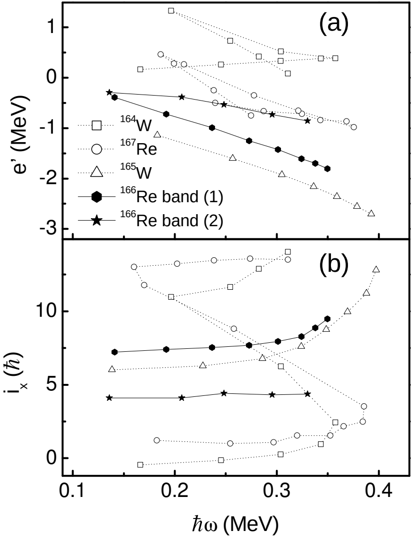
Figure courtesy of Dave Seddon (Liverpool)

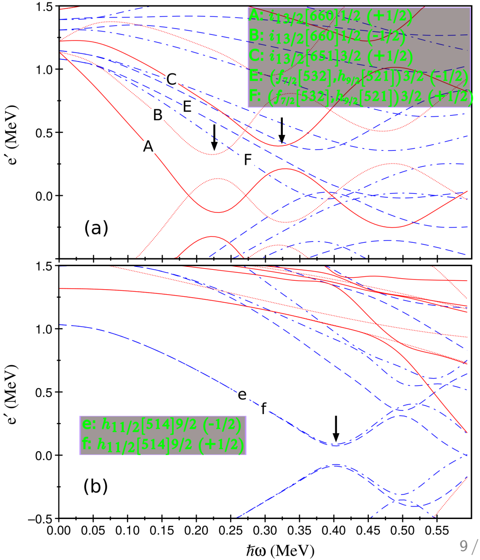


^{166}Re

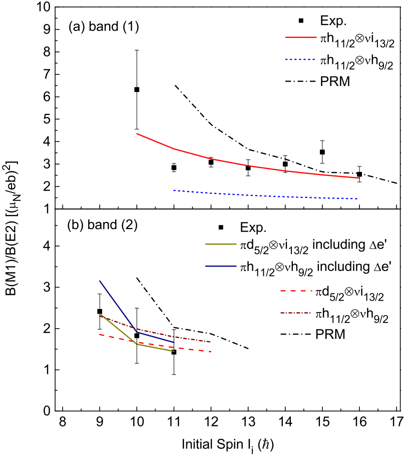

(1)
(2)
(17⁻)
(16⁻)
(15⁻)
(14⁻)
(13⁻)
(12⁻)
(11⁻)
(10⁻)
(9⁻)
(8⁻)
358
734
376
714
338
691
353
649
296
597
301
526
225
437
212
333
121
398
331
(13⁺)
(12⁺)
(11⁺)
(10⁺)
(9⁺)
(8⁺)
(7⁺)
(6⁺)
773
(423)
350
705
672
355
317
584
267
514
247
126
X2
110
176
122
68
(47)
54
75
X1

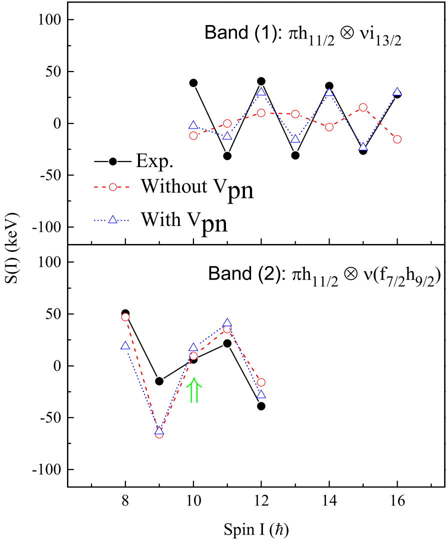
Routhian & Alignment & Cranked Routhian Calculations



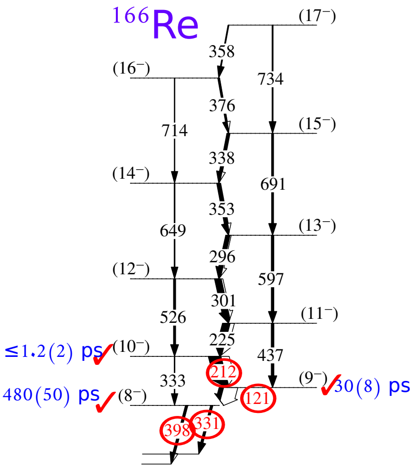


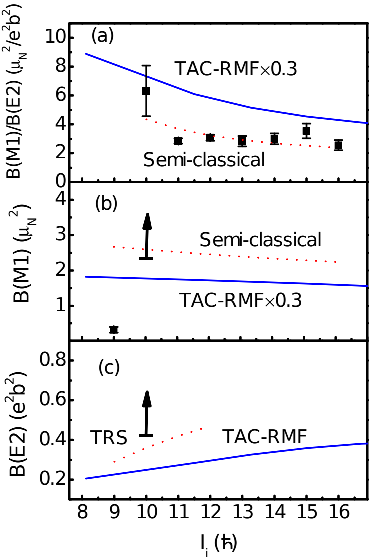
B(M1)/B(E2) & Signature Splitting & Particle Rotor Model Calculations



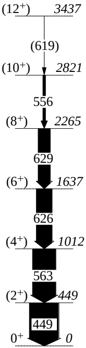


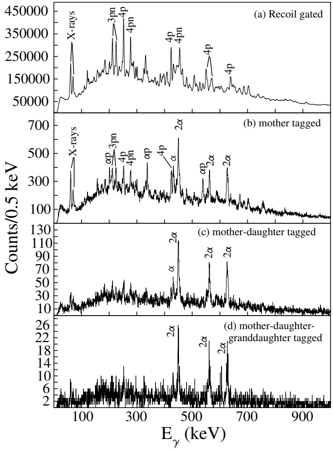
Lifetime Measurements of Excited States



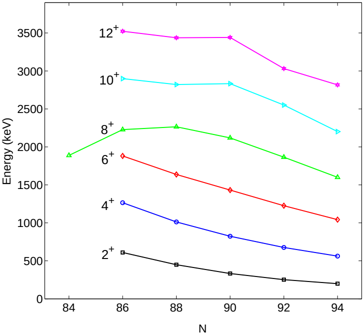


Level Scheme & Systematic Comparison & Total Routhian Surface





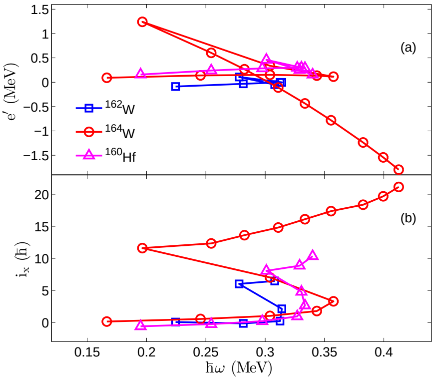
$E_{4_1^+}/E_{2_1^+}$=2.1 2.3 2.5 2.7 2.8

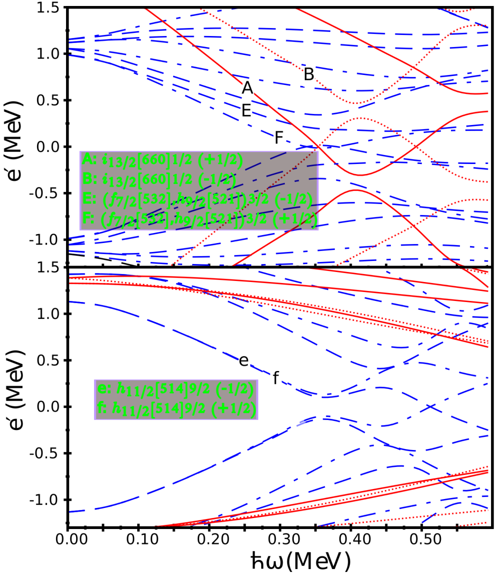


^{158}W[1] : $\nu(f_{7/2}h_{9/2})8^+$ isomer

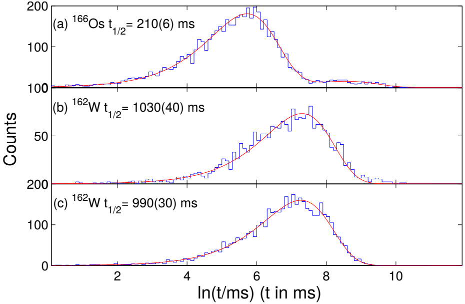
[1] S. Hofmann *et al.*, ZPA333, 107 (1989)

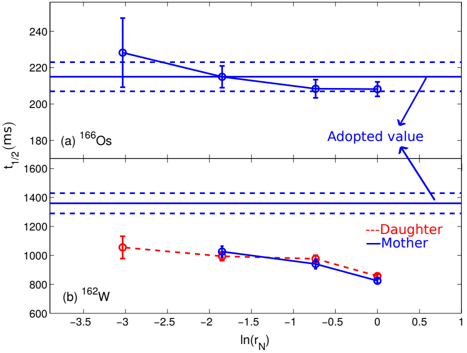
Routhian & Alignment & Cranked Routhian Calculations





Half-life Measurements of α-decaying States





Bell-shaped fitting function:

$$|\frac{dn}{d\Gamma}| = n_0 \exp(\Gamma + \lambda)\exp(-\exp(\Gamma + \ln\lambda)),$$

$$\Gamma = \ln(t)$$

^{166}Re

- ★ First identification of two rotational bands
- ★ Backbending of band (1) may originate from $i_{13/2}$ BC crossing
- ★ Signature inversion in band (2) is reproduced by PRM with mixed $\pi h_{11/2} \otimes \nu[f_{7/2}/h_{9/2}]$ configuration
- ★ Lifetimes of three excited states have been measured
- ★ Possibility of magnetic rotation has been tested

^{162}W

- ♠ Identification of a rotational band with RDT technique
- ♠ Band crossing may associate with $\nu[f_{7/2}/h_{9/2}]$ alignment
- ♠ Half-life of α-decay ground state has been measured, a big deviation with the adopted value

PHYSICAL REVIEW C **92**, 014310 (2015)

First identification of rotational band structures in $^{166}_{75}$Re$_{91}$

H. J. Li,[1,2,*] M. Doncel,[1] M. Patial,[1] B. Cederwall,[1] T. Bäck,[1] U. Jakobsson,[1,3] K. Auranen,[3] S. Bönig,[4] M. Drummond,[5] T. Grahn,[3] P. Greenlees,[3] A. Herzáň,[3] D. T. Joss,[5] R. Julin,[3] S. Juutinen,[3] J. Konki,[3] T. Kröll,[4] M. Leino,[3] C. McPeake,[5] D. O'Donnell,[5] R. D. Page,[5] J. Pakarinen,[3] J. Partanen,[3] P. Peura,[3] P. Rahkila,[3] P. Ruotsalainen,[3,†] M. Sandzelius,[3] J. Sarén,[3] B. Sayğı,[5,‡] C. Scholey,[3] J. Sorri,[3] S. Stolze,[3] M. J. Taylor,[6] A. Thornthwaite,[5] J. Uusitalo,[3] and Z. G. Xiao[2]

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Excited states in the odd-odd, highly neutron-deficient nucleus ^{166}Re have been investigated via the ^{92}Mo(^{78}Kr, $3p1n$)^{166}Re reaction. Prompt γ rays were detected by the JUROGAM II γ-ray spectrometer, and the recoiling fusion-evaporation products were separated by the recoil ion transport unit (RITU) gas-filled recoil separator and implanted into the Gamma Recoil Electron Alpha Tagging spectrometer located at the RITU focal plane. The tagging and coincidence techniques were applied to identify the γ-ray transitions in ^{166}Re, revealing two collective, strongly coupled rotational structures, for the first time. The more strongly populated band structure is assigned to the $\pi h_{11/2}[514]9/2^- \otimes \nu i_{13/2}[660]1/2^+$ Nilsson configuration, while the weaker structure is assigned to be built on a two-quasiparticle state of mixed $\pi h_{11/2}[514]9/2^- \otimes \nu[h_{9/2} f_{7/2}]3/2^-$ character. The configuration assignments are based on the electromagnetic characteristics and rotational properties, in comparison with predictions from total Routhian surface and particle-rotor model calculations.

DOI: 10.1103/PhysRevC.92.014310 PACS number(s): 21.10.Re, 23.20.Lv, 25.70.Jj, 27.70.+q

PHYSICAL REVIEW C **92**, 014326 (2015)

Recoil-decay tagging spectroscopy of $^{162}_{74}W_{88}$

H. J. Li,[1,2,*] B. Cederwall,[1] T. Bäck,[1] C. Qi,[1] M. Doncel,[1] U. Jakobsson,[1,3] K. Auranen,[3] S. Bönig,[4] M. C. Drummond,[5] T. Grahn,[3] P. Greenlees,[3] A. Herzáň,[3] R. Julin,[3] S. Juutinen,[3] J. Konki,[3] T. Kröll,[4] M. Leino,[3] C. McPeake,[5] D. O'Donnell,[5] R. D. Page,[5] J. Pakarinen,[3] J. Partanen,[3] P. Peura,[3,†] P. Rahkila,[3] P. Ruotsalainen,[3,‡] M. Sandzelius,[3] J. Sarén,[3] B. Sayğı,[5,§] C. Scholey,[3] J. Sorri,[3] S. Stolze,[3] M. J. Taylor,[6] A. Thornthwaite,[5] J. Uusitalo,[3] and Z. G. Xiao[2]

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(Received 27 May 2015; published 30 July 2015)

Excited states in the highly neutron-deficient nucleus ^{162}W have been investigated via the ^{92}Mo(^{78}Kr, 2α)^{162}W reaction. Prompt γ rays were detected by the JUROGAM II high-purity germanium detector array and the recoiling fusion-evaporation products were separated by the recoil ion transport unit (RITU) gas-filled recoil separator and identified with the gamma recoil electron alpha tagging (GREAT) spectrometer at the focal plane of RITU. γ rays from ^{162}W were identified uniquely using mother-daughter and mother-daughter-granddaughter α-decay correlations. The observation of a rotational-like ground-state band is interpreted within the framework of total Routhian surface (TRS) calculations, which suggest an axially symmetric ground-state shape with a γ-soft minimum at $\beta_2 \approx 0.15$. Quasiparticle alignment effects are discussed based on cranked shell model calculations. New measurements of the ^{162}W ground-state α-decay energy and half-life were also performed. The observed α-decay energy agrees with previous measurements. The half-life of ^{162}W was determined to be $t_{1/2} = 990(30)$ ms. This value deviates significantly from the currently adopted value of $t_{1/2} = 1360(70)$ ms. In addition, the α-decay energy and half-life of ^{166}Os were measured and found to agree with the adopted values.

DOI: 10.1103/PhysRevC.92.014326 PACS number(s): 21.10.Re, 23.20.Lv, 25.70.Jj, 27.70.+q

- Octupole Correlations in ^{147,152}Ce
  H. J. Li *et al*, Phys. Rev. C **86**, 067302 (2012)
  H. J. Li *et al*, Phys. Rev. C **90**, 047303 (2014)
- Multi-phonon γ-vibrational bands in ^{138}Nd and ^{105}Nb
  H. J. Li *et al*, Phys. Rev. C **87**, 057303 (2013)
  H. J. Li *et al*, Phys. Rev. C **88**, 054311 (2013)
- Traxiality in ^{99}Tc
  H. J. Li *et al*, Phys. Rev. C **91**, 054314 (2015)
- Band Structure and Lifetime Measurements in odd-odd ^{166}Re
  H. J. Li *et al*, Phys. Rev. C **92**, 014310 (2015)
  H. J. Li *et al*, Submitted to PRC in 2015, Lifetime measurements in ^{166}Re
- Collectivity in ^{162}W and odd-odd^{138}Pm
  H. J. Li *et al*, Phys. Rev. C **92**, 014326 (2015)
  H. J. Li *et al*, Eur. Phys. J. A **51**, 60 (2015)

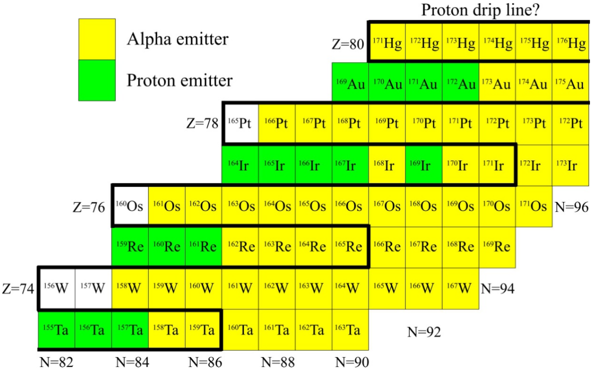
Thank you!

Proton Drip Line

Difficulities:

⇒Low cross section: Competition with fast fission

⇒Selectivity: Too many open reaction channels, Low α-decay branching ratio(^{166}Re)



courtesy of RD Page, LISA presentation

VMI

"Ground state bands" in even-even nuclei:
Rotational term: $\frac{\hbar^2 I(I+1)}{2\mathcal{J}_I}$ + Potential term: $\propto (\mathcal{J}_I - \mathcal{J}_0)^2$

The level energy: $E_I = \frac{1}{2}C(\mathcal{J} - \mathcal{J}_0)^2 + \frac{1}{2}[I(I+1)/\mathcal{J}]$.
(C: "restoring force constant", $\mathcal{J}_I$: moment of inertia for each state with spin I)

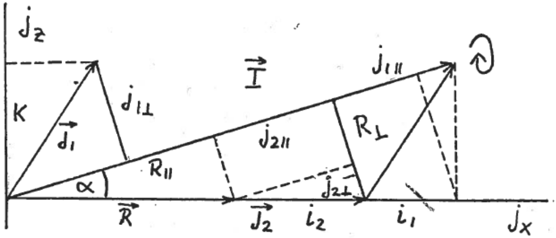
The equilibrium condition for each spin I: $\partial E(\mathcal{J})/\partial \mathcal{J} = 0$

each nucleus is characterized by $(\mathcal{J}_0, \sigma)$
($\mathcal{J}_0$ is the moment of inertia of the ground state, σ is a "softness parameter", $\sigma = 1/2C\mathcal{J}_0$)

Mariscotti *et.al* Phys Rev 178, 1864 (1968)

Back to

B(M1)/B(E2)



$$B(M1; I \rightarrow I-1) = |\langle \mathrm{II}|\mu(M1)|\mathrm{I}-1\ \mathrm{I}-1\rangle|^2 = \frac{3}{8\pi}\mu_\perp^2$$

$$\mu_\perp = \frac{K}{I}[(g_1 - g_R)(\sqrt{I^2-K^2} - i_1) - (g_2 - g_R)i_2]$$

$$\frac{B(M1; I\rightarrow I-1)}{B(E2: I\rightarrow I-2)} = 0.697\frac{1}{\lambda}\frac{E_\gamma^5(E2)}{E_\gamma^3(M1)}\frac{1}{1+\delta^2}[\frac{\mu_N^2}{e^2b^2}]\ \text{(exp.)}$$

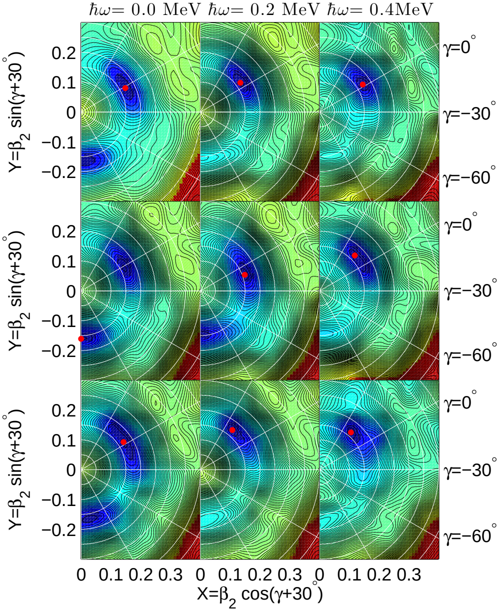
$$= \frac{12}{5Q_0^2 cos^2(\gamma+30^\circ)}[1-\frac{K^2}{(I-1/2)^2}]^{-2}\frac{K^2}{I^2}\times[(g_1-g_R)(\sqrt{I^2-K^2} - i_1)(1\pm\frac{\Delta e'}{\hbar\omega}) - (g_2-g_R)i_2]^2\ \text{(theo.)}$$

F. Dönau and S. Frauendor, High angular momentum properties of nuclei, 1983

Back to

Total Routhian Surface

$\beta_2 \sim 0.17$

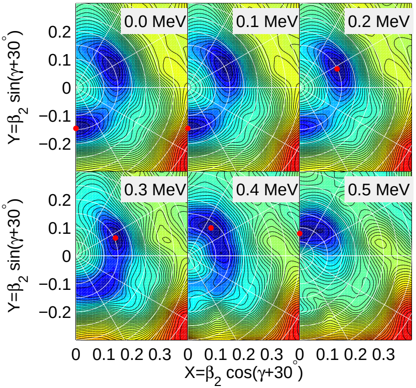


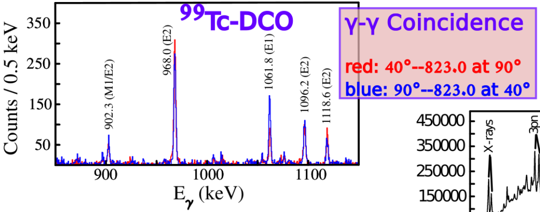
$\Leftarrow \pi(-,-1/2)\nu(+,+1/2)$

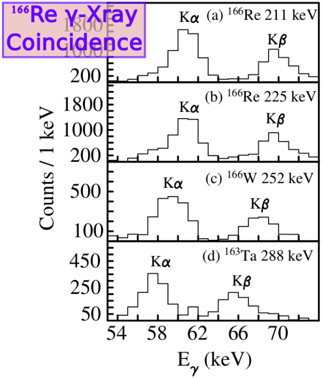
$\Leftarrow \pi(-,-1/2)\nu(-,+1/2)$

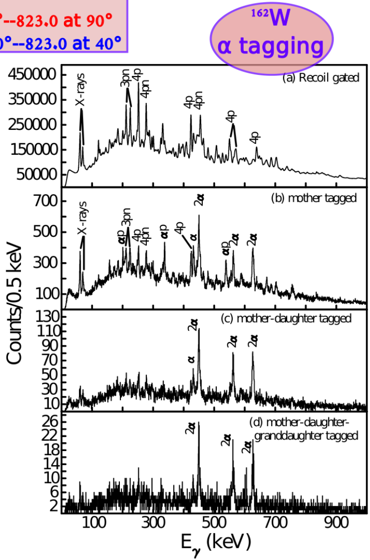
$\Leftarrow \pi(+,-1/2)\nu(+,+1/2)$

^{162}W-TRS

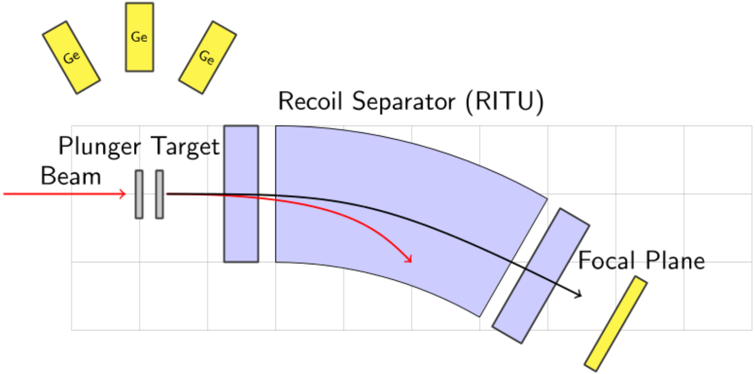

0.0 MeV
0.1 MeV
0.2 MeV
0.3 MeV
0.4 MeV
0.5 MeV
Y=β2 sin(γ+30°)
0.2
0.1
0
−0.1
−0.2
0 0.1 0.2 0.3
X=β2 cos(γ+30°)


99Tc-DCO
γ-γ Coincidence
red: 40°--823.0 at 90°
blue: 90°--823.0 at 40°
Counts / 0.5 keV
902.3 (M1/E2)
968.0 (E2)
1061.8 (E1)
1096.2 (E2)
1118.6 (E2)
Eγ (keV)


166Re γ-Xray Coincidence
(a) 166Re 211 keV
(b) 166Re 225 keV
(c) 166W 252 keV
(d) 163Ta 288 keV
Kα
Kβ
Counts / 1 keV
Eγ (keV)


162W α tagging
(a) Recoil gated
(b) mother tagged
(c) mother-daughter tagged
(d) mother-daughter-granddaughter tagged
X-rays
Counts/0.5 keV
Eγ (keV)

Recoil Decay Tagging experiments with the gas-filled magnetic separator RITU



Courtesy of Torbjörn Bäck

$B\rho = \frac{mv}{q_{\mathrm{ave}}} \approx 0.0227 \frac{A}{Z^{1/3}}$ [Tm], $v/c \approx 0.04$, time-of-flight$\approx$0.5 μs

Outlook

Open Questions	♣ Consistent explanation of signature inversion ♣ Lack of lifetime data on odd-odd nuclei
Fingerprints of Radioactive Ion Beam Facilities	★ RIBF at RIKEN in Japan ★ SPIRAL2, SPES and FAIR in Europe ★ FRIB in USA ★ RIBLL in China ★ RAON (happy) in South Korea (HIA) ★ and so on...
Tracking Spectrometers	♠ AGATA in Europe ♠ GRETA in USA