High Precision Spectroscopy of $^{177}HfF^{+}$ and $^{179}HfF^{+}$

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Claremont, CA

Motivation

The Search for Physics beyond the Standard Model

(Aggarwal, 2018)

The Search for Physics beyond the Standard Model

Why do we observe more matter than antimatter?

(Aggarwal, 2018)

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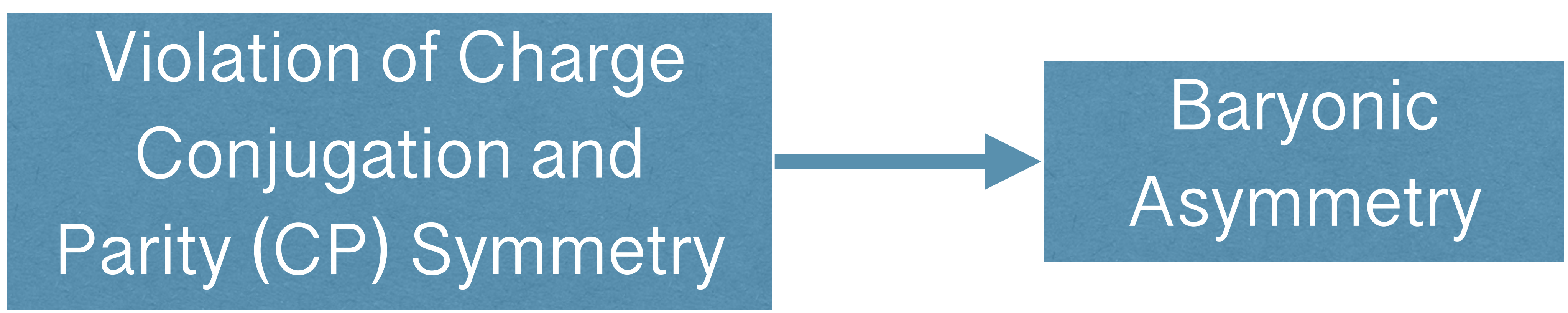

(Aggarwal, 2018)

The Search for Physics beyond the Standard Model

Why do we observe more matter than antimatter?

Violation of Charge Conjugation and Parity (CP) Symmetry → Baryonic Asymmetry

The Standard Model (SM) does **not** contain sufficient CP Violation

(Aggarwal, 2018)

The Electron’s Electric Dipole Moment

Where are new sources of CP Violation?

(Leanhardt, 2011)

(DeMille, 2000)

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Dr. Eric Cornell's group at JILA in Colorado is probing HfF+

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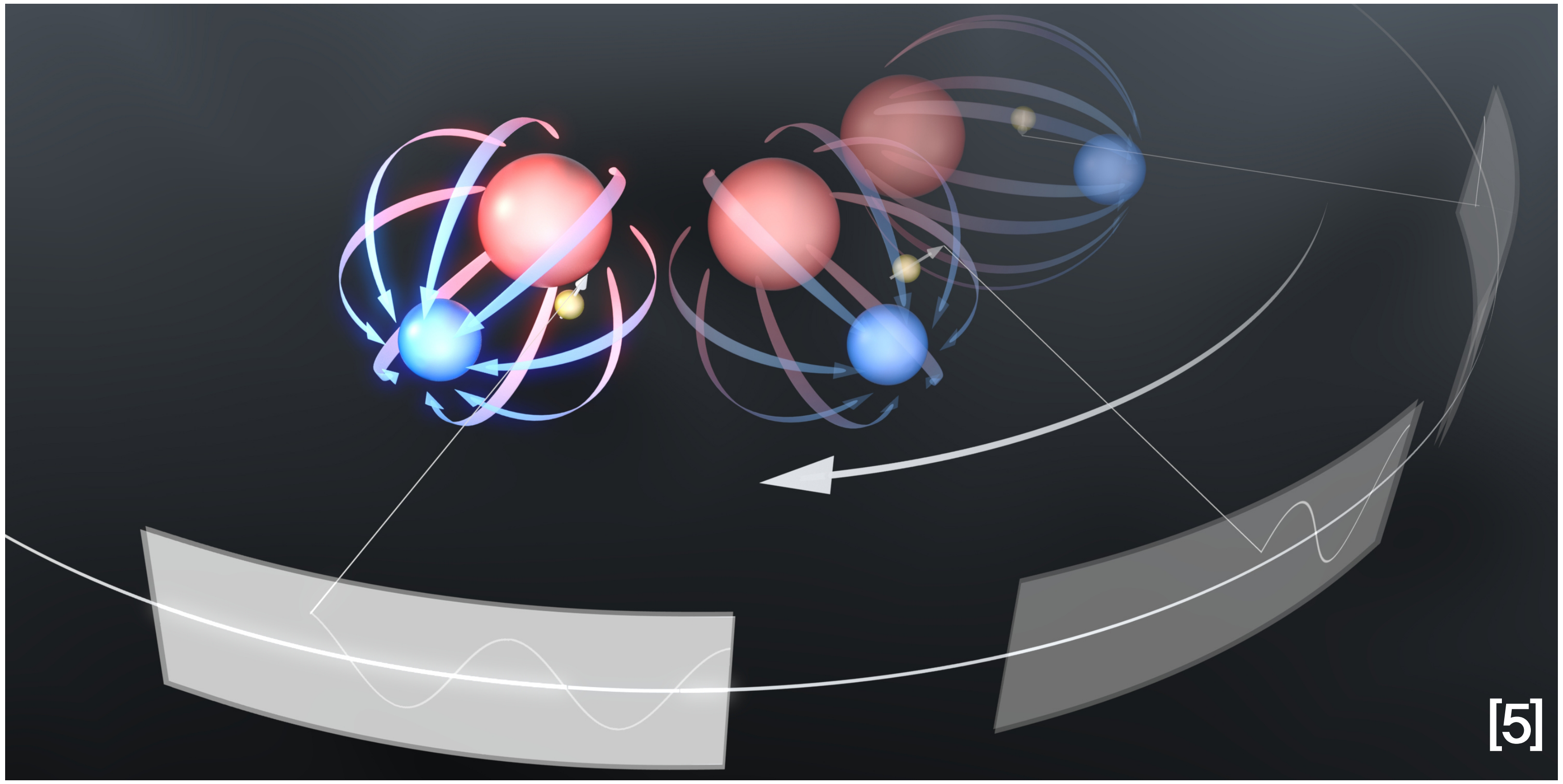
EDM with HfF^+ at JILA

Experimental Advantages of HfF^+



(Leanhardt, 2011)

(Skripnikov, 2015)

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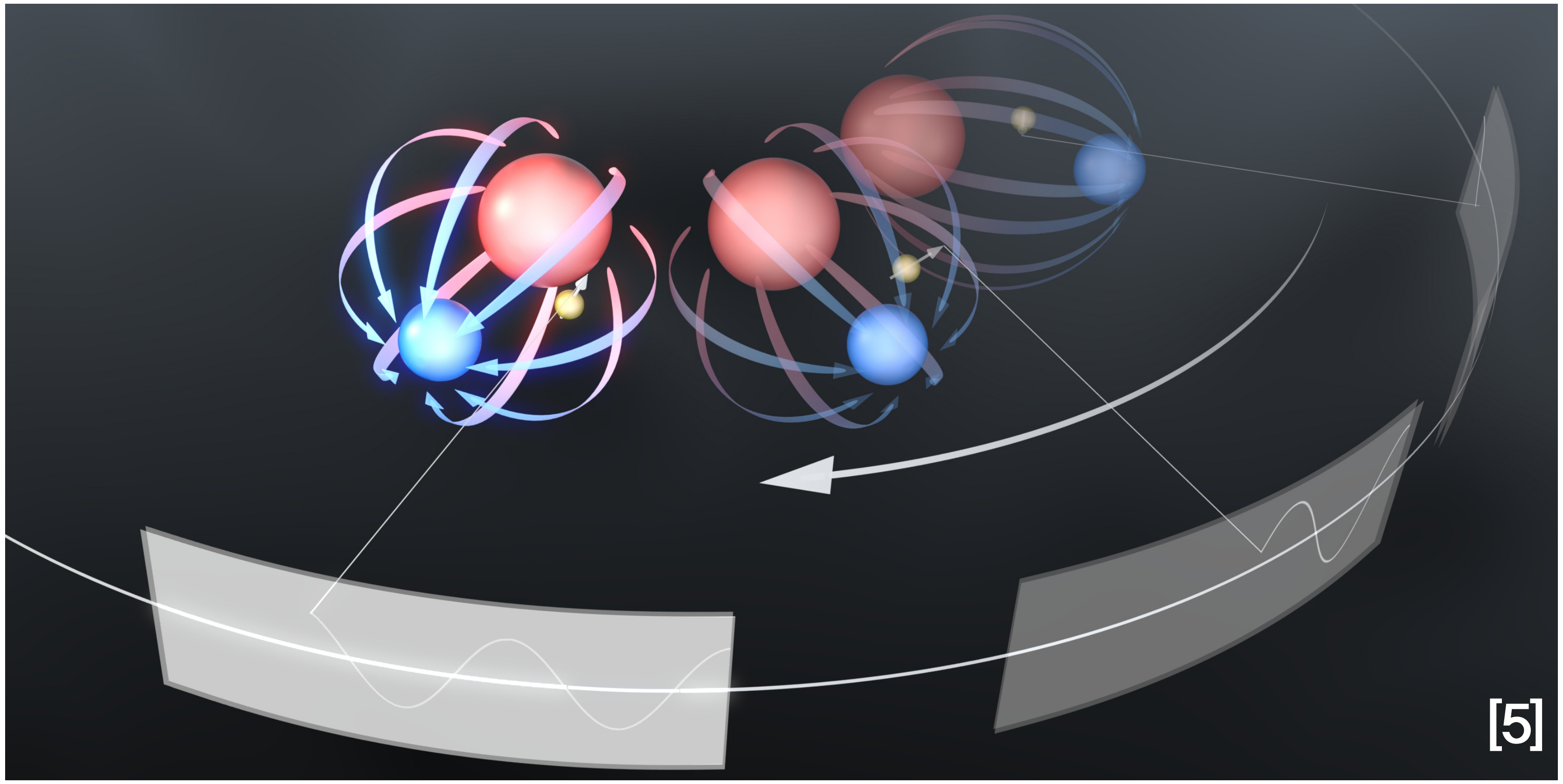
Experimental Advantages of HfF^+

(1) Ease of constructing traps



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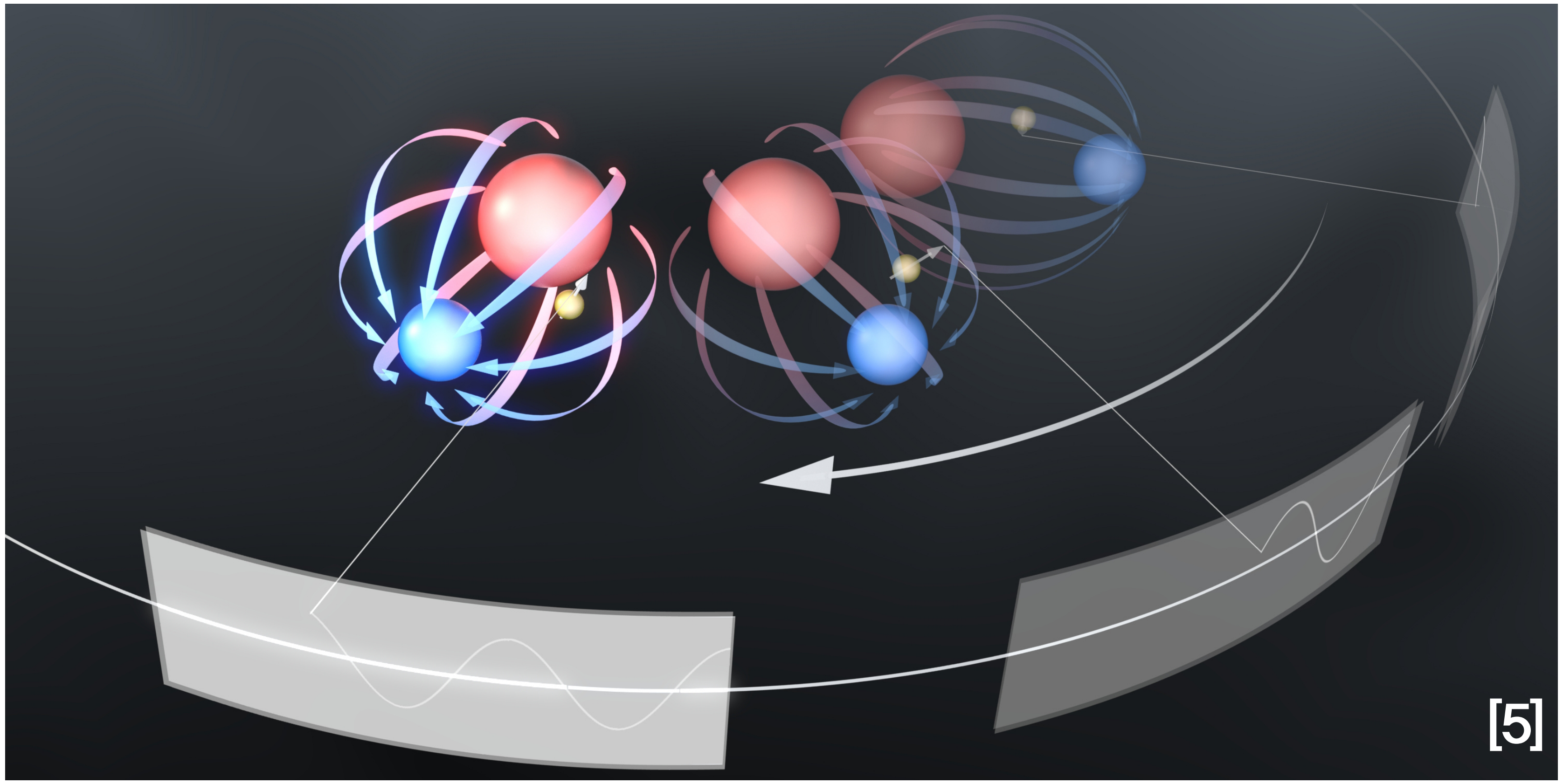

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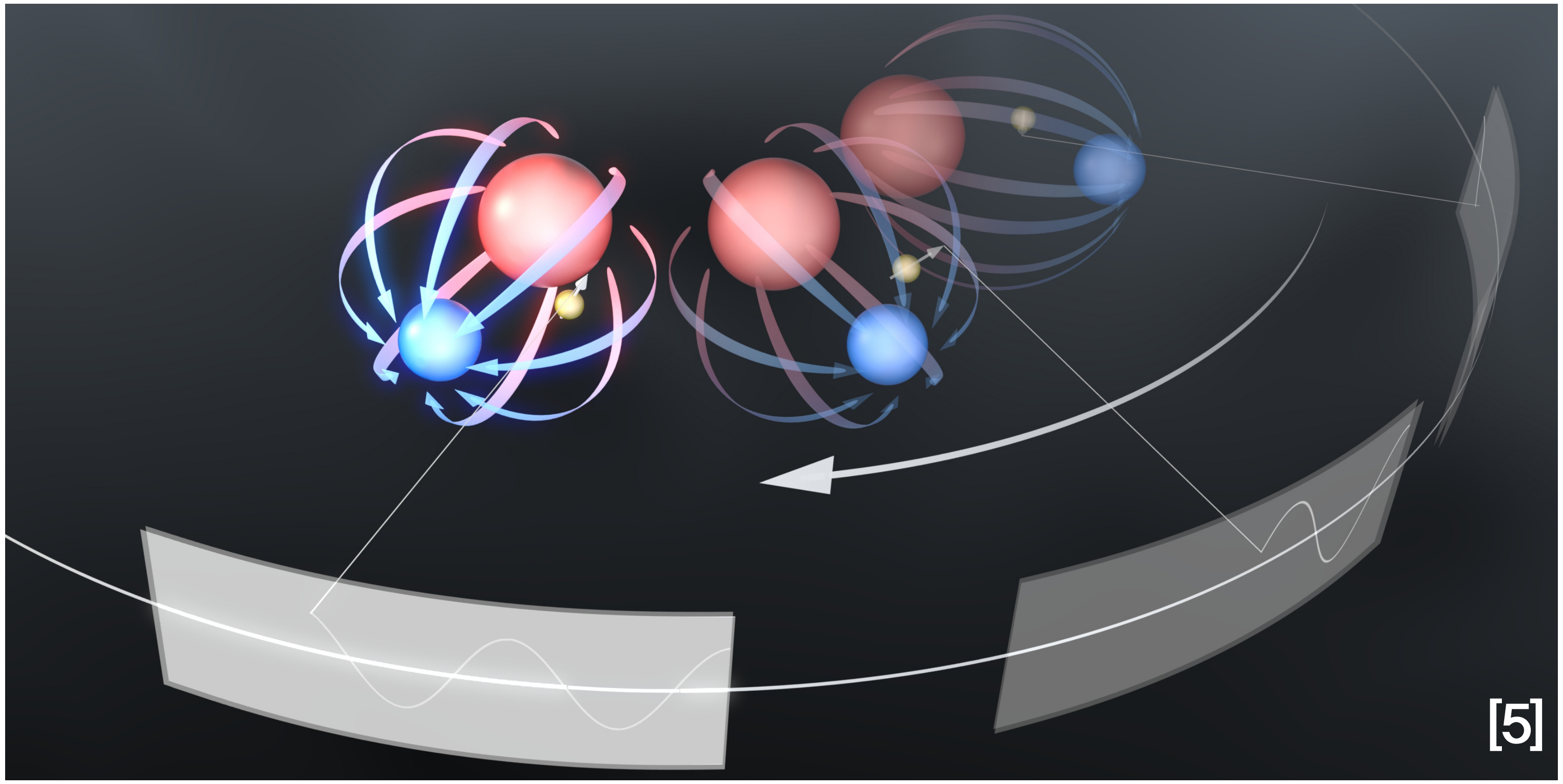

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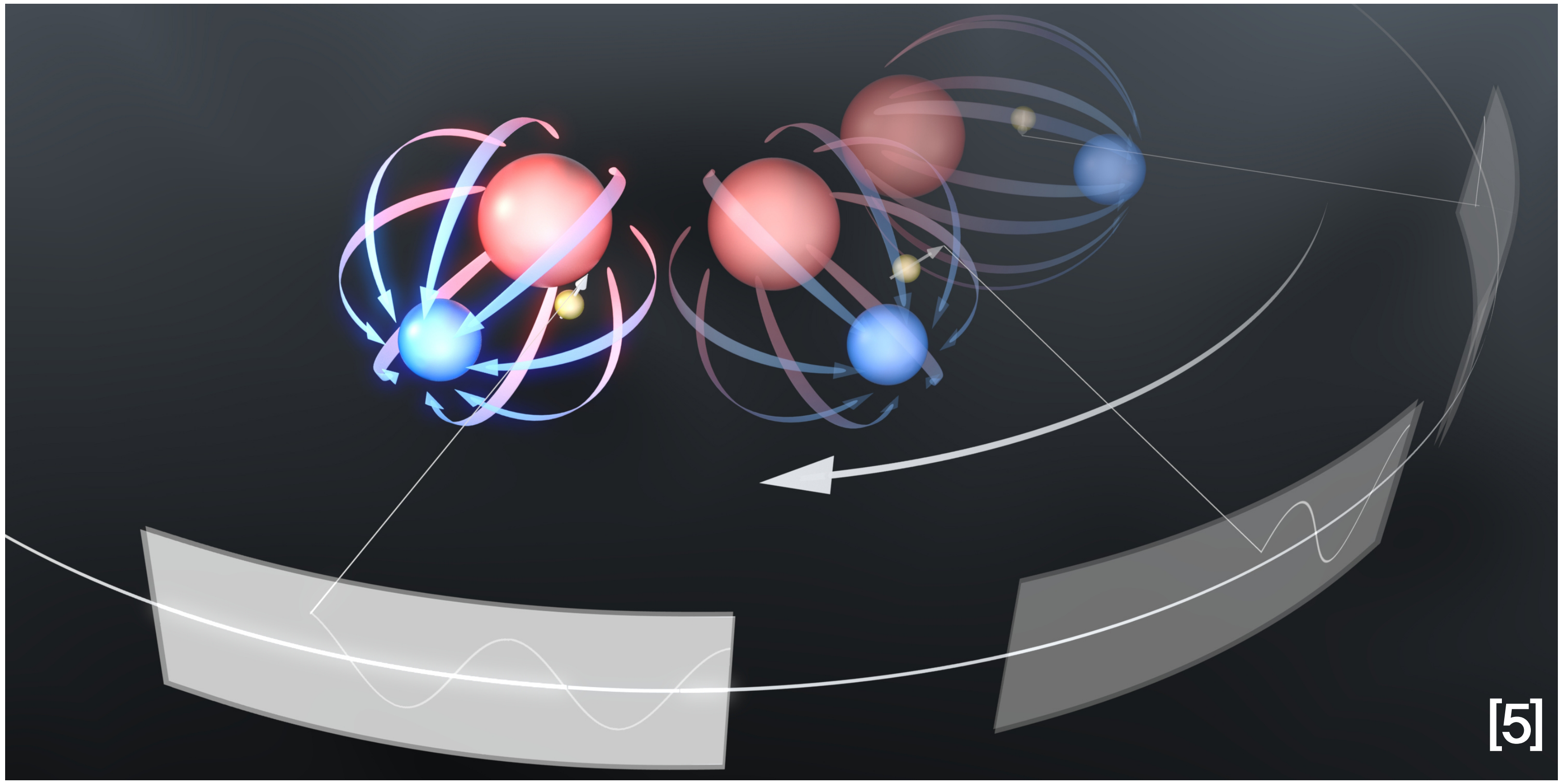
Parity Non-Conserving (PNC) effects are enhanced in $^{177}HfF^+$ and $^{179}HfF^+$ due to **deformed nuclei**



(Leanhardt, 2011)

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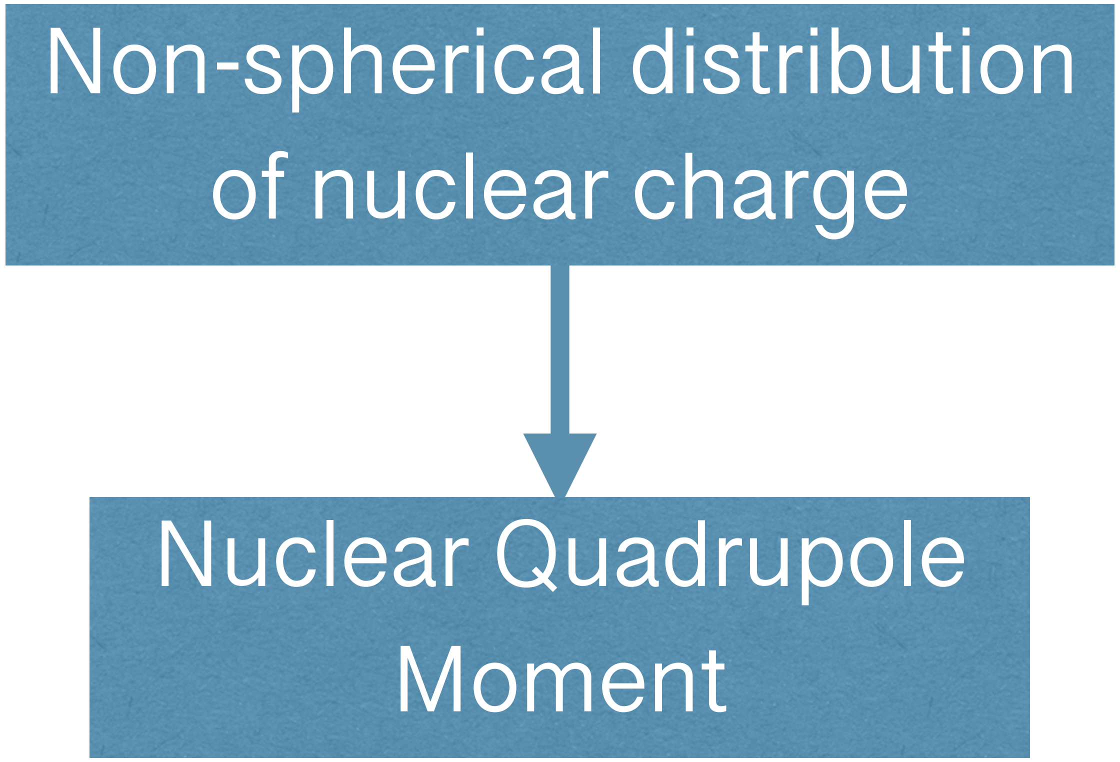
What are the physical consequences of the highly deformed nuclei of the odd isotopologues of HfF^+?

(Gordy, 1984)


Non-spherical distribution of nuclear charge
Nuclear Quadrupole Moment

(Gordy, 1984)

Non-spherical distribution of nuclear charge

↓

Nuclear Quadrupole Moment

$$\mathbf{F} = \mathbf{J} + \mathbf{I}$$

$\mathbf{J}$ Molecular Rotational Angular Momentum

$\mathbf{I}$ Nuclear Spin

$$F = J + I, J + I - 1, \ldots, |J - I|$$

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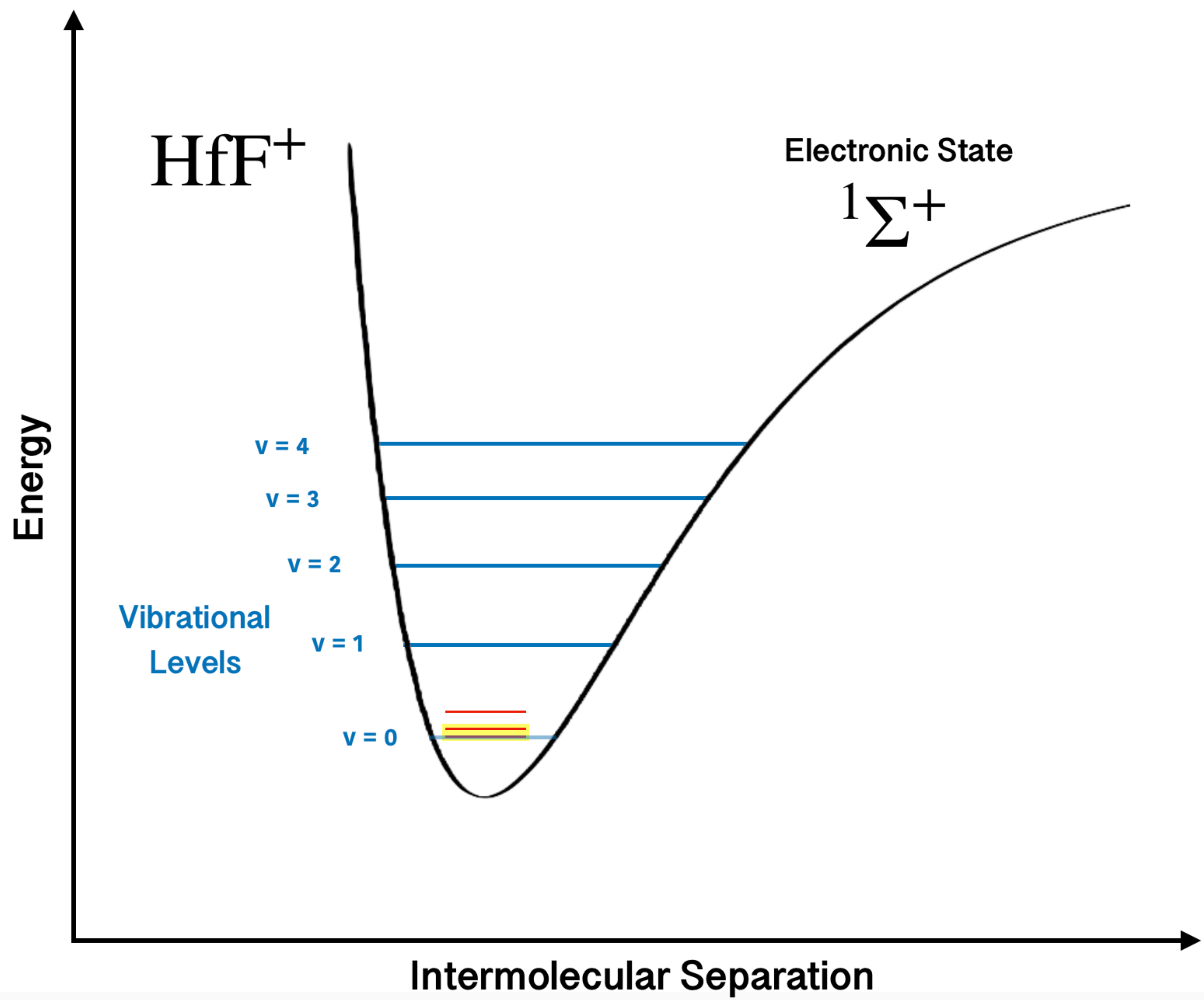
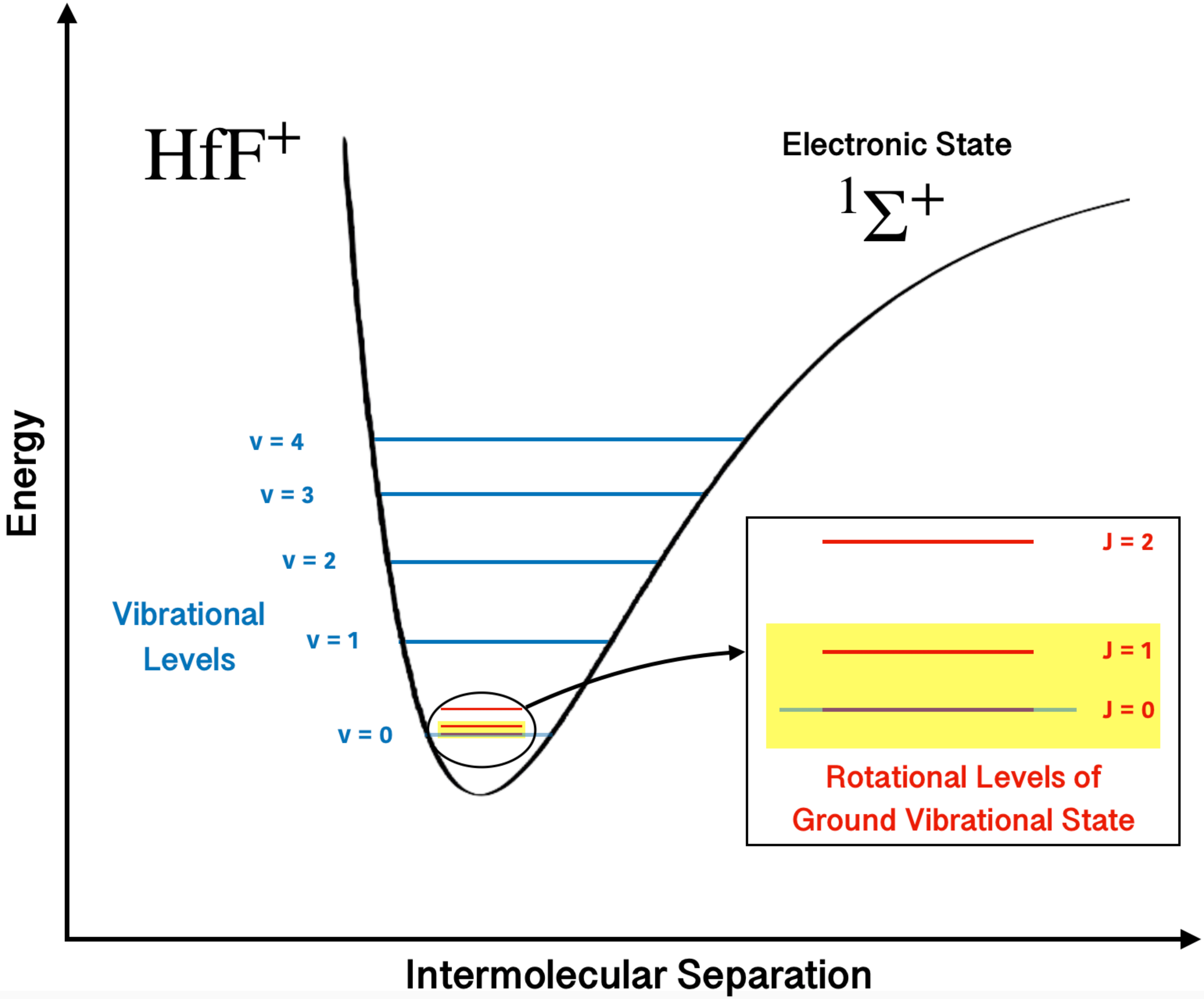
Energy of Quadrupole Interaction

Asymmetric Shape of Nucleus and Elec. Field Gradient

Rotational levels will split due to quadrupole interaction



HfF+
Electronic State
$^1\Sigma^+$
Energy
v = 4
v = 3
v = 2
v = 1
v = 0
Vibrational Levels
Intermolecular Separation


HfF$^+$
Electronic State
$^1\Sigma^+$
Energy
v = 4
v = 3
v = 2
v = 1
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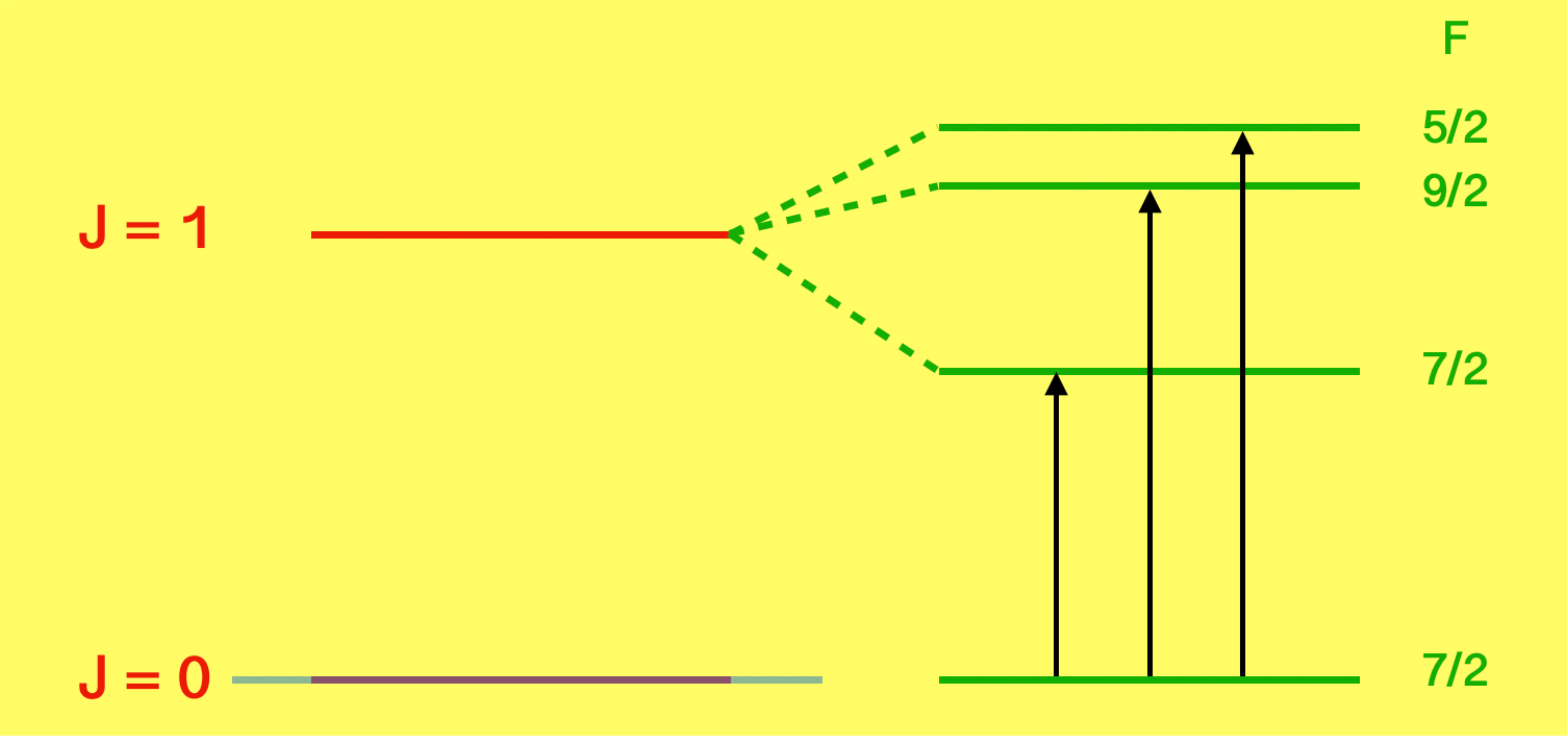
Vibrational Levels
J = 2
J = 1
J = 0
Rotational Levels of Ground Vibrational State
Intermolecular Separation

$^{177}HfF^+$ $I = 7/2$



Nuclear Quadrupole Hyperfine Structure for J = 0→1 Rotational Transition in Ground Vibrational State of $^{177}HfF^+$

Objective: Predict frequencies of these three hyperfine transitions

Method

Input

Output

SPCAT

(Petrov, 2018)

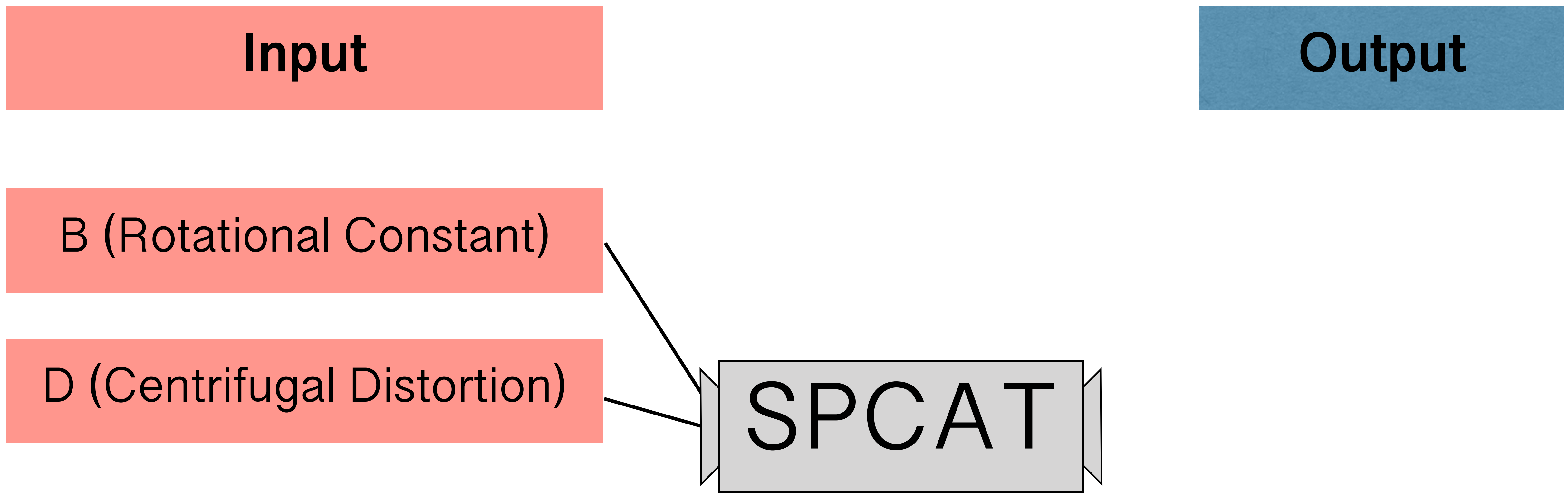
Input

Output

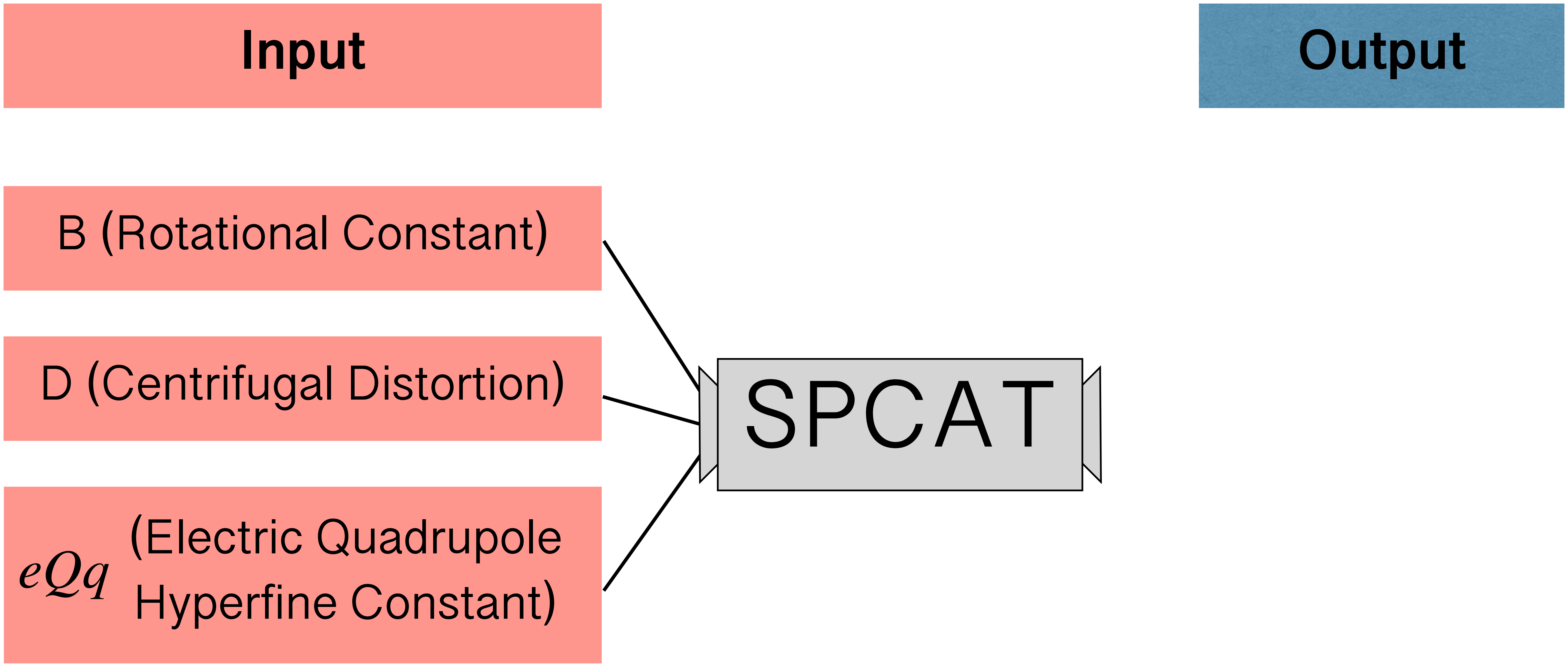
B (Rotational Constant)

SPCAT

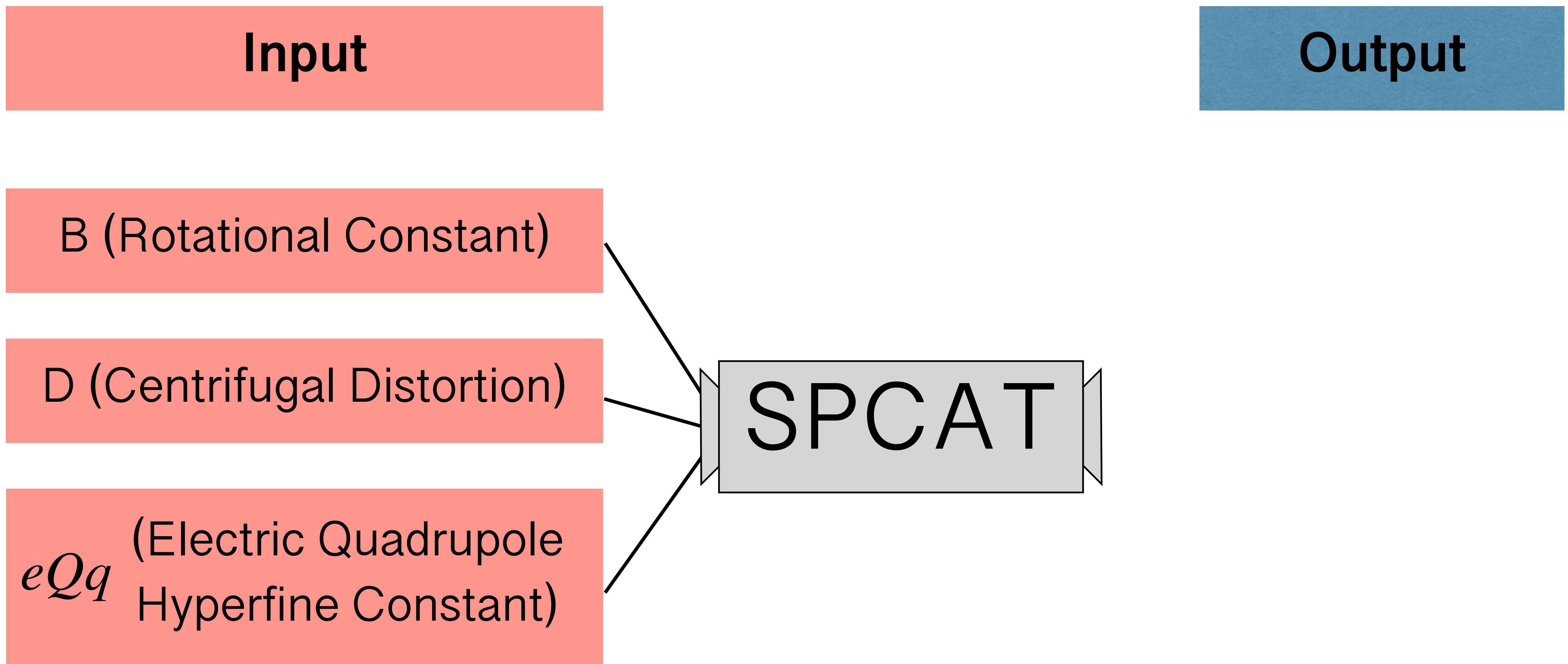
(Petrov, 2018)


Input
Output
B (Rotational Constant)
D (Centrifugal Distortion)
SPCAT

(Petrov, 2018)


Input
Output
B (Rotational Constant)
D (Centrifugal Distortion)
eQq (Electric Quadrupole Hyperfine Constant)
SPCAT

(Petrov, 2018)



Calculated by A. Petrov et. al	MHz	
	eQq_0	eQq_2
$^{177}HfF^+$	-2100	110
$^{179}HfF^+$	-2400	125

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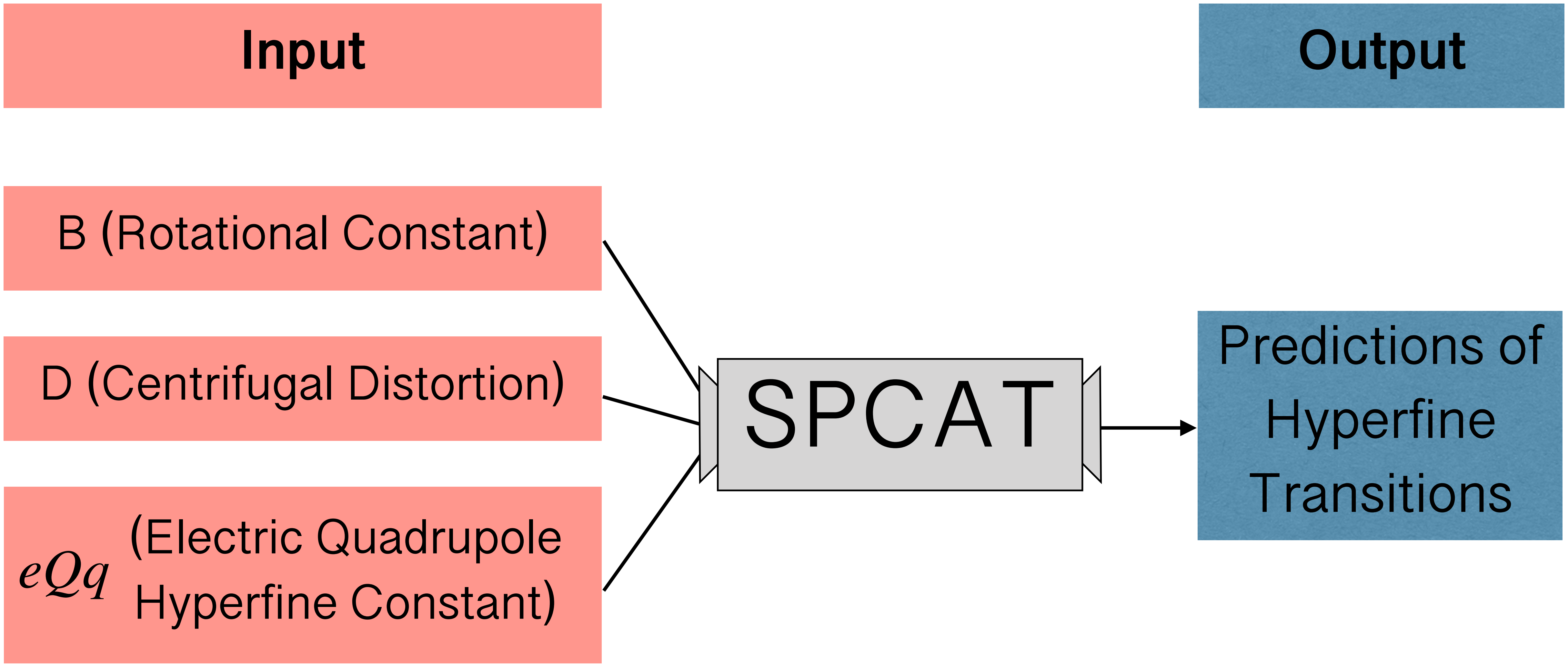

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Calculation of B and D Parameters for $^{177}HfF^+$ and $^{179}HfF^+$

- Analyze JILA's high precision data on $^{180}HfF^+$ (Cossel, 2012) to calculate B_{180} and D_{180} for ground vibrational state of $^{180}HfF^+$.
- Use isotopic scaling relationships (Drouin, 2001) to calculate B and D for odd isotopologues $^{177}HfF^+$ and $^{179}HfF^+$.

$$\frac{B_{177}}{B_{180}} = \left(\frac{\mu_{180}}{\mu_{177}}\right)$$

μ_{177} Reduced Mass of $^{177}HfF^+$

$$\frac{D_{177}}{D_{180}} = \left(\frac{\mu_{180}}{\mu_{177}}\right)^2$$

μ_{180} Reduced Mass of $^{180}HfF^+$

Evaluation of Isotopic Scaling Method with HfO

HfO

(Lesarri, 2002)

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HfO

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- Use isotopic scaling relationships to calculate B and D for $^{177}Hf^{16}O$ and $^{179}Hf^{16}O$.

(Lesarri, 2002)

Evaluation of Isotopic Scaling Method with HfO

HfO

(1) Isoelectronic to HfF^{+}

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- ✦ Use isotopic scaling relationships to calculate B and D for $^{177}Hf^{16}O$ and $^{179}Hf^{16}O$.

- ✦ Predict quadrupole splitting for $^{177}Hf^{16}O$ $^{179}Hf^{16}O$ and compare to measured values.

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$^{177}Hf^{16}O$	MHz		
Hyperfine Transition	**Calculated Frequency**	**Observed Frequency**	**Calc. – Obs.**
F = 7/2 ← 7/2	22312.4895	22312.4512	**0.0383**
F = 9/2 ← 7/2	23459.8427	23459.8047	**0.0380**
F = 5/2 ← 7/2	23804.1560	23804.1172	**0.0388**

(Lesarri, 2002)

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$^{179}Hf^{16}O$	MHz		
Hyperfine Transition	**Calculated Frequency**	**Observed Frequency**	**Calc. – Obs.**
F = 9/2 ← 9/2	22244.9685	22244.9570	**0.0115**
F = 11/2 ← 9/2	23478.1362	23478.1250	**0.0112**
F = 7/2 ← 9/2	23762.1896	23762.1777	**0.0119**

(Lesarri, 2002)

Predictions of Hyperfine Transitions in $^{177}HfF^+$ and $^{179}HfF^+$

$^{177}HfF^+$	
Hyperfine Transition	**Calculated Frequency (MHz)**
F = 7/2 ← 7/2	18007.8775
F = 9/2 ← 7/2	18412.7680
F = 5/2 ← 7/2	18533.4282

$^{179}HfF^+$	
Hyperfine Transition	**Calculated Frequency (MHz)**
F = 9/2 ← 9/2	17968.1161
F = 11/2 ← 9/2	18408.1104
F = 7/2 ← 9/2	18508.7038

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