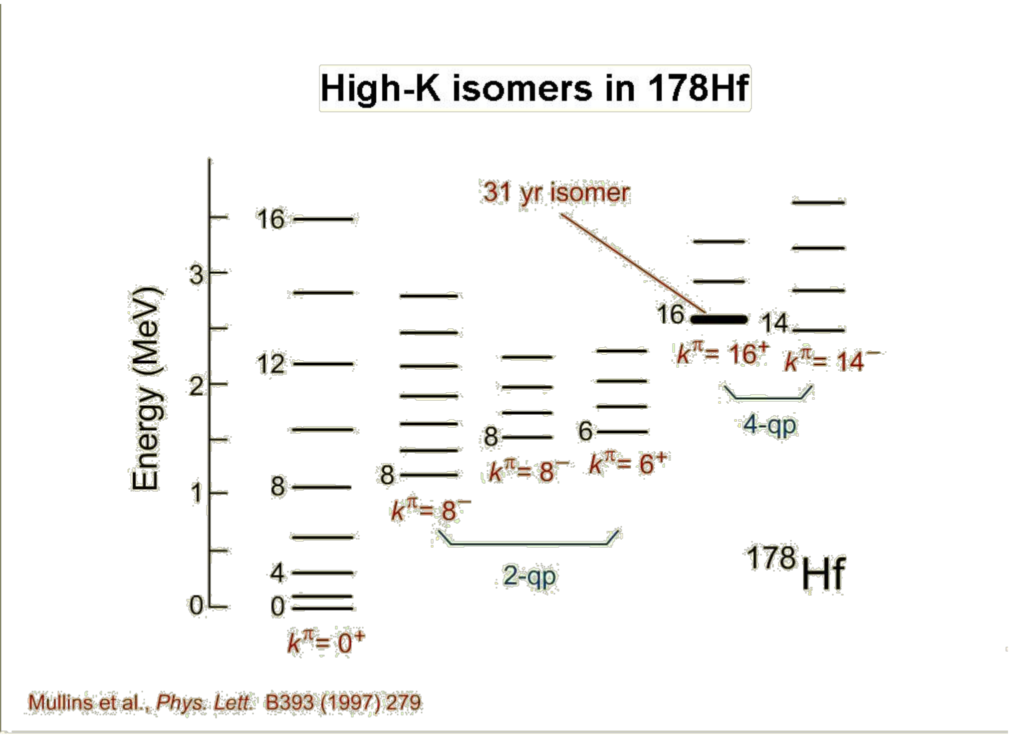
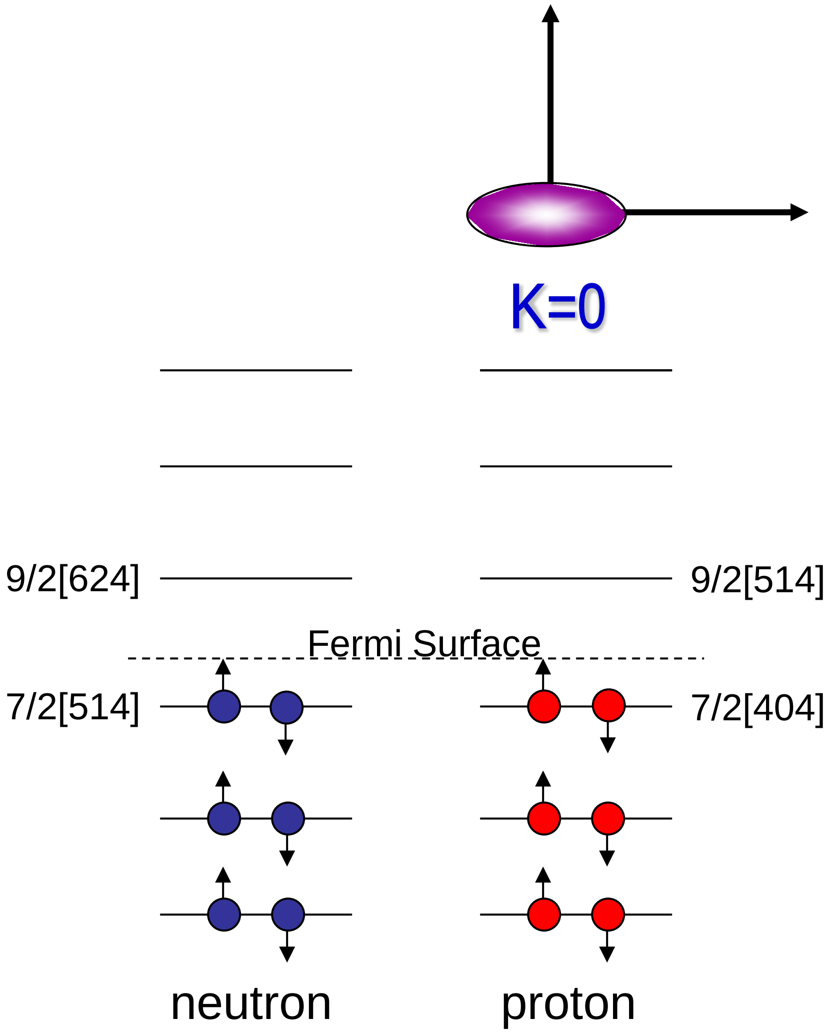
Investigation of ^{178}Hf – K-Isomers

- A well-known example:





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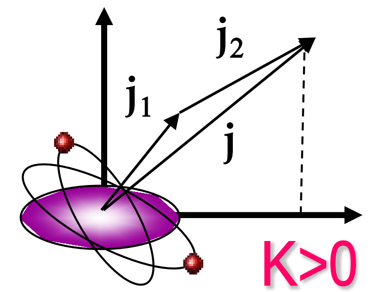
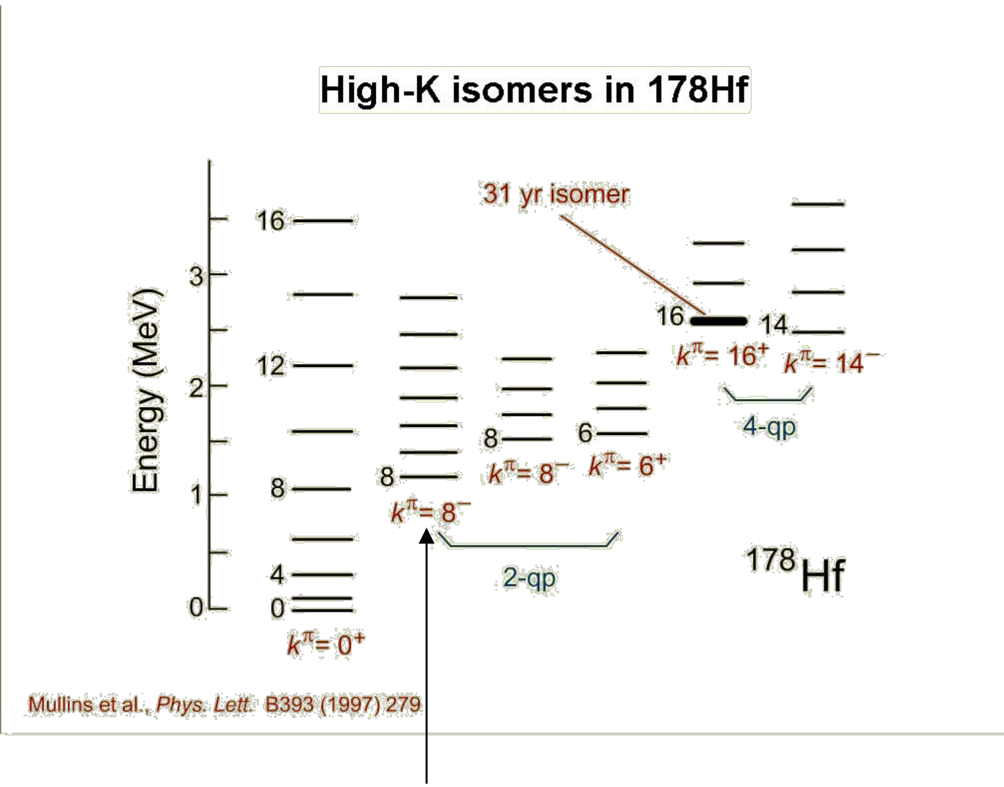
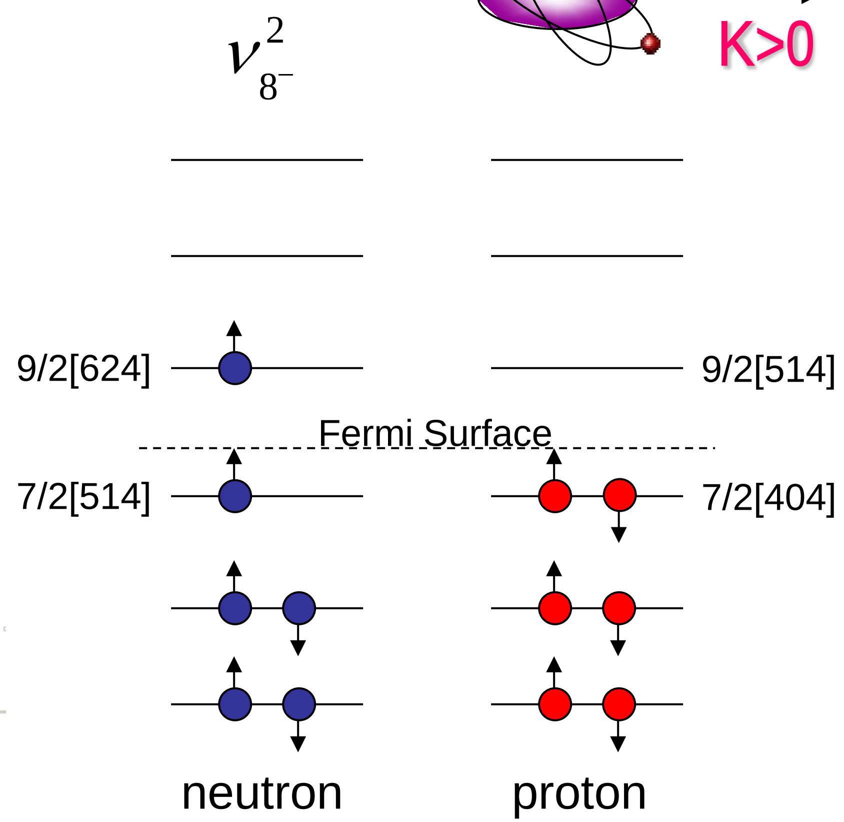




$\nu^2_{8^-}$



Investigation of ^{178}Hf – K-Isomers

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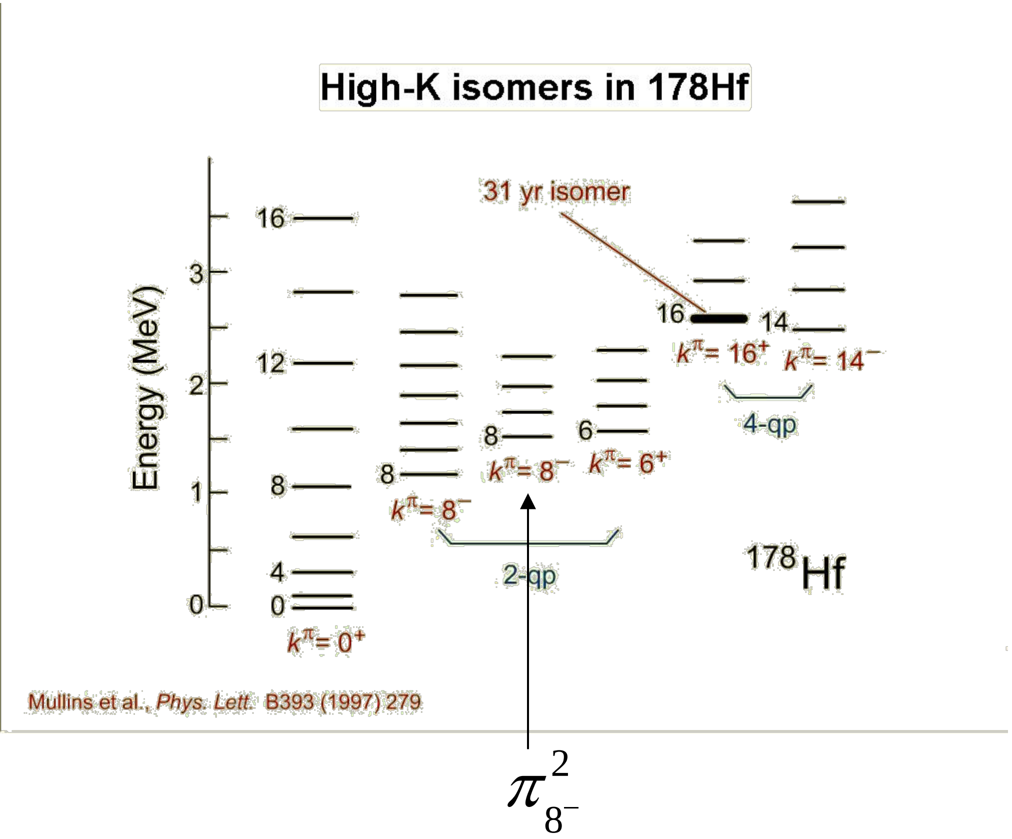
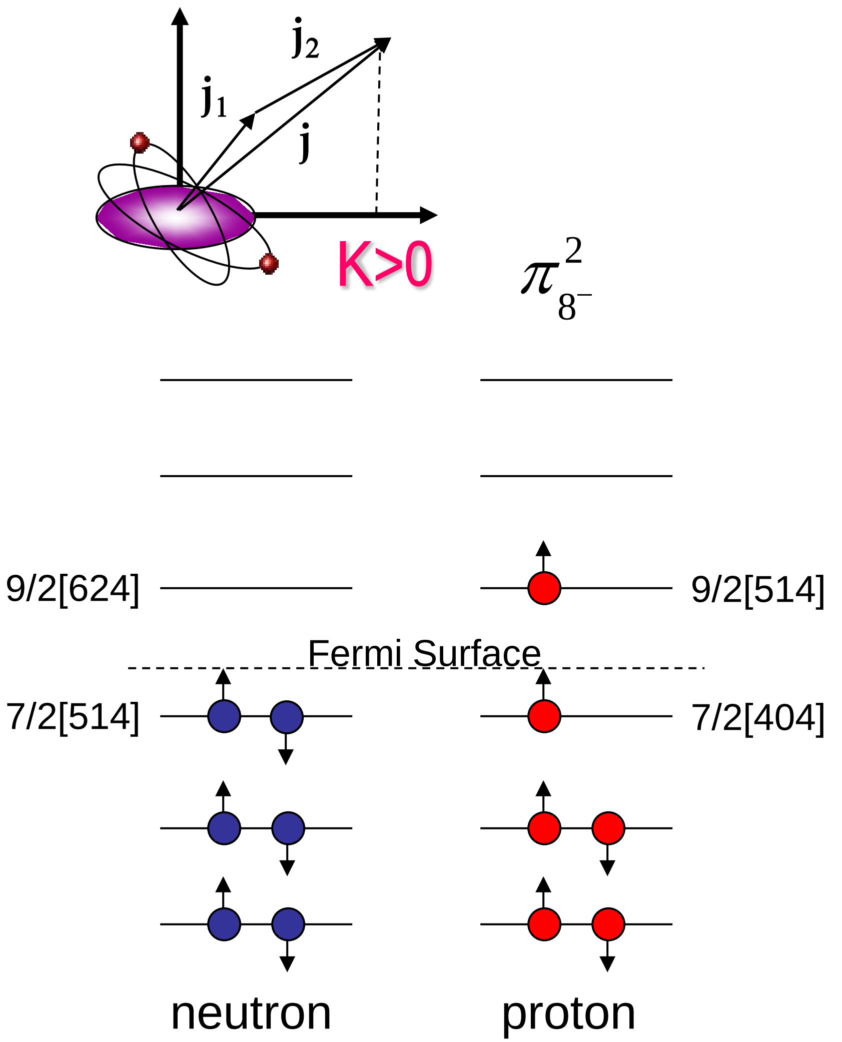
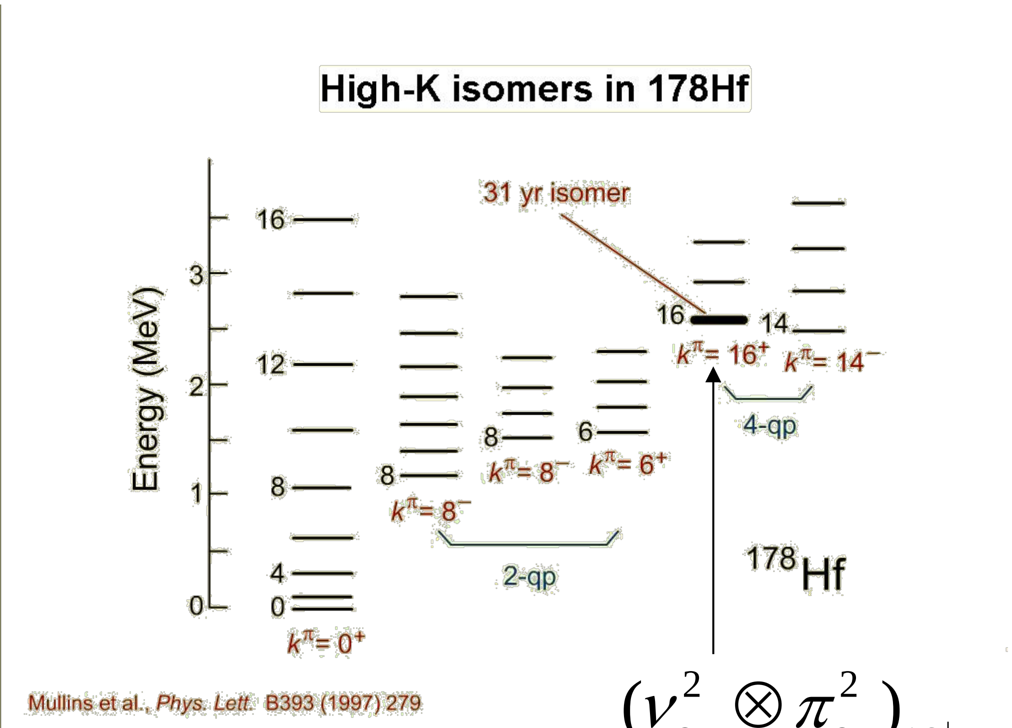


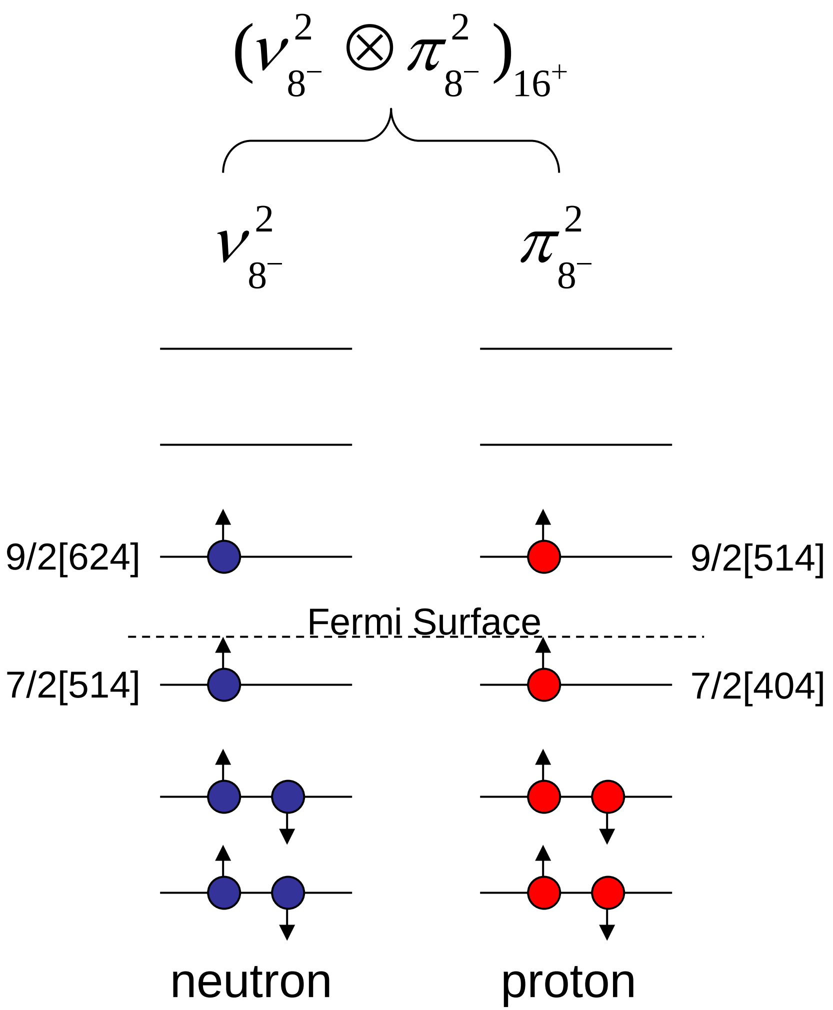


Investigation of ^{178}Hf – K-Isomers

- A well-known example:



$$(\nu^2_{8^-} \otimes \pi^2_{8^-})_{16^+}$$



Magnetic Moments in ^{178}Hf

$$g(j)=\begin{cases}\dfrac{2\cdot\ell\cdot g_\ell+g_s}{2\cdot\ell+1} & \text{for } j=\ell+1/2\\[2ex] \dfrac{2\cdot(\ell+1)\cdot g_\ell-g_s}{2\cdot\ell+1} & \text{for } j=\ell-1/2\end{cases}$$

proton $g_\ell=1 \quad g_s=5.59$

neutron $g_\ell=0 \quad g_s=-3.83$

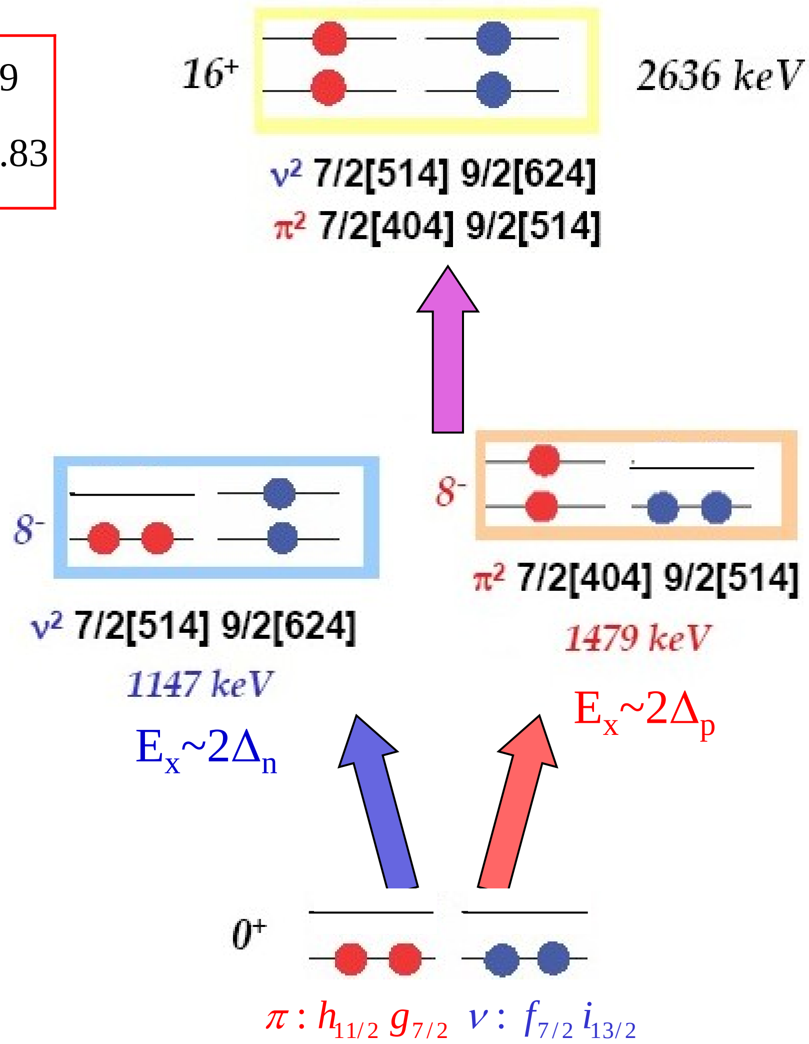
$g(h_{11/2}) = 1.42$ $\quad g(g_{7/2}) = 0.49$ $\quad g(f_{7/2}) = -0.55$ $\quad g(i_{13/2})=-0.29$

$$g(j_1\times j_2;J)=\frac{1}{2}\cdot(g_1+g_2)+\frac{j_1\cdot(j_1+1)-j_2\cdot(j_2+1)}{2\cdot J\cdot(J+1)}\cdot(g_1-g_2)$$

$g(h_{11/2}\ \text{x}\ g_{7/2}; 8^-) = 1.08$ $\quad g(f_{7/2}\ \text{x}\ i_{13/2}) = -0.36$

$g(8^-\ \text{x}\ 8^-; 16^+) = 0.36 \quad \rightarrow \quad \mu = g\cdot I = 5.76$ nm

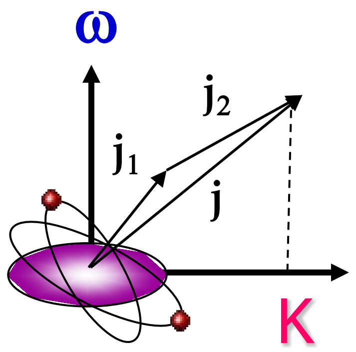
7.26±0.16 nm



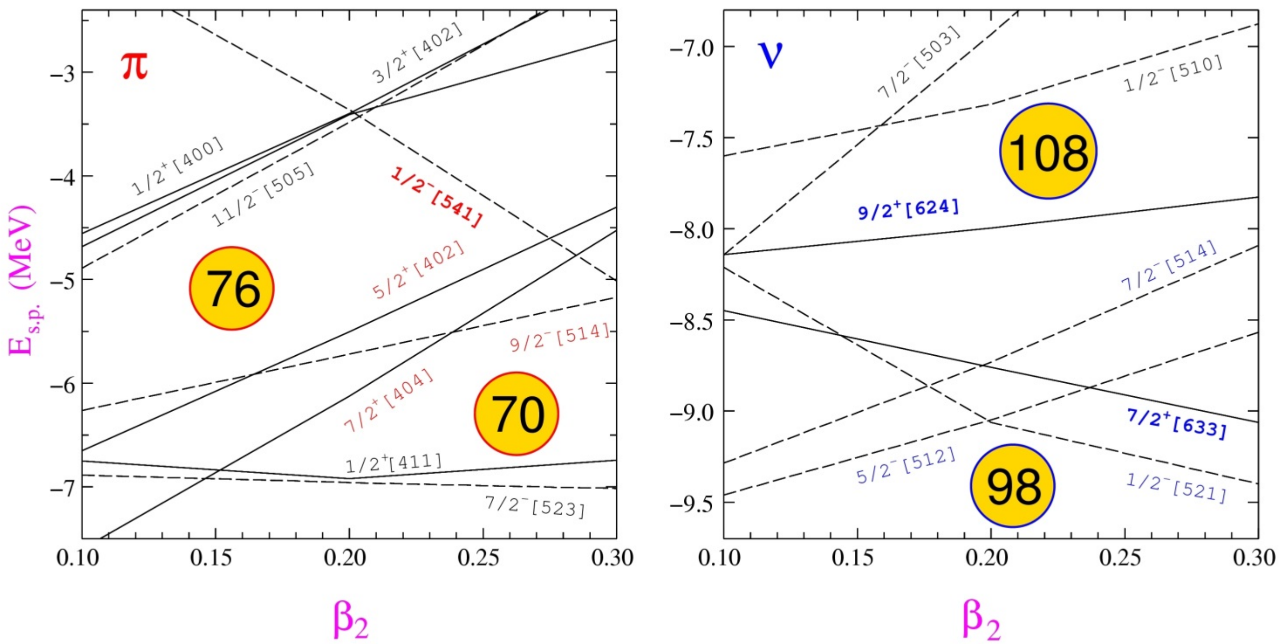
Helmer & Reich; Nucl. Phys. A114 (1968), 649

K-isomers: Where to find them?

- Deformed nuclei with axially-symmetric shape



Mass 180 region : Yb (Z=70) **- *Ir*** (Z=77)

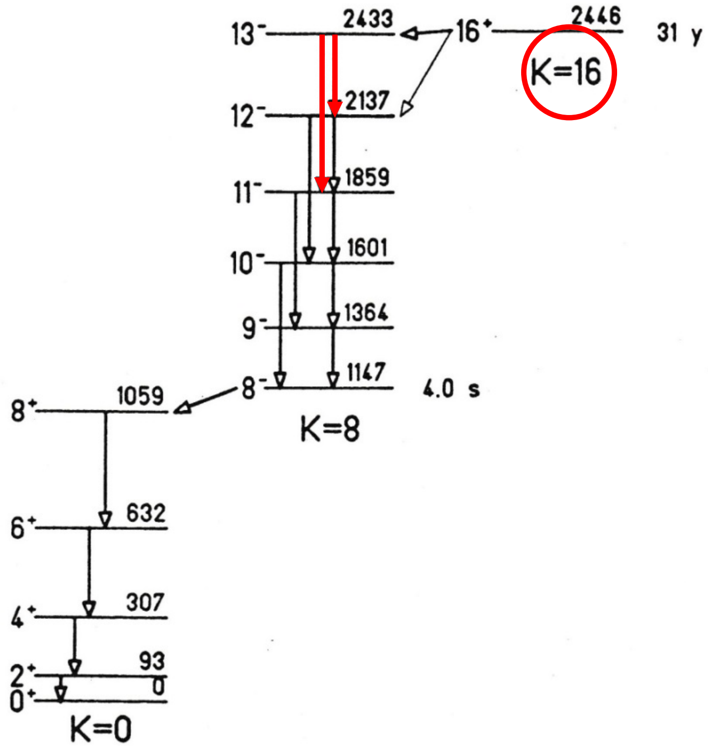


- High-K orbitals near the Fermi surface

π: 7/2[404], 9/2[514], 5/2[402]

ν: 7/2[514], 9/2[624], 5/2[512], 7/2[633]

Decay Study of the K = 16 Isomeric State



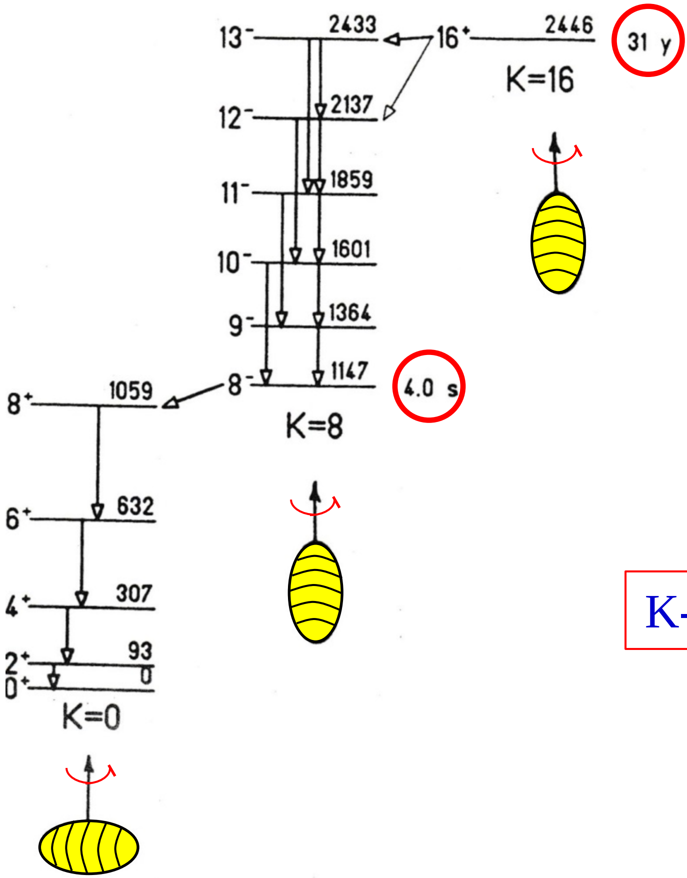
	$\frac{B(E2, I \rightarrow I-2)}{B(E2, I \rightarrow I-1)}$	**rigid rotor K=8**
10^-	0.104±0.012	0.0769
11^-	0.171±0.009	0.1607
12^-	0.230±0.017	0.2517
13^-	0.313±0.016	0.3500

E2/M1 mixing ratios are related to $\frac{g_K - g_R}{Q_{20}}$

mixed 2-quasiparticle configuration: $g_K = 0.36(2) > \mathbf{0}$

$\{\pi[514]9/2 + \pi[404]7/2\}8^-$ and $\{\nu[514]7/2 + \nu[624]9/2\}8^-$

K - Isomerism

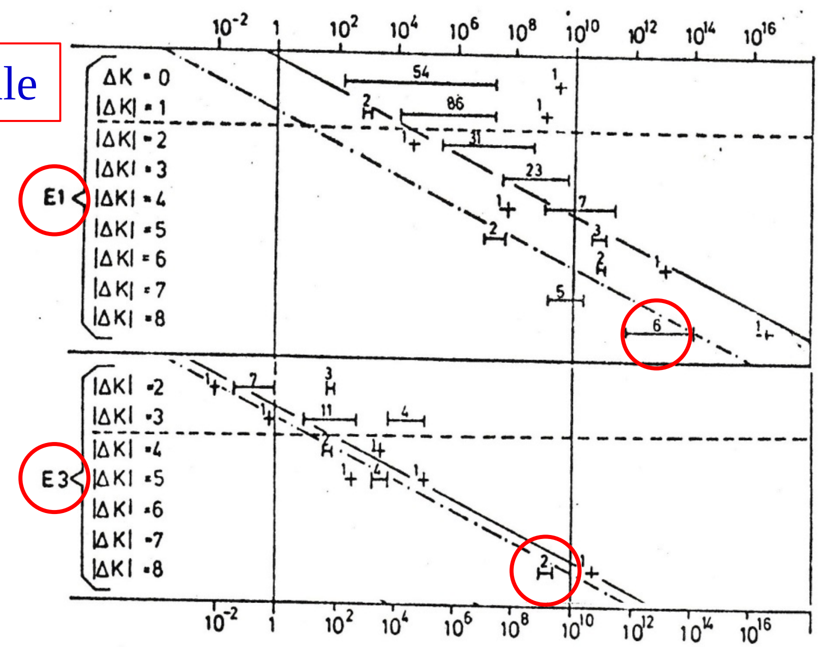


H = 10^9

H = $2 \cdot 10^{13}$

$$H = \frac{t_{1/2}(experiment)}{t_{1/2}(Weisskopf\ estimate)}$$

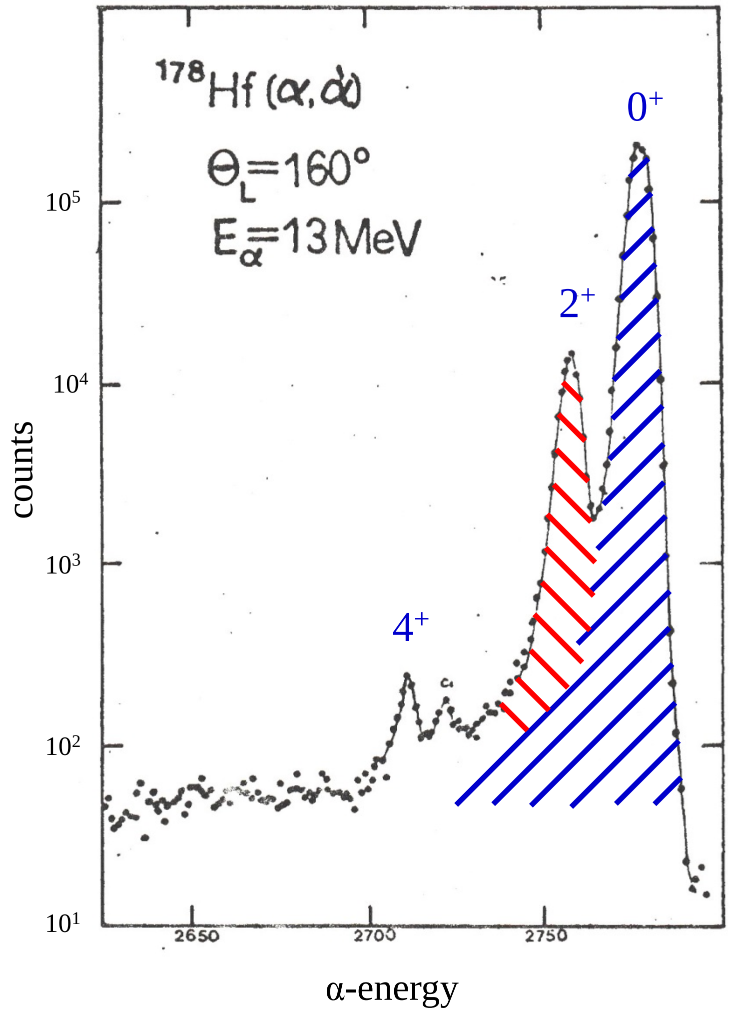
K-selection rule

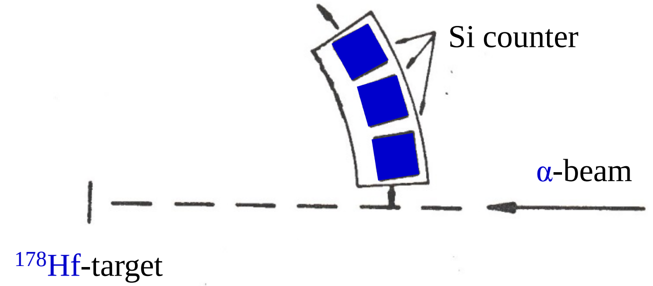


Helmer & Reich; Nucl. Phys. A114 (1968), 649

K.E.G. Löbner; Phys. Lett 26B (1968), 369

^{178}Hf: Particle Spectroscopy





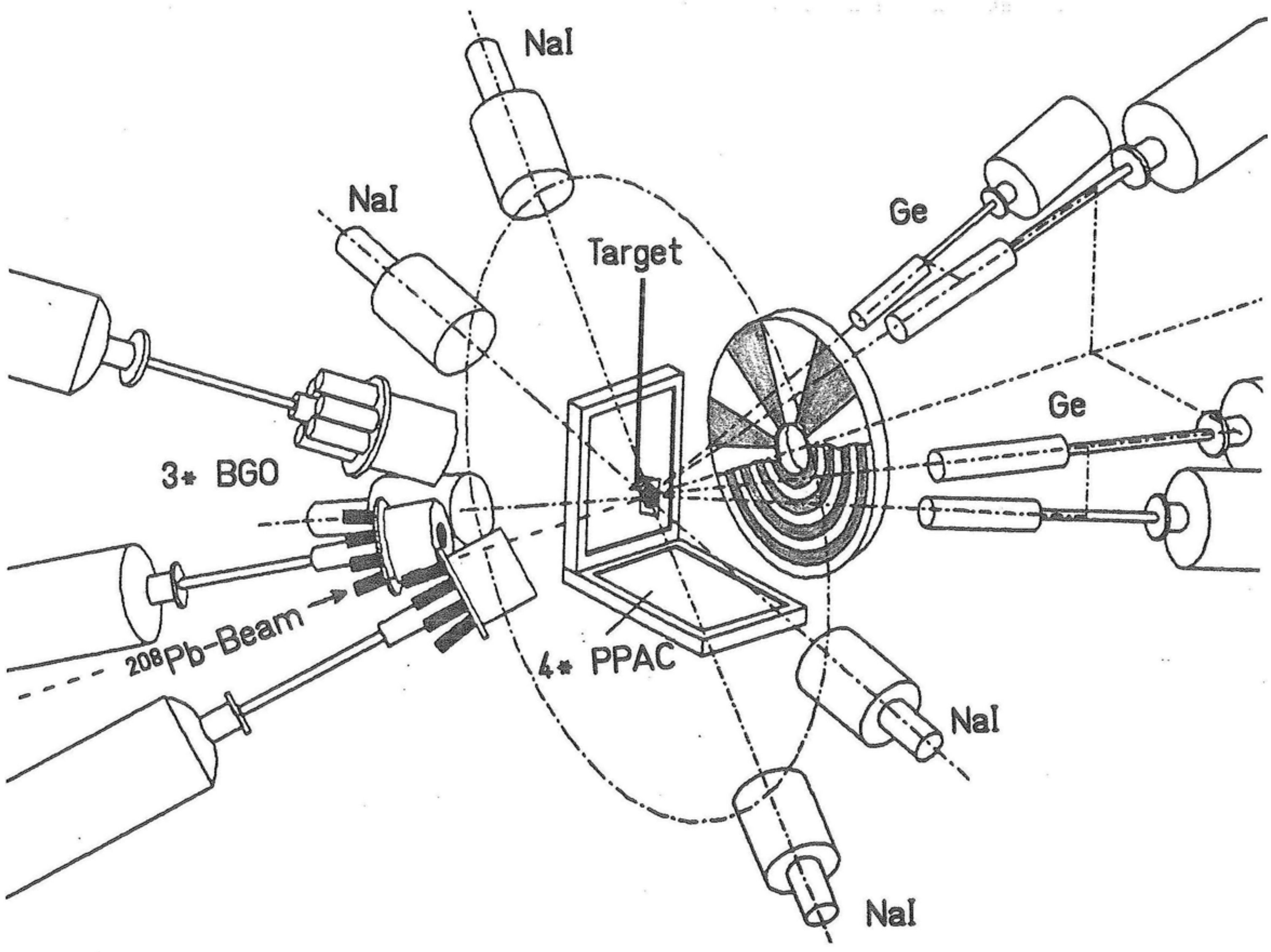
$$d\sigma_{C.E.}(E,\theta_{cm}) = P_I(E,\theta_{cm}) \cdot d\sigma_{Ruth}(E,\theta_{cm})$$

$$= 4.82\left(1+\frac{A_p}{A_t}\right)^{-2}\frac{A_p}{Z_t^2}(E_{lab}-\Delta E')\cdot B(E2,0^+\to 2^+)\cdot df_{E2}(\xi,\theta_{cm})$$

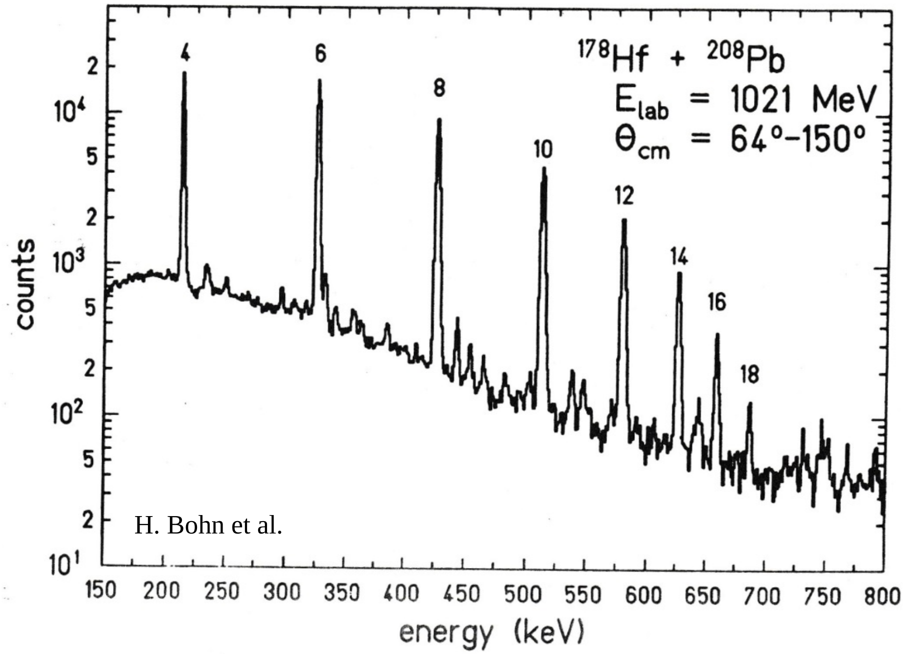
I	P_I/P_{0^+} (160^0)	
2	$6.8\cdot 10^{-2}$	
4	$7.6\cdot 10^{-4}$	
17	$4.0\cdot 10^{-4}$	$\sigma_{m2}/\sigma_{gs} = 0.05$

G. Ebel, diploma thesis

Coulomb Excitation of ^{178}Hf with ^{208}Pb ions



Coulomb Excitation of ^{178}Hf with ^{208}Pb ions



E2, E3 excitation of collective states:

ground state band K = 0

γ-vibrational band K = 2

determination of K-quantum number:

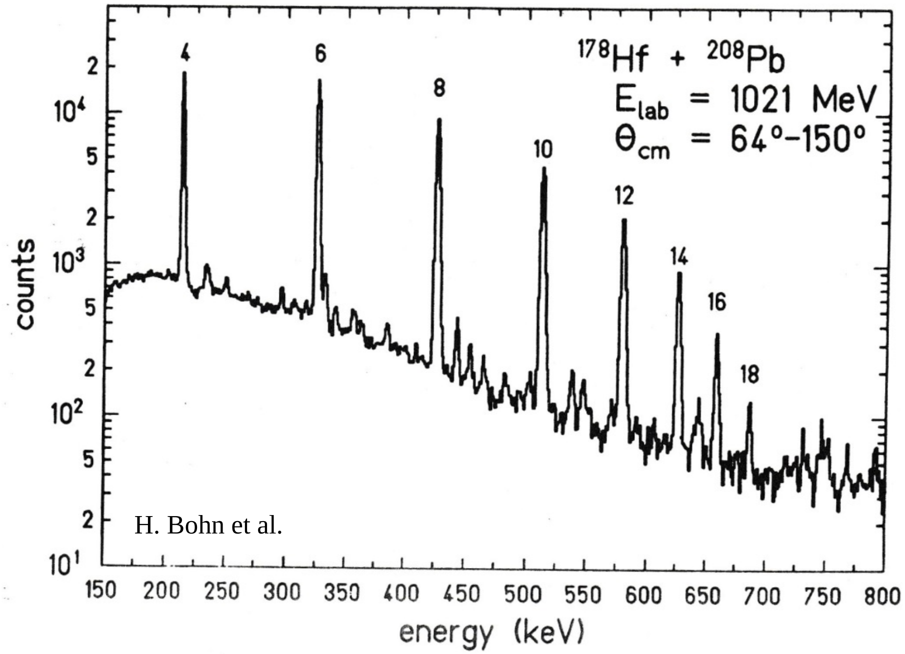
$$B(E2;I\rightarrow I-2)=\frac{[(I-1)^2-K^2][I^2-K^2]}{(4I^2-1)I(I-1)}\frac{15}{32\pi}\cdot Q_{20}^2$$

$$Q_{20}=6.99(4)\ b \qquad Q_{40}=0.54\binom{26}{47}\ b^2\ \ or\ -1.58(48)\ b^2$$

β_2 = 0.29(1) β_4 = -0.20(4)

J.H. Hamilton et al.; Phys. Lett. 112B (1982), 327: lifetime measurement R.M. Ronningen et al.; Phys. Rev C16 (1977), 2218; Phys. Rev. Lett. 40 (1978), 364

Coulomb Excitation of ^{178}Hf with ^{208}Pb ions



E2, E3 excitation of collective states:

ground state band K = 0

γ-vibrational band K = 2

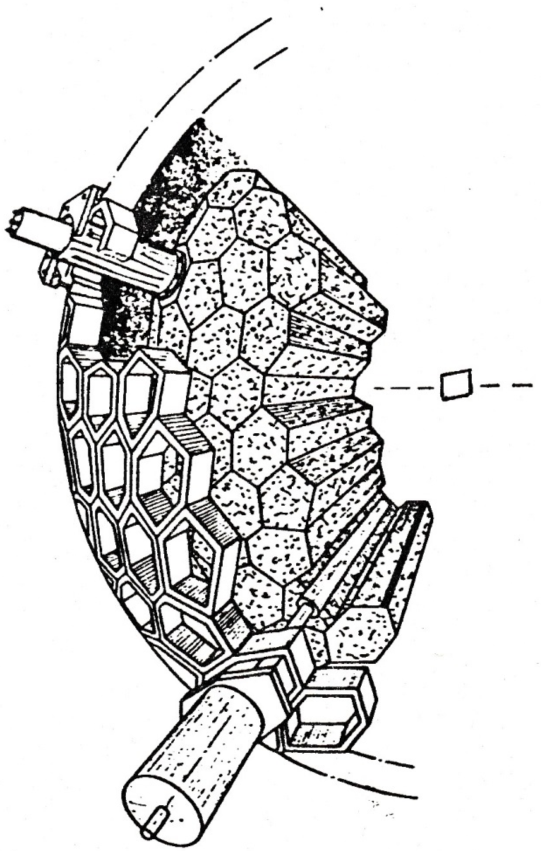
- excitation of the K = 8 isomeric state **!**

observation of delayed γ-rays in the K = 0 ground state band

- ^{178}Hf + ^{86}Kr, ^{178}Hf + ^{136}Xe

J.H. Hamilton et al.; Phys. Lett. 112B (1982), 327: lifetime measurement

Coulomb Excitation of the K = 8 Isomer in ^{178}Hf



162 **NaI** detectors
6 **Ge** detector

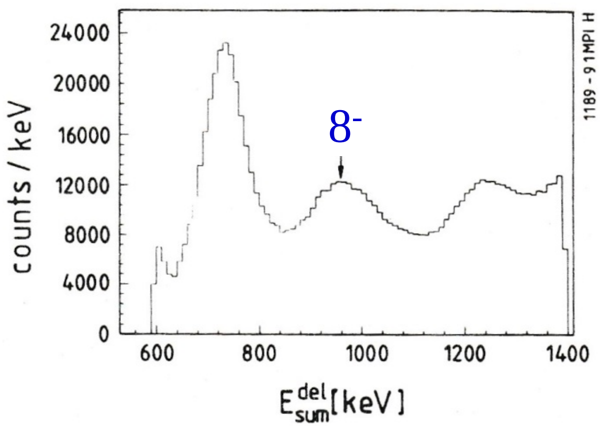
H. Xie et al.; Phys. Rev. C48 (1993), 2517

parameters and resolutions FWHM

E_i	5.5% at 1332 keV
t_i	2.8 ns
W(θ)	14^0
E_{total}	18-22% for M_γ=20
M_γ	25-30% for M_γ=20

The two basic observables which can be measured for the resulting γ-ray shower are the **total energy** emitted as γ-radiation and the **number of γ-rays**.

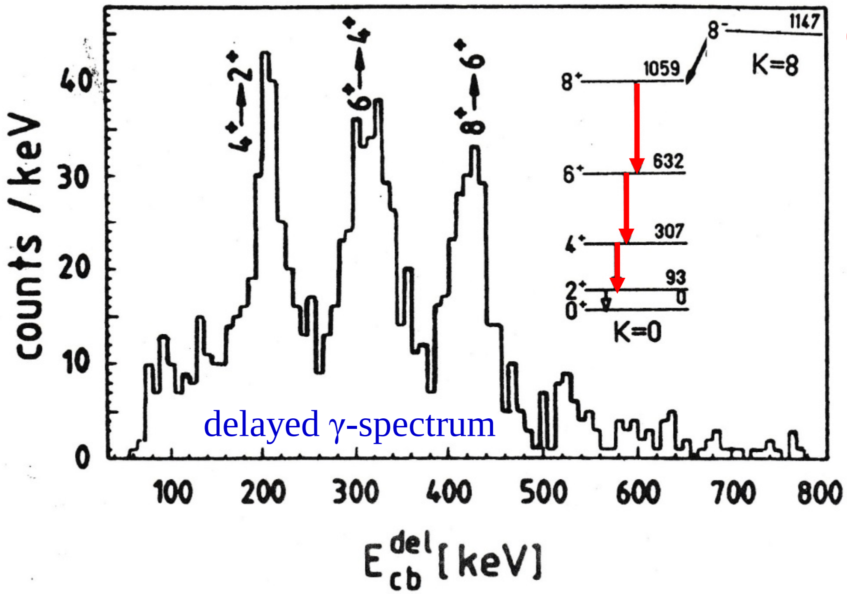
- ^{178}Hf + ^{130}Te at 560, 590, 620 MeV
  particle detection at ~180^0, Pb catcher (0.5 mm thickness) was positioned 1cm downstream to stop the recoiling ^{178}Hf ions.



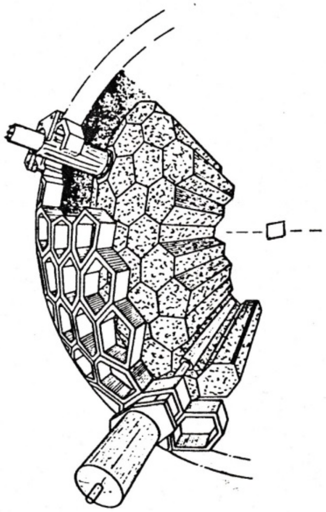
Delayed sum-energy spectrum taken at 590 MeV. (delayed time window 20-65ns with respect to beam pulse) A peak associated to the $K^\pi=8^-$ shows up.
The other peaks correspond to isomers of fusion products from target contaminants and β-decay.

Coulomb Excitation of the K = 8 Isomer in ^{178}Hf

- ^{178}Hf + ^{130}Te at 560, 590, 620 MeV



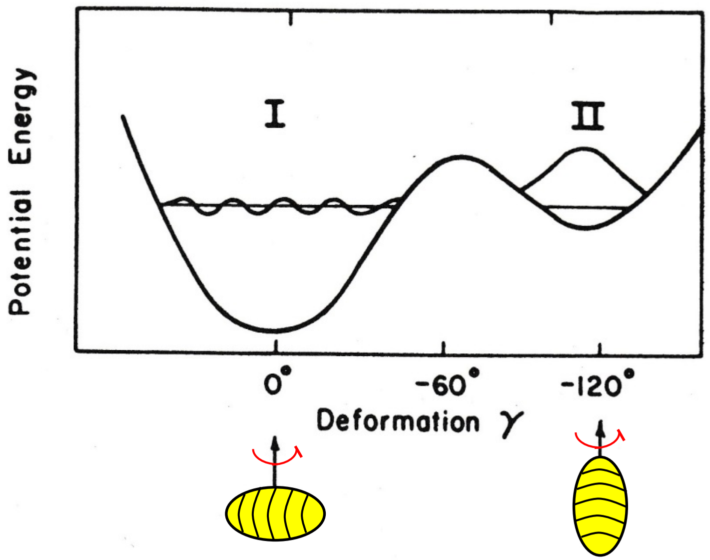
4 s → M_{30} $(E3) \leq 0.01$



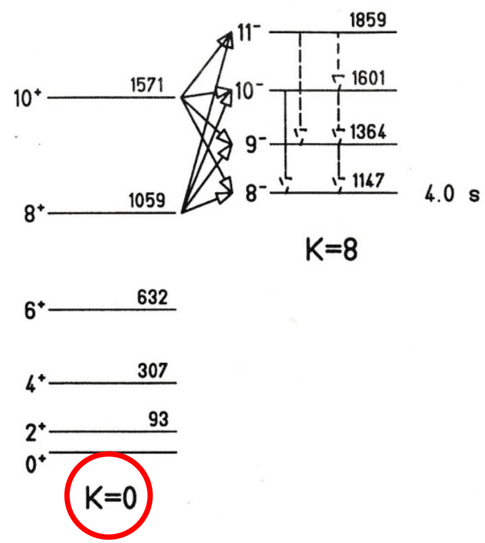
Delayed γ-ray spectrum of the Crystal Ball with $850keV \leq E_{sum}^{del} \leq 1100keV$ and $3 \leq N_{det} \leq 6$. In addition at least one of the delayed γ-rays must have been detected in one of the Ge-detectors.

H. Xie et al.; Phys. Rev. C48 (1993), 2517

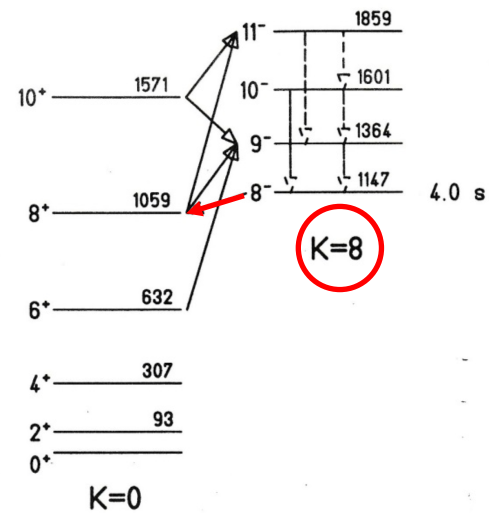
Decay of the Isomer by Barrier Penetration



+ small K=8 admixture



+ small K=0 admixture



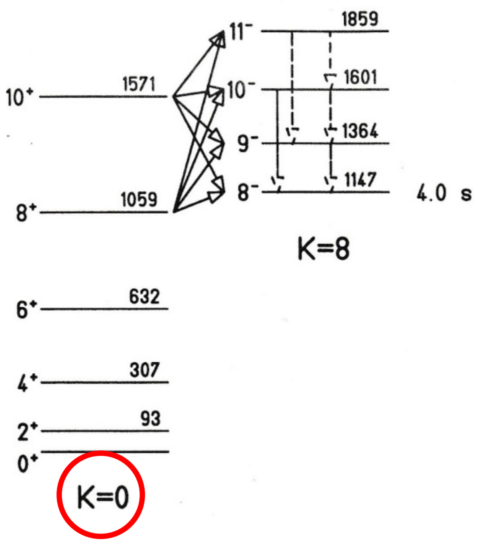
rigid rotor model:

$$\langle I_f \| M(E2) \| I_i \rangle = \sqrt{2I_i + 1} \cdot (I_i 3 K 0 | I_f K) \cdot M_{30}$$

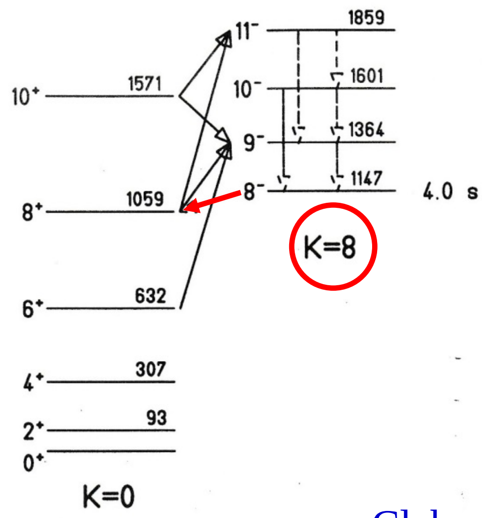
8^- lifetime is independent from excitation

2-Band K-Mixing Model

+ small K=8 admixture



+ small K=0 admixture



8^- lifetime is independent from excitation

Clebsch Gordan coefficient:

$$< I3K0|(I-3)K > \;=\; -\sqrt{\frac{5(I+K-2)(I+K-1)(I+K)(I-K-2)(I-K-1)(I-K)}{2(I-2)(I-1)I(2I-3)(2I-1)(2I+1)}}$$

$$< I3K0|(I-2)K > \;=\; \sqrt{\frac{15(I+K-1)(I+K)(I-K-1)(I-K)}{(I-2)(I-1)I(2I-1)(2I+1)(2I+2)}} * K$$

$$< I3K0|(I-1)K > \;=\; -\sqrt{\frac{3(I+K)(I-K)}{(I-1)I(2I-3)(2I+1)(2I+2)(2I+3)}} * (5K^2-I^2+1)$$

$$< I3K0|IK > \;=\; \frac{5K^2-3I^2-3I+1}{\sqrt{(I-1)I(I+1)(I+2)(2I-1)(2I+3)}} * K$$

$$< I3K0|(I+1)K > \;=\; \sqrt{\frac{3(I+K+1)(I-K+1)}{I(I+1)(2I-1)(2I+1)(2I+4)(2I+5)}} * (5K^2-I^2-2I)$$

$$< I3K0|(I+2)K > \;=\; \sqrt{\frac{15(I+K+1)(I+K+2)(I-K+1)(I-K+2)}{I(I+1)(I+2)(2I+1)(2I+3)(2I+6)}} * K$$

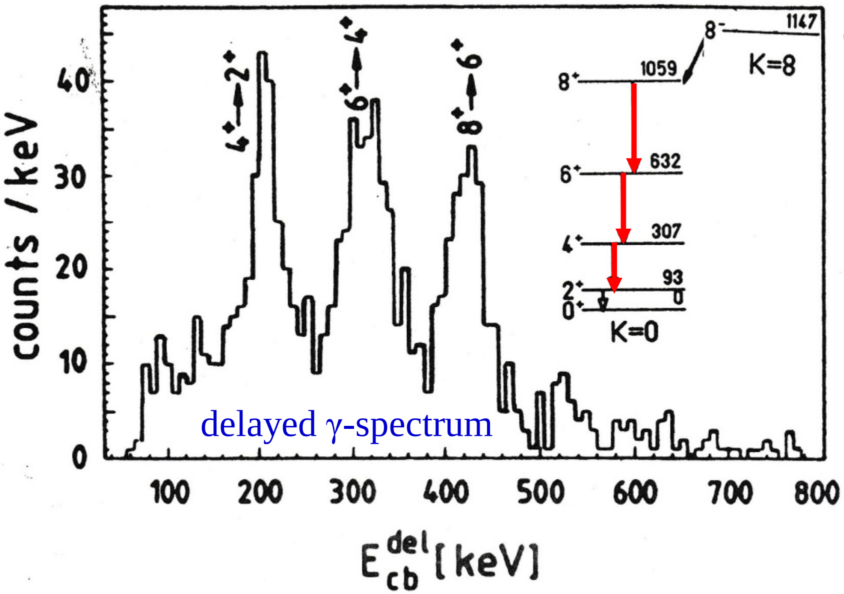
$$< I3K0|(I+3)K > \;=\; \sqrt{\frac{5(I+K+1)(I+K+2)(I+K+3)(I-K+1)(I-K+2)(I-K+3)}{2(I+1)(I+2)(I+3)(2I+1)(2I+3)(2I+5)}}$$

rigid rotor model:

$$\langle I_f \| M(E3) \| I_i \rangle = \sqrt{2I_i+1} \cdot \left(I_i 3 K 0 | I_f K \right) \cdot M_{30}$$

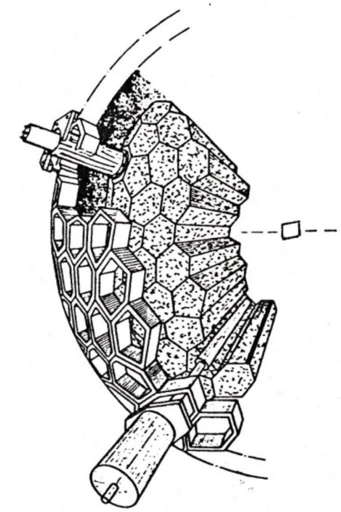
Coulomb Excitation of the K = 8 Isomer in ^{178}Hf

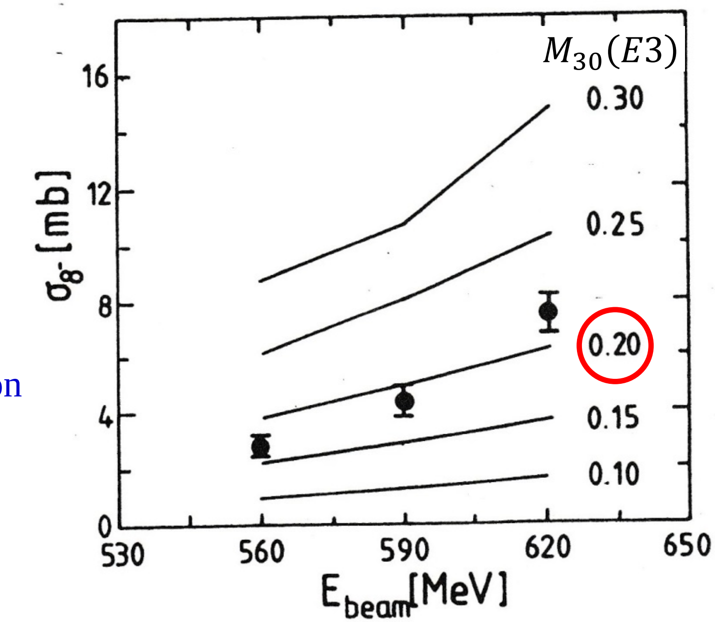
- ^{178}Hf + ^{130}Te at 560, 590, 620 MeV



4 s

$\rightarrow M_{30}\ (E3) \leq 0.01$





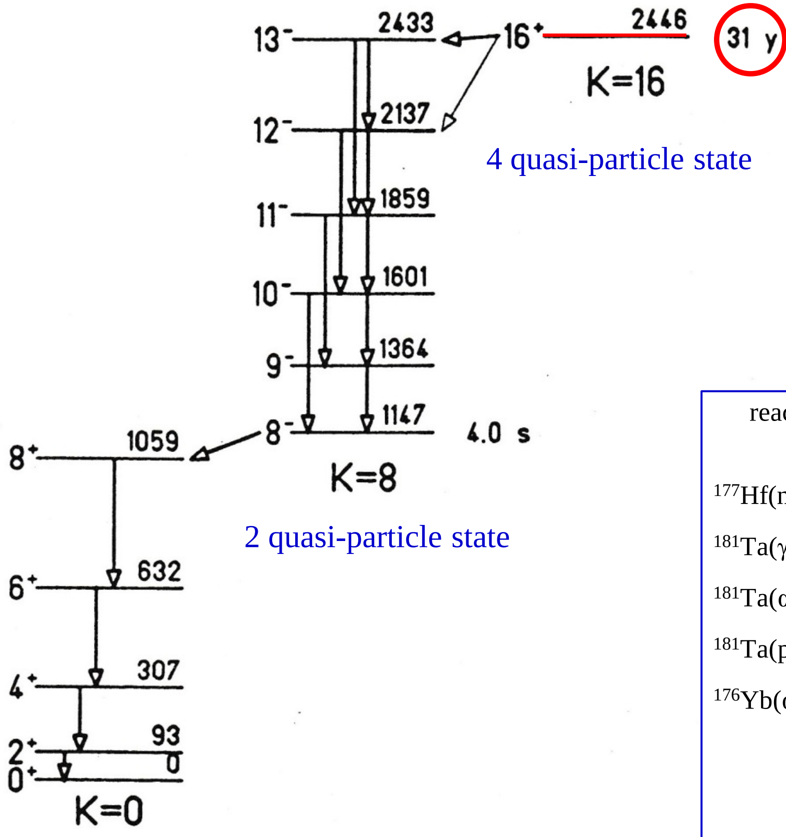
coupling between rotational motion
and single particle excitation

$$\psi(8^-) \cong |K=8\rangle + \alpha|K=0\rangle$$

H. Xie et al.; Phys. Rev. C48 (1993), 2517

Investigation of the K=16 isomer in ^{178}Hf

decay scheme of ^{178m2}Hf



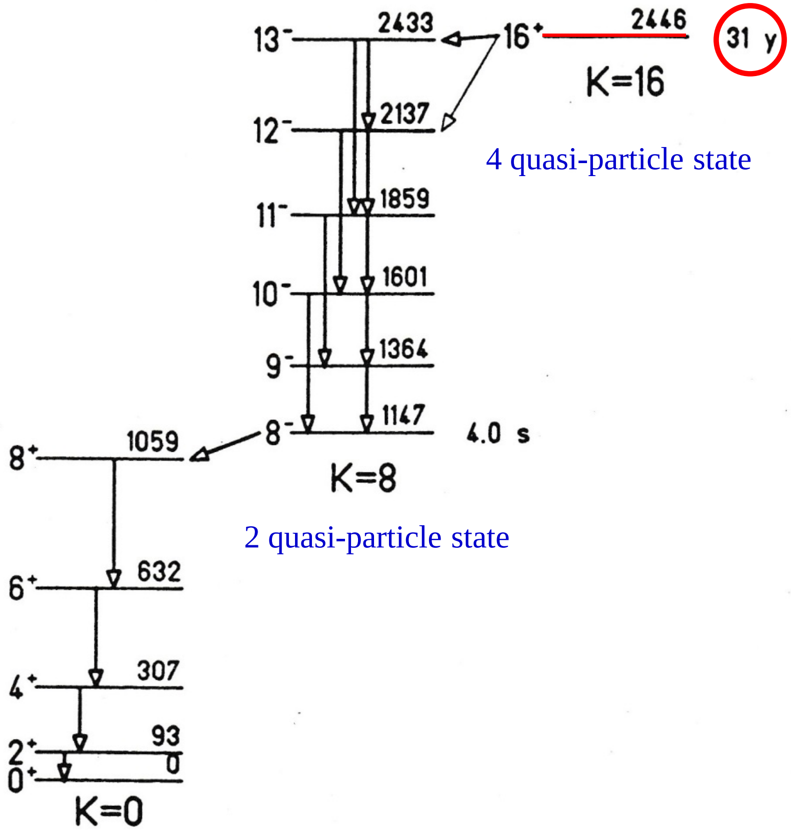
Helmer & Reich; Nucl. Phys. A114 (1968), 649

Production of ^{178m2}Hf in the past

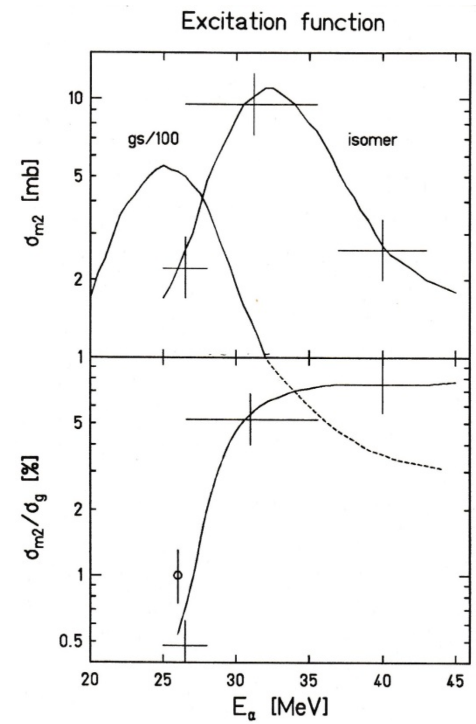
reaction	projectile energy (MeV)	σ_m/σ_{gs}	reference
^{177}Hf(n,γ)	thermal	10^{-9}	R.G. Helmer et al.; Nucl. Phys. A211, 1 (1973)
^{181}Ta(γ,p2n)	≤85	low	F.W.N. de Boer et al.; Nucl. Phys. A263,1 (1976)
^{181}Ta(α,αp2n)	120	-	J. Van Klinken et al.; Nucl. Phys. A339, 189 (1980)
^{181}Ta(p,α)	92.5	10^{-3}	W. Kutschera et al.; Radio. Beam Conf., 345 (1989)
^{176}Yb(α,2n)	26	0.01	T. Khoo et al.; Phys. Lett. 67B, 271 (1977)
	27	0.005	A. Kugler et al.; priv. communication
	32	0.05	NUPECC News 1991
	40	0.08	

Investigation of the K=16 isomer in ^{178}Hf

decay scheme of $^{178m2}Hf$



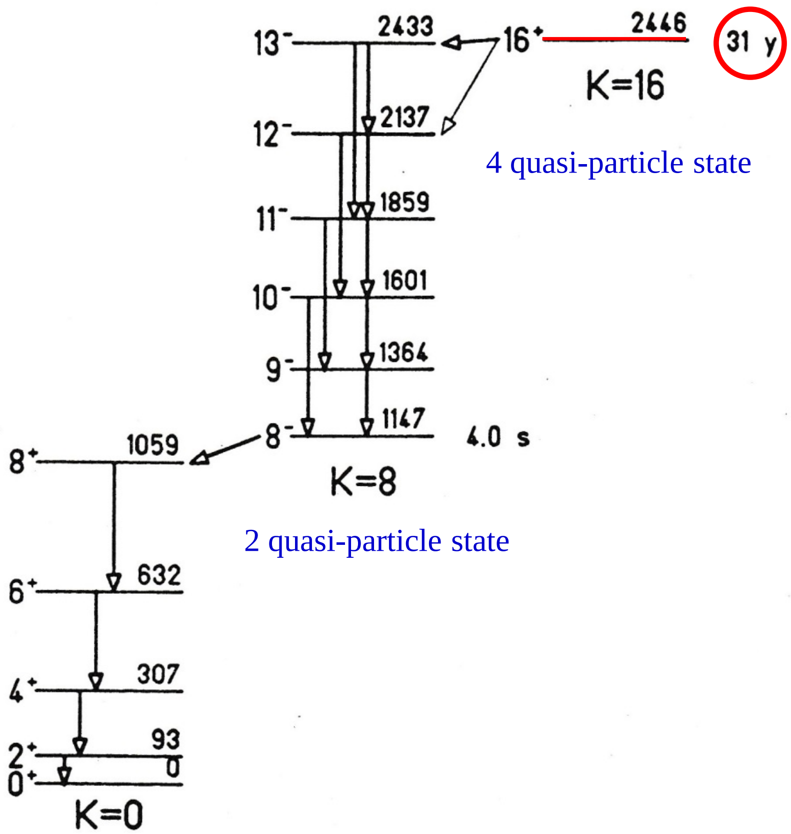
Production of $^{178m2}Hf$ using $^{176}Yb(\alpha,2n)$



Helmer & Reich; Nucl. Phys. A114 (1968), 649

Investigation of the K=16 isomer in ^{178}Hf

decay scheme of ^{178m2}Hf



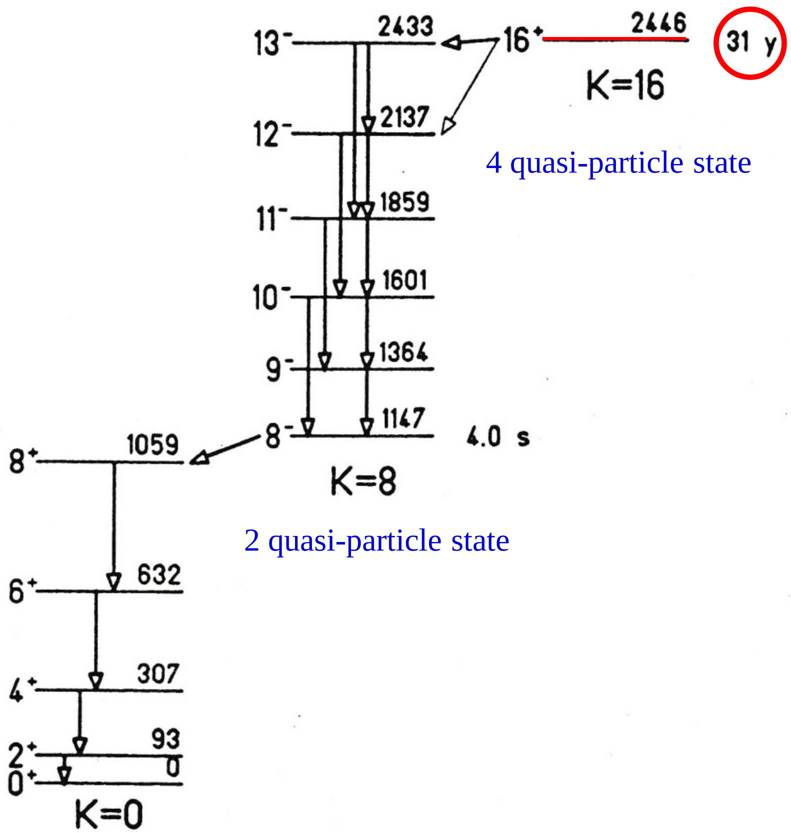
The isotopic distribution of radioactive Hf nuclei produced in the irradiation ^{4}He + ^{176}Yb

Mass	**170**	**171**	**172**	**173**	**175**	**178m**	**178g**	**179m**
$T_{1/2}$	**15.9h**	**12.2h**	**1.9y**	**24h**	**70d**	**31y**	**stable**	**24.8d**
Experiment	510^{10}	1.510^{11}	4.510^{12}	1.310^{13}	2.210^{13}	1.610^{13}	--	7.610^{11}
Calculation	810^{10}	1.510^{12}	4.410^{12}	0.810^{13}	2.210^{13}	--	2.910^{14}	--

Helmer & Reich; Nucl. Phys. A114 (1968), 649

Investigation of the K=16 isomer in ^{178}Hf

decay scheme of ^{178m2}Hf



- magnet moment $\mu(16^+) = 7.3 \pm 0.2$ nm
- 4-qp state: $\pi[514]9/2 + \pi[404]7/2 + \nu[514]7/2 + \nu[624]9/2$

- production: ^{176}Yb(α,2n)^{178}Hf Dubna
- chemical separation Orsay, Dubna
- mass separation Orsay
- target preparation Orsay

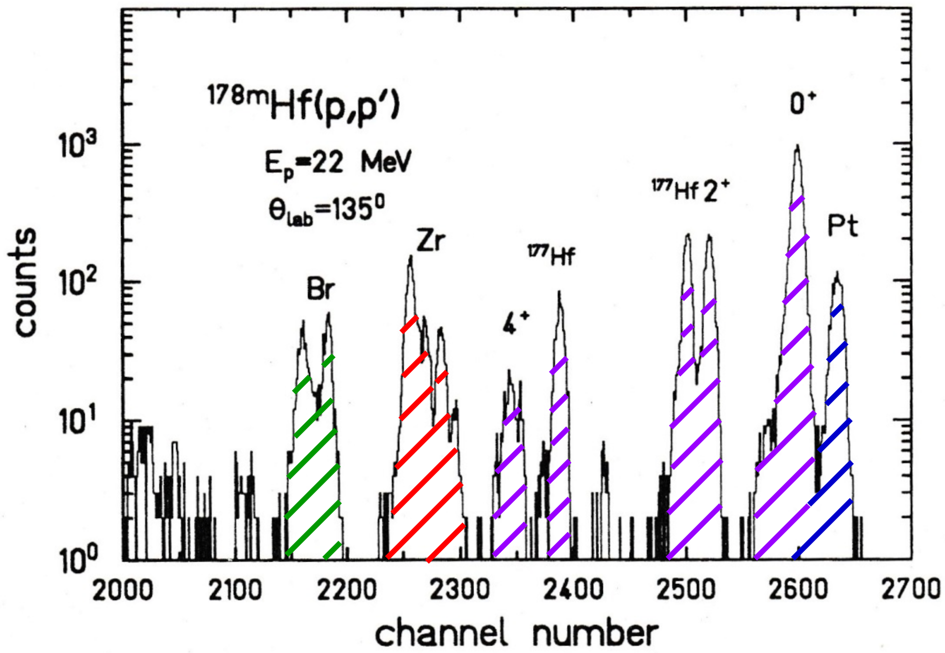
chemistry by M. Hussonnois (IN2P3-CNRS Orsay, France)

Yu. Ts. Oganessian; J. Phys. G: Nucl. Part. Phys. 18 (1992),393

Helmer & Reich; Nucl. Phys. A114 (1968), 649

Target Analysis

- inelastic p-scattering experiment

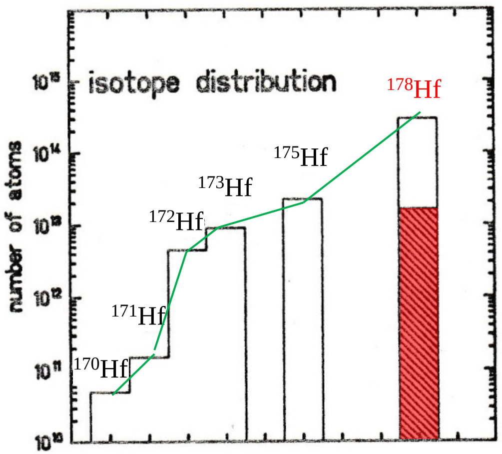


- X-ray analysis

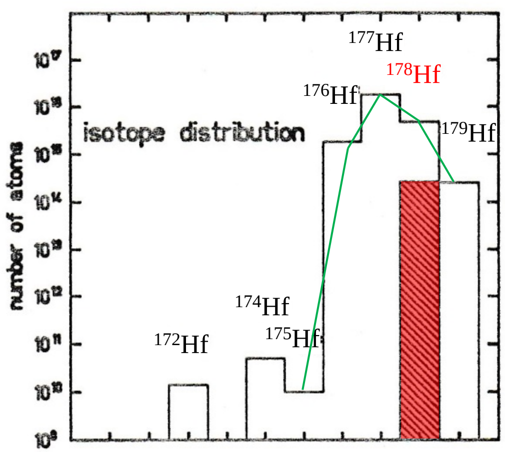
		Br	Zr	Hf	Pt	
^{178m2}Hf	15μg	**107**	**320**	**1278**	**33**	counts/s
^{nat}Hf	40μg	**-**	**223**	**3645**	**-**	counts/s

- isomer-to ground state ratio: $\sigma_{m2}/\sigma_{gs} = 2\%$

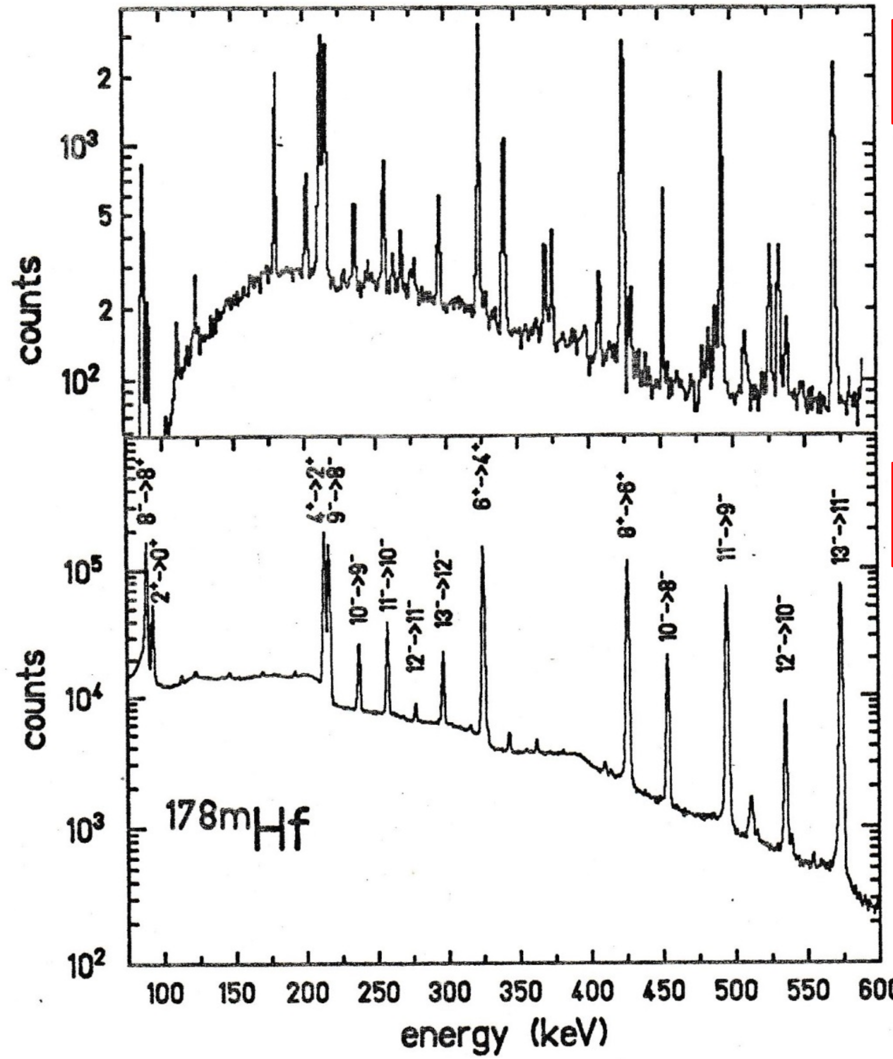
The ^{176}Yb(α,2n) Reaction



96% enriched ^{176}Yb



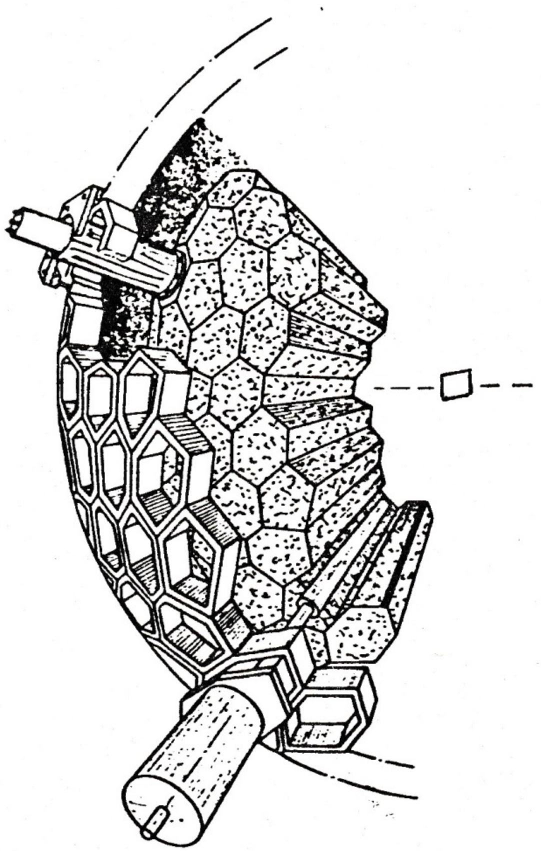
99.998% enriched ^{176}Yb



96%
enriched ^{176}Yb

99.998%
enriched ^{176}Yb

Decay Study with the GSI-MPI Crystal Ball

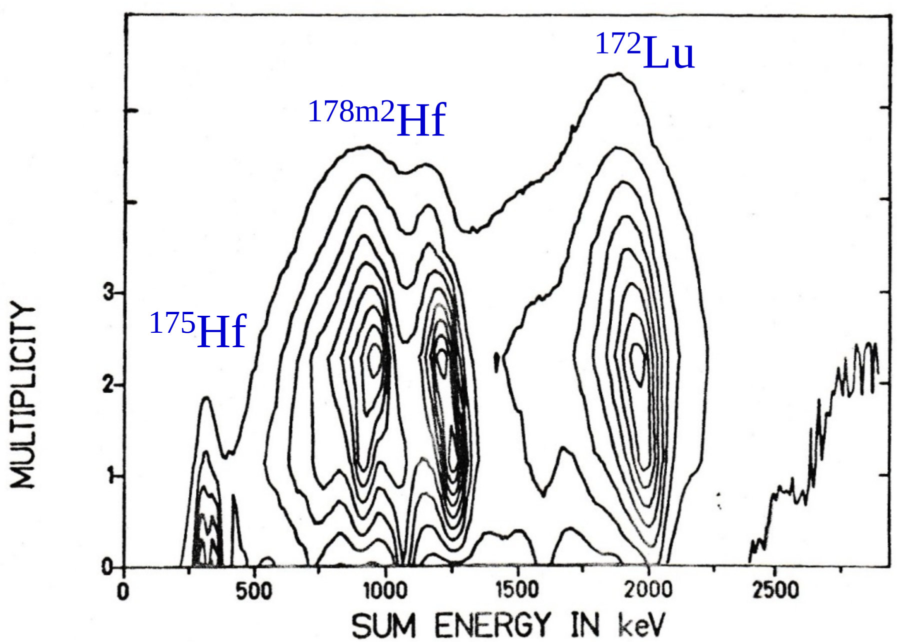


162 **NaI** detectors
1 **Ge** detector

parameters and resolutions FWHM

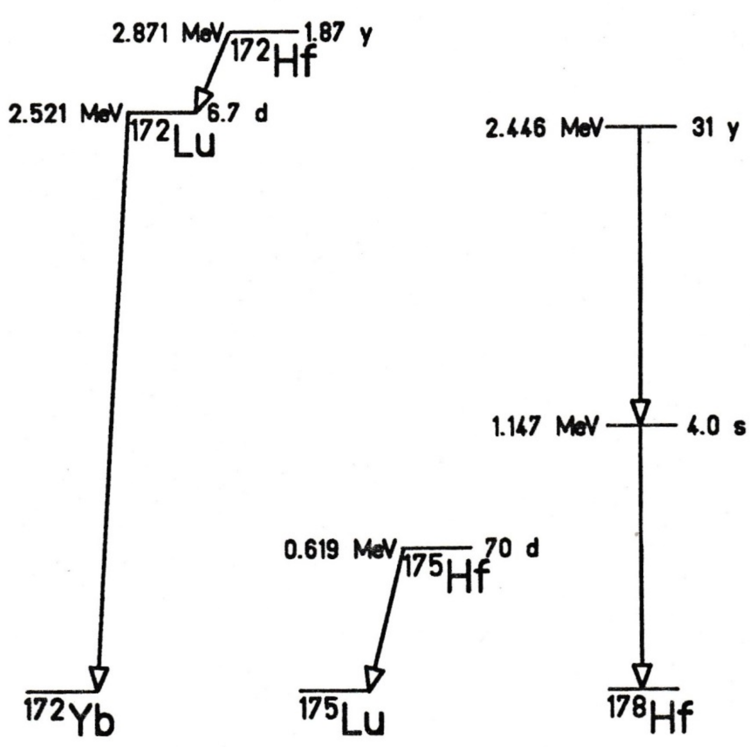
E_i	5.5% at 1332 keV
t_i	2.8 ns
$W(\theta)$	14^0
E_{total}	18-22% for M_γ=20
M_γ	25-30% for M_γ=20

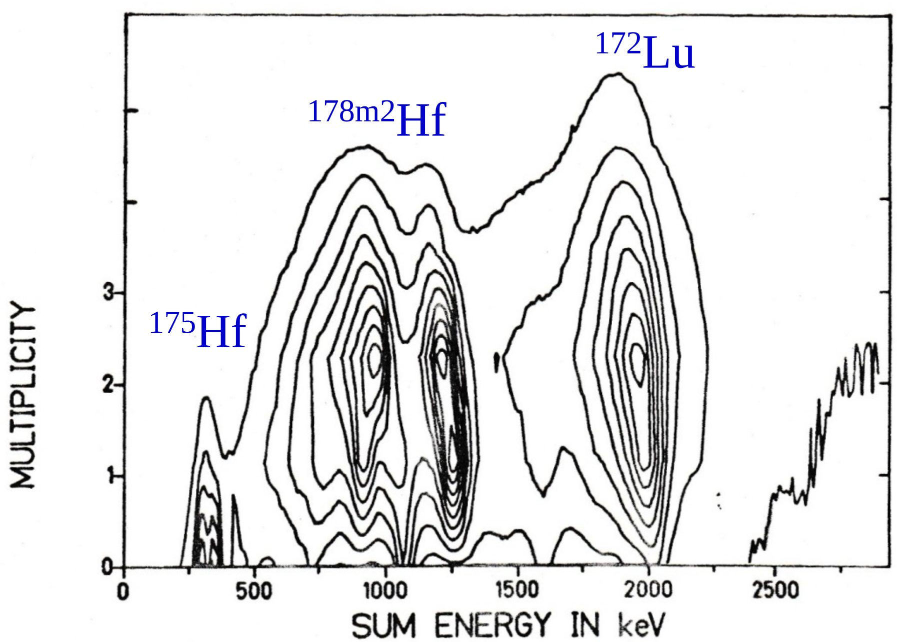
The two basic observables which can be measured for the resulting γ-ray shower are the **total energy** emitted as γ-radiation and the **number of γ-rays**.



H. Xie et al.; Phys. Rev. C48 (1993), 2517

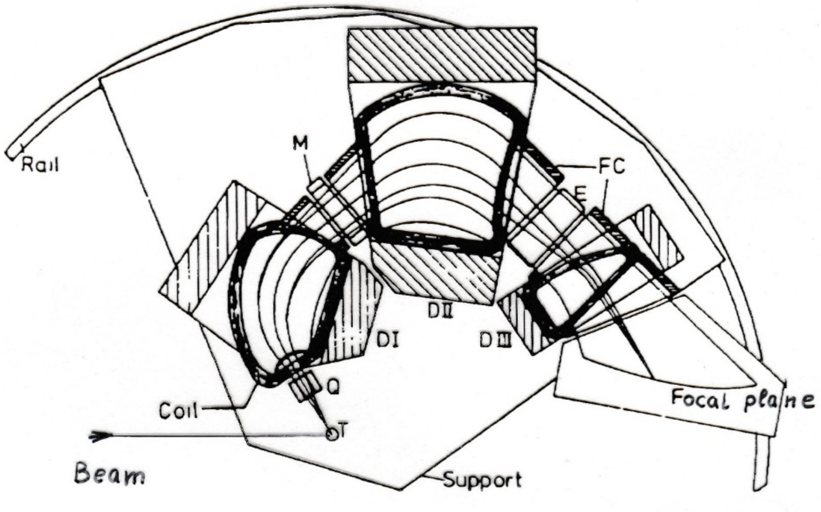
Decay Scheme of ^{175,178m2}Hf, ^{172}Lu





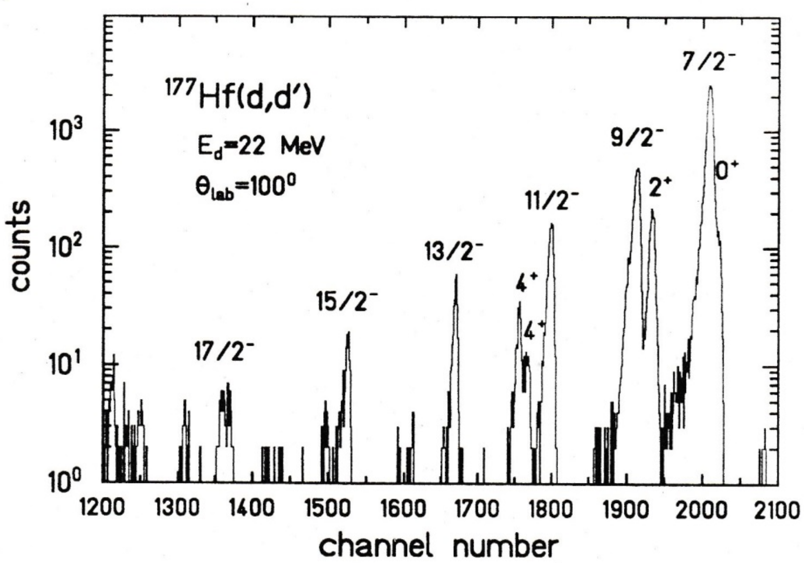
H. Xie et al.; Phys. Rev. C48 (1993), 2517

Inelastic d-Scattering Experiment



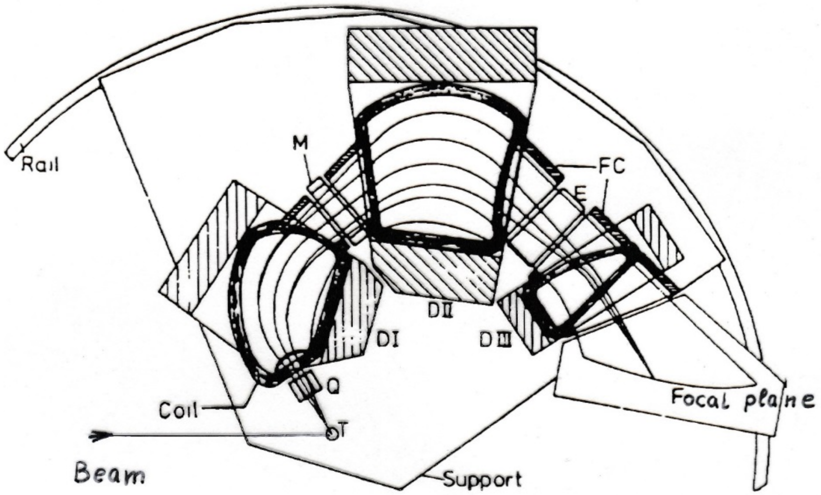
Q3D measurement at the Munich tandem

energy resolution: 12 keV



S. Deylitz et al. Phys. Rev. C53 (1996), 1266

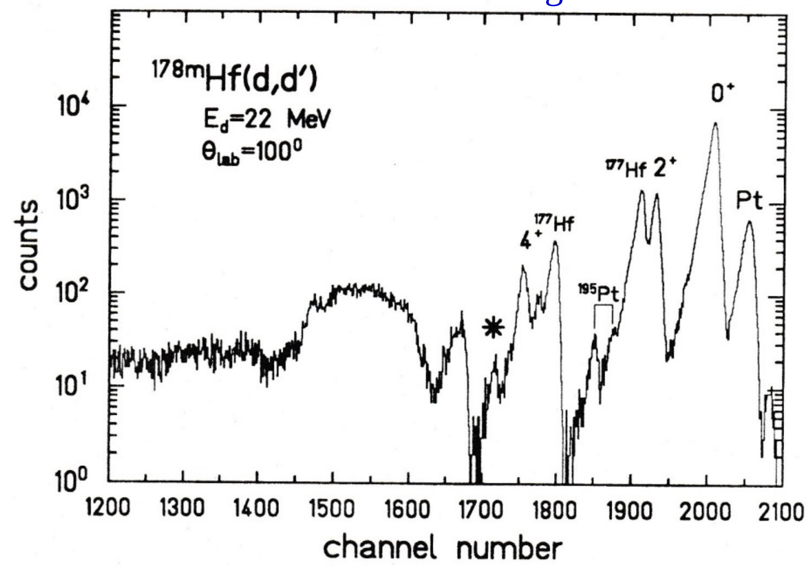
Inelastic d-Scattering Experiment

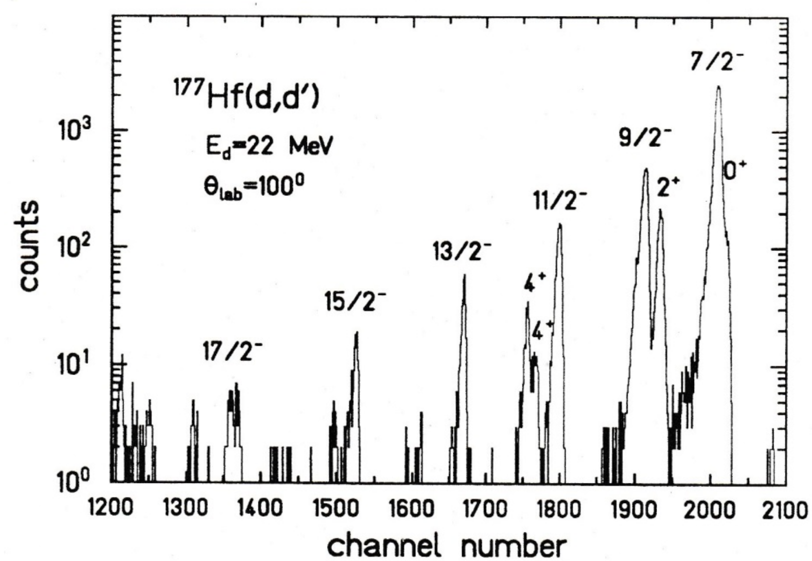


Q3D measurement at the Munich tandem

energy resolution: 12 keV

isomeric ^{178}Hf target





S. Deylitz et al. Phys. Rev. C53 (1996), 1266

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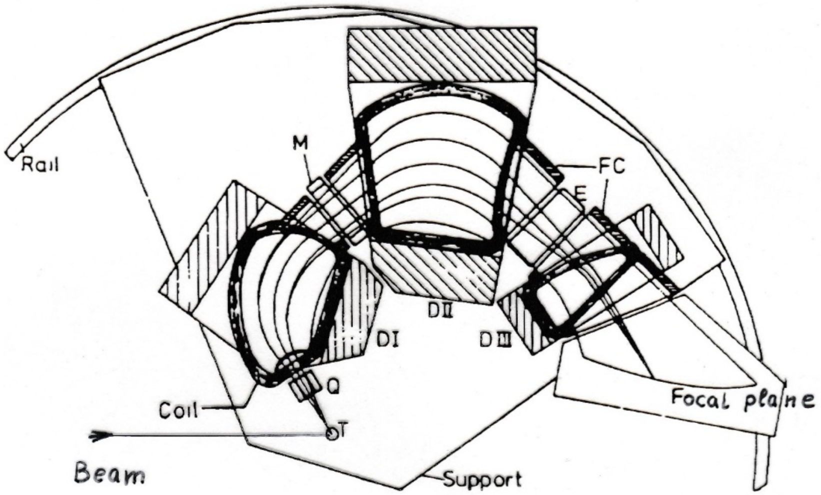

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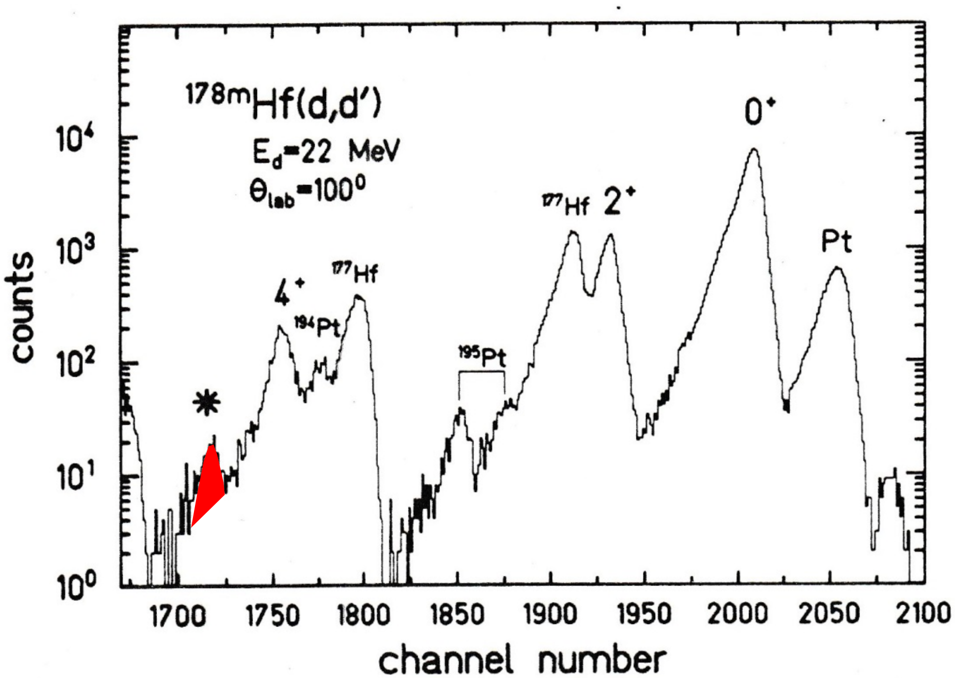
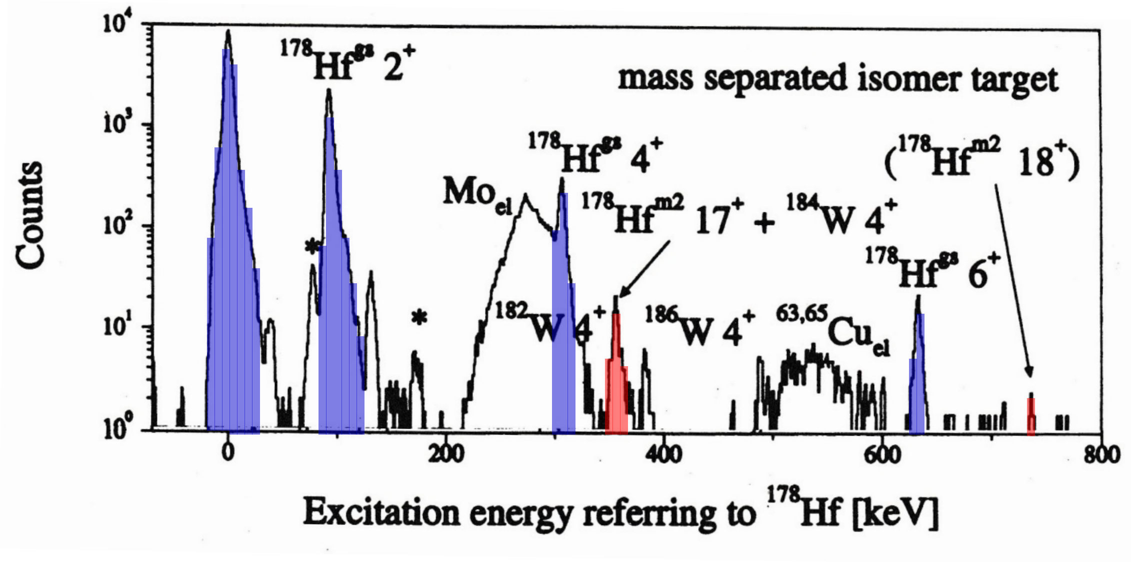


S. Deylitz et al. Phys. Rev. C53 (1996), 1266

Inelastic Deuteron Scattering from K=16 Isomer



$$\frac{^{178m2}Hf}{^{178}Hf} \cong 3\%$$

experiment performed at Munich tandem accelerator with Q3D spectrograph ($45^0 - 100^0$)

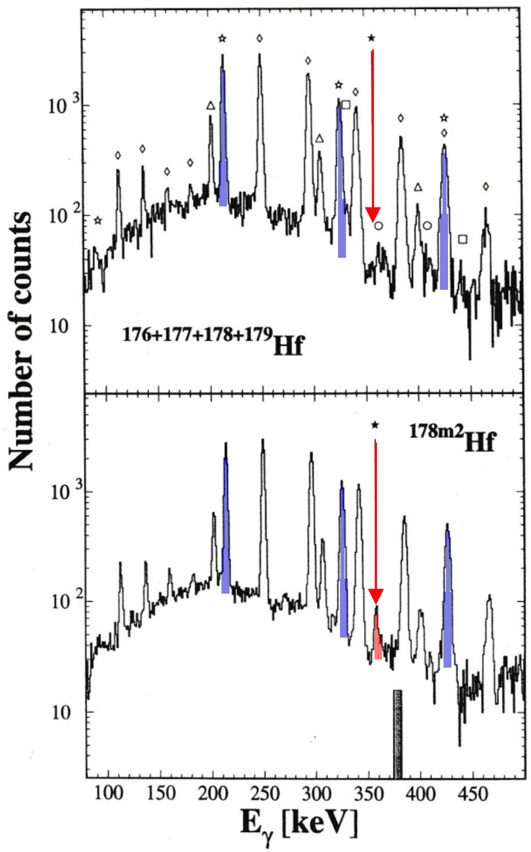
W, Ta, Mo, Cu result from sputtering and migration process in the mass-separator facility

❖ E_x = 356.5±0.4 keV 17^+ member of rotational band

$$\frac{\Im(^{178m2}Hf)}{\Im(^{178}Hf)} = 1.48$$

S. Deylitz et al. Phys. Rev. C53 (1996), 1266

Coulomb Excitation of the K=16 Isomer



$^{208}Pb \rightarrow Hf$; 4.8 MeV/u

"artificial" γ-spectrum

γ-spectrum with isomeric target

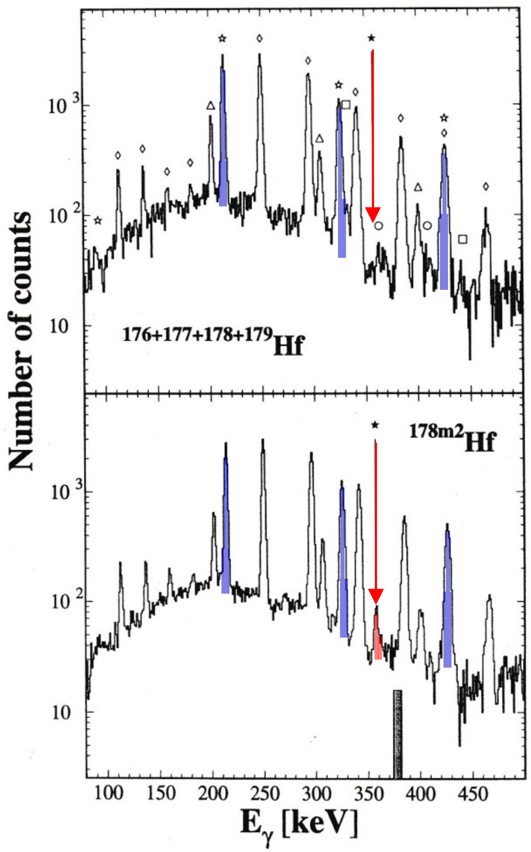
$$\frac{^{178m2}Hf}{Hf} = 0.6\% \qquad \mathbf{10^{14}}\ {}^{178m2}Hf\ atoms$$

experiment performed at UNILAC accelerator

- E_γ = 357.4±0.3 keV $17^+ \rightarrow 16^+$ transition
- Q_0 (K=16) = 8.2±1.1 b rigid rotor model

E. Lubkiewicz et al.; Z. Phys. A355 (1996), 377

Coulomb Excitation of the K=16 Isomer



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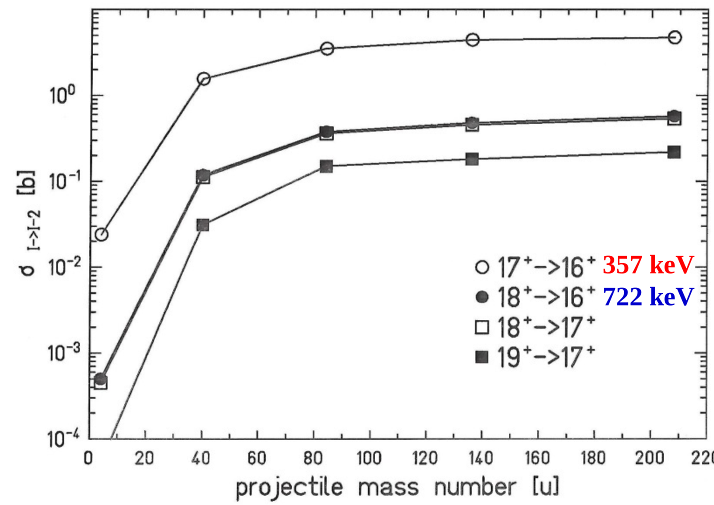

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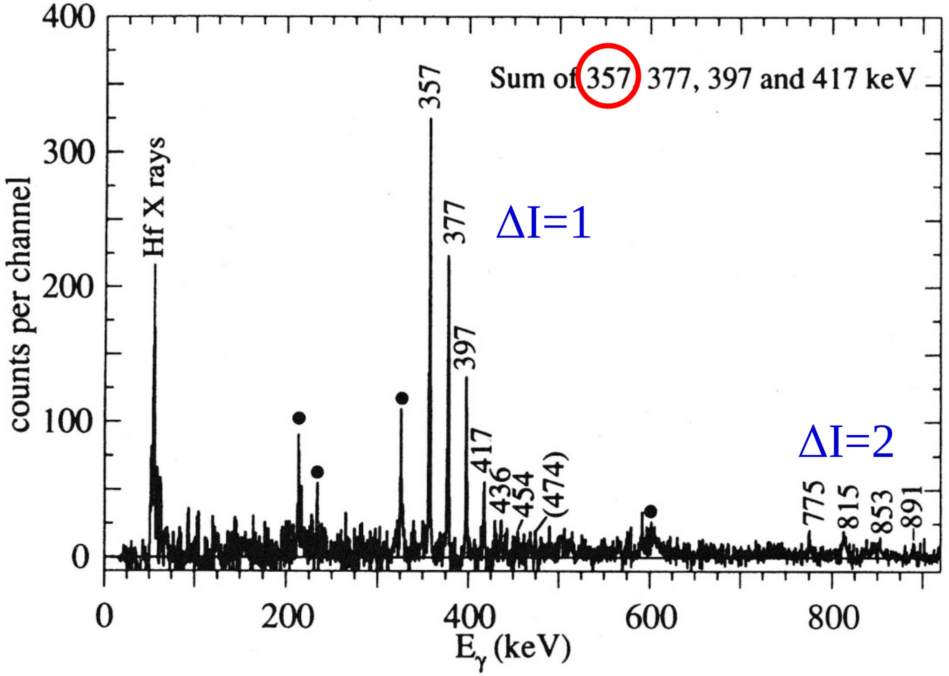
E. Lubkiewicz et al.; Z. Phys. A355 (1996), 377

Rotational Band on the K=16 Isomer in ^{178}Hf



Summed coincidence spectrum from projections made on transitions in the rotational band assigned to ^{178m2}Hf.

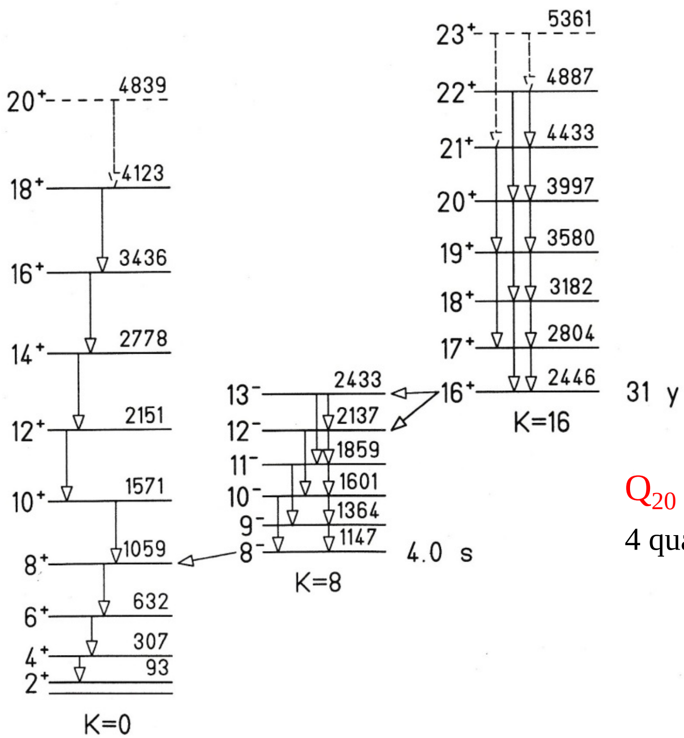
^{176}Yb(^{9}Be,α3n) ^{178}Hf   55, 60 MeV

incomplete fusion reaction
14 charged-particle detectors cover 85% of 4π

E2/M1 mixing ratios g_K=0.52(6) $\nu^2\pi^2$ – qp band

S.M. Mullins et al. Phys. Lett. B393 (1997), 279

Partial Level Scheme of ^{178}Hf



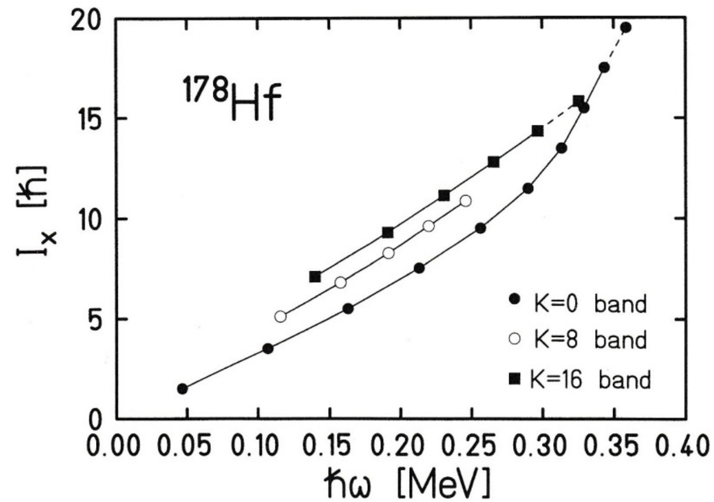
Q_{20} = 8.2±1.1 b

4 quasi-particle state

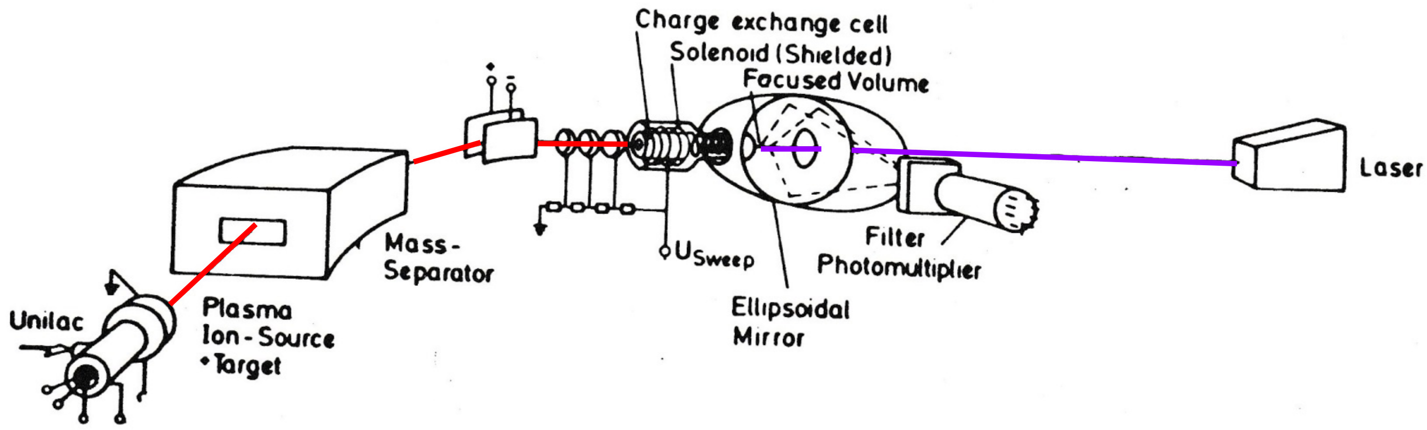
Q_{20} = 7.0 b

$$I_x = \{(I+1/2)^2 - K^2\}^{1/2}$$

$$\hbar\omega = \frac{E(I+1) - E(I-1)}{I_x(I+1) - I_x(I-1)}$$

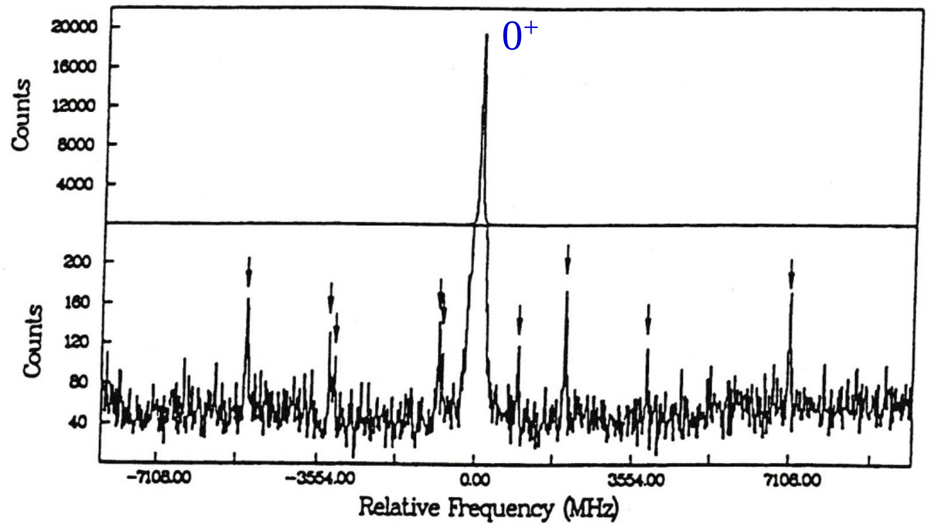


Collinear Laser Spectroscopy



kinetic energy spread in ion source: $\Delta E = mv \cdot \Delta v =$ few eV

residual Doppler width after acceleration: $\Delta \nu = \frac{\nu_0 \Delta E}{\sqrt{2eU \cdot mc^2}}$ Δν=60 MHz for 60 kV



$$\Delta W_{HFS} = \frac{A}{2}K + B\frac{\frac{3}{4}K(K+1) - I(I+1)J(J+1)}{2I(2I-1)\cdot J(2J-1)}$$

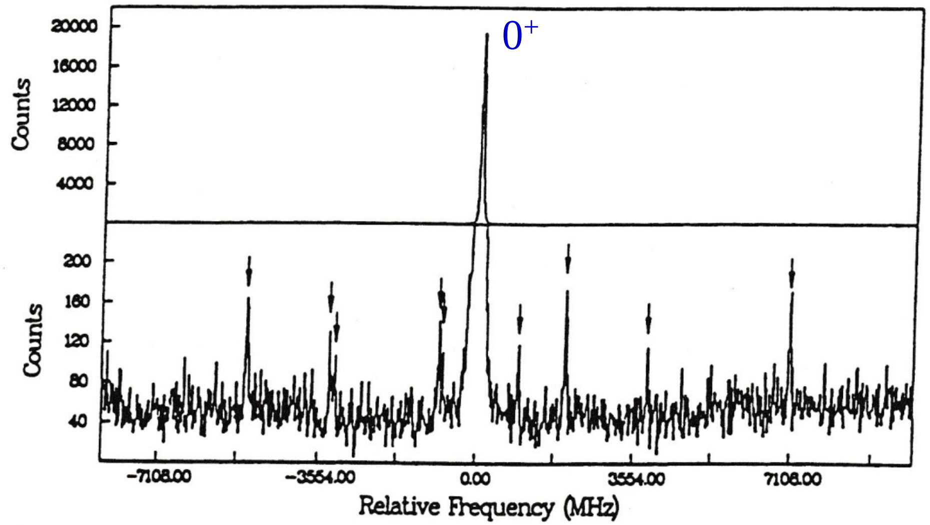
$$K = F(F+1) - I(I+1) - J(J+1)$$

$$A = \frac{\mu_I \cdot \langle H(0)\rangle}{I \cdot J}$$

$$B = eQ_s \cdot \langle V_{zz}(0)\rangle$$

The single peak at 0 MHz corresponds to the ground state ^{178}Hf.
The nine hyperfine resonances 0f 178m2Hf are marked by arrows.

Collinear Laser Spectroscopy



$$\Delta W_{HFS} = \frac{A}{2}K + B\frac{\frac{3}{4}K(K+1) - I(I+1)J(J+1)}{2I(2I-1)\cdot J(2J-1)}$$

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The single peak at 0 MHz corresponds to the ground state ^{178}Hf.
The nine hyperfine resonances 0f 178m2Hf are marked by arrows.

$$\mu_I^{178m2} = +8.16(4)\ nm$$

$$Q_s^{178m2} = +6.00(7)\ b \quad\rightarrow\quad Q_0 = 7.2(1)\ b$$

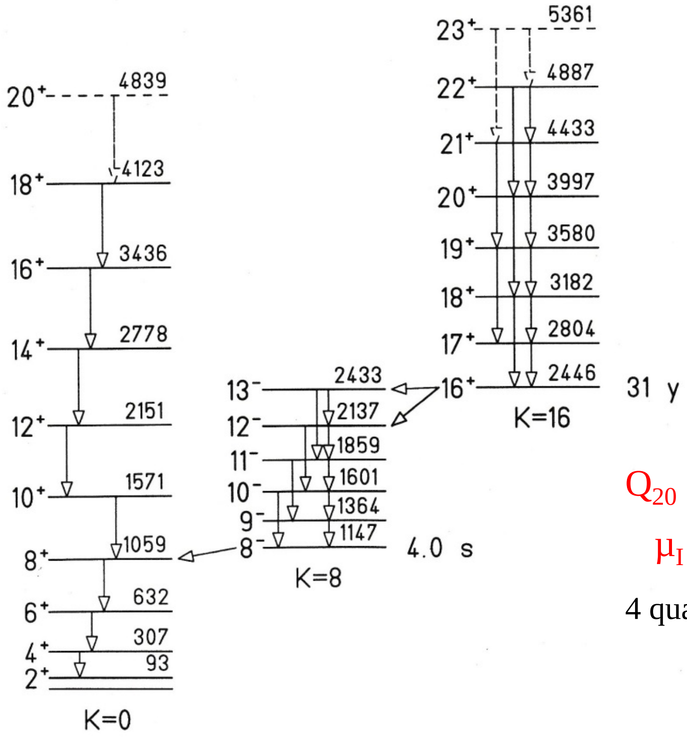
$$\delta\langle r^2\rangle^{178,178m2} = -0.059(9)\ \ fm^2$$

strong coupling scheme:

$$Q_s = \frac{3K^2 - I(I+1)}{(I+1)(2I+3)}\cdot Q_0 \quad\rightarrow\quad Q_s\ (K=I) = \frac{I\cdot(2I-1)}{(I+1)(2I+3)}\cdot Q_0$$

$$\delta\langle r^2\rangle = \delta\langle r^2\rangle_0 + \frac{5}{4\pi}\langle r^2\rangle_0 \sum_\lambda \delta\langle\beta_\lambda^2\rangle$$

Partial Level Scheme of ^{178}Hf



$Q_{20} = 7.2 \pm 0.1$ b

$\mu_I = +8.16(4)$ n.m.

4 quasi-particle state

$Q_{20} = 8.2 \pm 1.1$ b (Coulomb excitation)

$Q_{20} = 7.0$ b

$$I_x = \{(I + 1/2)^2 - K^2\}^{1/2}$$

$$\hbar\omega = \frac{E(I+1) - E(I-1)}{I_x(I+1) - I_x(I-1)}$$