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

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Contents

Background and Motivation
  The neutron-deficient A~160 nuclei

Experimental Setups
  JYFL: JUROGAM II + RITU + GREAT

Data Analysis and Results
  Rotational bands and Lifetime Measurements in $^{166}$Re
  Recoil-decay Tagging Spectroscopy of $^{162}$W

Summary
Collectivity and Deformation

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

\[ \alpha_0 = \beta \cos \gamma, \quad \alpha_{-2} = \alpha_2 = \beta \sin \gamma \]

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

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

\[ \delta R_z = \sqrt{\frac{5}{4\pi}} R_0 \beta \cos \gamma \]
Moller Chart of Nuclides 2000
Quadrupole Deformation

http://ie.lbl.gov/systematics/chart_thb2.pdf
Collective excitations in $^{166}$Re and $^{162}$W

**Background and Motivation**

The neutron-deficient $A\sim160$ nuclei

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</table>

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

$^92\text{Mo}(^{78}\text{Kr}, 2\alpha)^{162}\text{W}$
Prior knowledge of excited states in $^{166}$Re and $^{162}$W

\(\alpha\)-decay of $^{170}$Ir

B. Hadinia \textit{et al.}, PRC76, 044312 (2007)

Experimental Details

- Reactions: $^{92}\text{Mo}(^{78}\text{Kr}, 3\text{pn})^{166}\text{Re}$
- $^{92}\text{Mo}(^{78}\text{Kr}, 2\alpha)^{162}\text{W}$
- $E_{\text{beam}}=380$ MeV
- Accelerator: K-130 cyclotron
- Target: 0.6-mg/cm$^2$ $^{92}\text{Mo}$
- DPUNS Plunger: 1-mg/cm$^2$ Mg degrader with the distances of 5, 100, 200, 500, 1000, 2000, 3000, 5000, 8000 $\mu$m
- JUROGAM II + RITU + GREAT
- Beam time: $\sim7$ days

Figure courtesy of Dave Seddon (Liverpool)
Collective excitations in $^{166}\text{Re}$ and $^{162}\text{W}$

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Data Analysis and Results

Rotational bands and Lifetime Measurements in $^{166}\text{Re}$
Routhian & Alignment & Cranked Routhian Calculations

(a) Graph showing the energy levels $e'(\text{MeV})$ versus rotational frequency $\hbar\omega (\text{MeV})$. The bands for $^{164}W$, $^{167}Re$, $^{165}W$, $^{166}Re$ band (1), and $^{166}Re$ band (2) are plotted.

(b) Graph showing the alignment $i_x (\hbar)$ versus rotational frequency $\hbar\omega (\text{MeV})$.
Collective excitations in $^{166}$Re and $^{162}$W

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Data Analysis and Results

Rotational bands and Lifetime Measurements in $^{166}$Re

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

Calculations

![Graph](image)

Band (1): $\pi h_{11/2} \otimes \nu_{i_{13/2}}$

- Exp.
- $\pi h_{11/2} \otimes \nu_{i_{13/2}}$
- $\pi h_{11/2} \otimes \nu_{h_{9/2}}$
- PRM

Band (2): $\pi h_{11/2} \otimes \nu(f_{7/2}h_{9/2})$

- Exp. Without $V_{pn}$
- With $V_{pn}$
Lifetime Measurements of Excited States

\[ \begin{array}{c}
166\text{Re} \\
(16^-) \\ 358 \\ 734 \\
(15^-) \\ 714 \\ 376 \\
(14^-) \\ 649 \\ 338 \\
(12^-) \\ 526 \\ 296 \\
(10^-) \\ 225 \\ 353 \\
(9^-) \\ 437 \\ 301 \\
(8^-) \\ 597 \\ 212 \\
(7^-) \\ 333 \\ 358 \\
(6^-) \\ 714 \\ 331 \\
(5^-) \\ 338 \\ 333 \\
(4^-) \\ 437 \\ 338 \\
(3^-) \\ 597 \
\end{array} \]

- Lifetime $\leq 1.2(2)$ ps
- Lifetime $480(50)$ ps
- Lifetime $30(8)$ ps

\[ \begin{align*}
B(M1)/B(E2) & \mu^2/\mu, \epsilon^2/\epsilon^2 \\
B(M1) & \mu^2, \epsilon^2 \\
B(E2) & \epsilon^2/\epsilon^2 
\end{align*} \]

- TAC-RMF x 0.3
- Semi-classical
- TAC-RMF x 0.3
- Semi-classical
- TRS
- TAC-RMF

11 / 18
Level Scheme & Systematic Comparison & Total Routhian Surface

\[ E_{4^+} / E_{2^+} = 2.1 \quad 2.3 \quad 2.5 \quad 2.7 \quad 2.8 \]

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

Collective excitations in $^{166}$Re and $^{162}$W

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Data Analysis and Results

Recoil-decay Tagging Spectroscopy of $^{162}$W

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**Routhian & Alignment & Cranked Routhian Calculations**

![Graph](https://via.placeholder.com/150)

- **Graph (a)**: Data for $^{162}$W, $^{164}$W, and $^{160}$Hf.
- **Graph (b)**: Plot of $i_x$ vs. $\hbar \omega$ for different isotopes.

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**Graph (a)** includes lines labeled A, B, E, and F with specific quantum numbers.

**Graph (b)** includes points labeled e and f with quantum numbers.

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**Legend**:
- A: $i_{13/2}[560]1/2 (+1/2)$
- B: $i_{13/2}[660]1/2 (-1/2)$
- E: $(f_{7/2}[532], h_{11/2}[525])3/2 (-1/2)$
- F: $(f_{7/2}[532], d_{9/2}[527])3/2 (+1/2)$
- e: $h_{11/2}[514]9/2 (-1/2)$
- f: $h_{11/2}[514]9/2 (+1/2)$
Half-life Measurements of $\alpha$-decaying States

Bell-shaped fitting function:

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

$$\Gamma = \ln(t)$$
Collective excitations in $^{166}\text{Re}$ and $^{162}\text{W}$

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**Summary**

- 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

$^{166}\text{Re}$

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

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$^{162}\text{W}$
First identification of rotational band structures in $^{166}_{75}$Re$_{91}$

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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, 3$\text{p}_{1\text{g}}$)$^{166}$Re reaction. Prompt $\gamma$ rays were detected by the JUROGAM II $\gamma$-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 $\gamma$-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 $\pi h_{11/2}[514]9/2^- \otimes \nu l_{13/2}[660]1/2^+$ 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.Rc, 23.20.Lv, 25.70.Jj, 27.70.+q
Excited states in the highly neutron-deficient nucleus $^{162}$W have been investigated via the $^{92}$Mo($^{78}$Kr, 2α)$^{162}$W reaction. Prompt $\gamma$ 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. $\gamma$ rays from $^{162}$W were identified uniquely using mother-daughter and mother-daughter-granddaughter $\alpha$-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 $\gamma$-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 $\alpha$-decay energy and half-life were also performed. The observed $\alpha$-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 $\alpha$-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
Collective excitations in $^{166}\text{Re}$ and $^{162}\text{W}$

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— Summary

▶ Octupole Correlations in $^{147,152}\text{Ce}$

▶ Multi-phonon $\gamma$-vibrational bands in $^{138}\text{Nd}$ and $^{105}\text{Nb}$

▶ Traxiality in $^{99}\text{Tc}$

▶ Band Structure and Lifetime Measurements in odd-odd $^{166}\text{Re}$
  H. J. Li *et al.*, Submitted to PRC in 2015, Lifetime measurements in $^{166}\text{Re}$

▶ Collectivity in $^{162}\text{W}$ and odd-odd $^{138}\text{Pm}$

Thank you!
Proton Drip Line

Difficulties:

⇒ Low cross section: Competition with fast fission

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

courtesy of RD Page, LISA presentation


**VMI**

“Ground state bands” in even-even nuclei:
Rotational term: $\frac{\hbar^2 I(I+1)}{2J_I} +$ Potential term: $\propto (J_I - J_0)^2$

The level energy: $E_I = \frac{1}{2} C(J - J_0)^2 + \frac{1}{2} [I(I+1)/J].$
(C: “restoring force constant”, $J_I$: moment of inertia for each state with spin $I$)

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

Each nucleus is characterized by $(J_0, \sigma)$
($J_0$ is the moment of inertia of the ground state, $\sigma$ is a “softness parameter”, $\sigma = 1/2CJ_0$)


Back to
Collective excitations in $^{166}$Re and $^{162}$W

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Backup

**B(M1)/B(E2)**

\[
B(M1; \ell \rightarrow \ell - 1) = |\langle \ell \ell | \mu(M1) | \ell - 1 \ell - 1 \rangle|^2 = \frac{3}{8\pi} \mu^2 \\
\mu_\perp = \frac{K}{I} \left[ (g_1 - g_R)(\sqrt{I^2 - K^2} - i_1) - (g_2 - g_R)i_2 \right]
\]

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

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

F. Dönau and S. Frauendor, High angular momentum properties of nuclei, 1983
Collective excitations in $^{166}$Re and $^{162}$W

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Total Routhian Surface

$\beta_2 \sim 0.17$

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

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

$\pi(+, -1/2)\nu(+, +1/2)$
Collective excitations in $^{166}$Re and $^{162}$W

$^{162}$W-TRS

$Y = \beta_2 \sin(\gamma + 30^\circ)$

$X = \beta_2 \cos(\gamma + 30^\circ)$
Collective excitations in $^{166}$Re and $^{162}$W

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Backup

$^{166}$Re $\gamma$-X-ray Coincidence

$^{162}$W $\alpha$ tagging

$^{99}$Tc-DCO

$\gamma-\gamma$ Coincidence

red: 40°--823.0 at 90°
blue: 90°--823.0 at 40°
Recoil Decay Tagging experiments with the gas-filled magnetic separator RITU

\[ B \rho = \frac{mv}{q_{\text{ave}}} \approx 0.0227 \frac{A}{Z^{1/3}} \, \text{[Tm]}, \quad v/c \approx 0.04, \quad \text{time-of-flight} \approx 0.5 \, \mu\text{s} \]
Collective excitations in $^{166}$Re and $^{162}$W

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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

Open Questions

- Consistent explanation of signature inversion
- Lack of lifetime data on odd-odd nuclei

Backup

Outlook