Outline: K-isomers in ^{178}Hf

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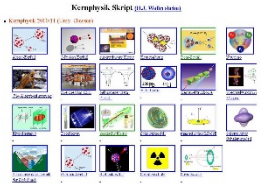
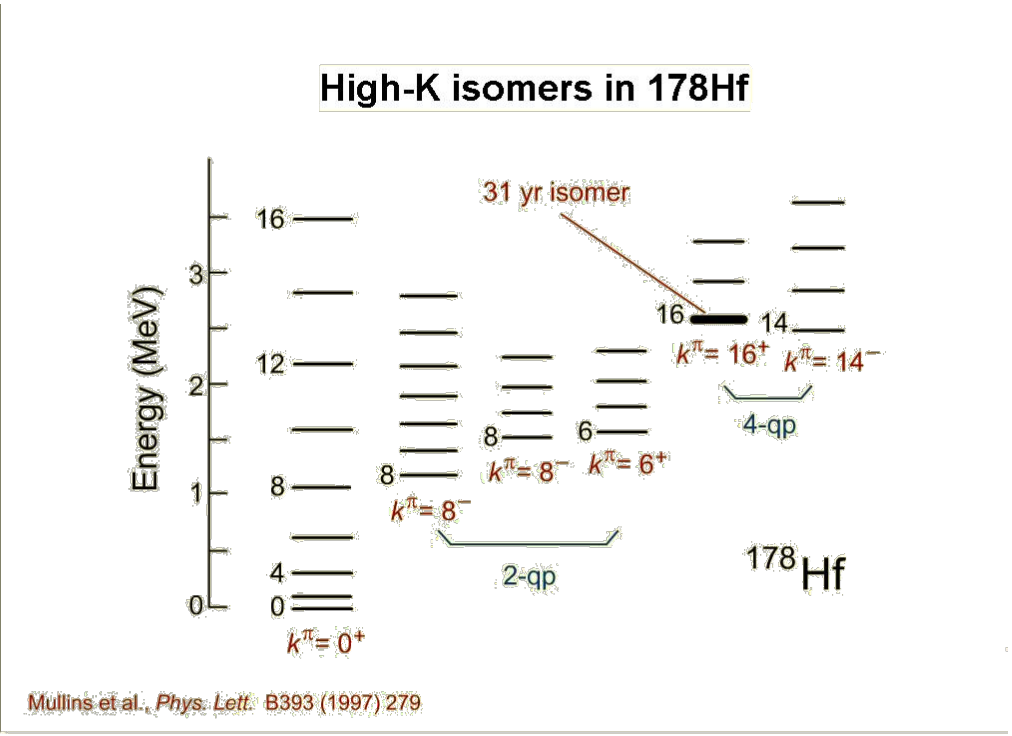
web-page: https://web-docs.gsi.de/~wolle/ and click on

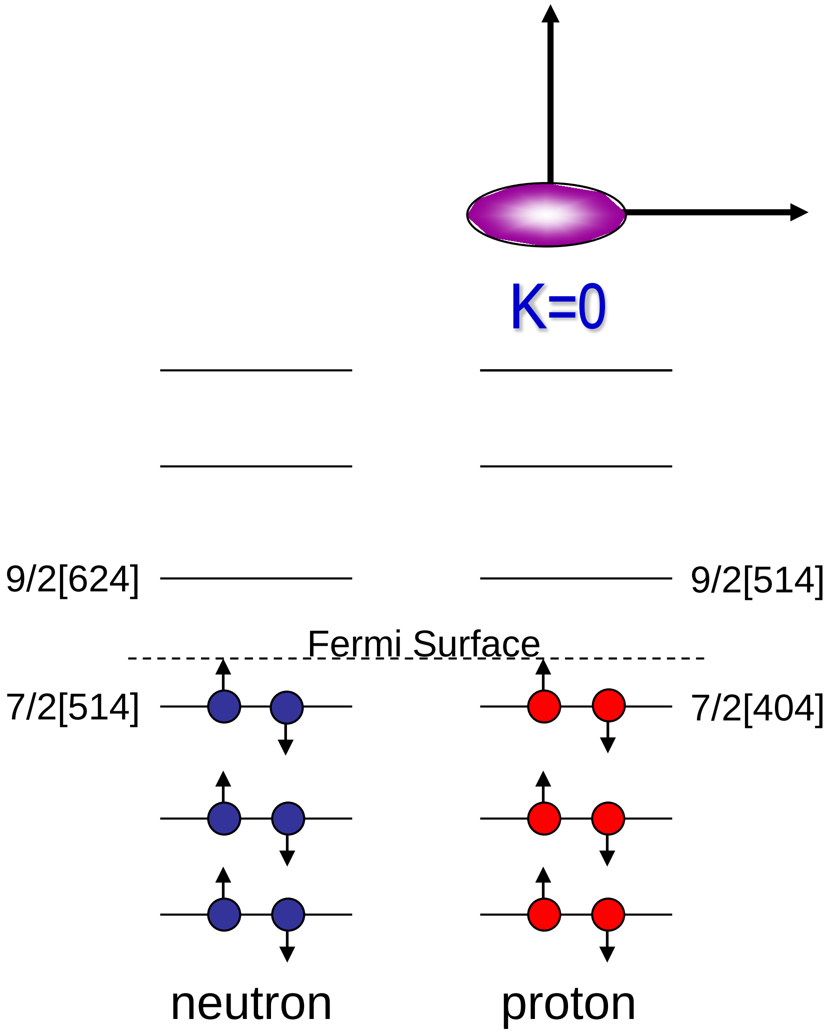


1. magnetic moments
2. K-selection rule
3. Coulomb excitation of the 8^- isomer in ^{178}Hf
4. investigation of the K=16 isomer in ^{178}Hf
5. deuteron and ^{208}Pb inelastic scattering, laser spectroscopy

Investigation of ^{178}Hf – K-isomers

- A well-known example:





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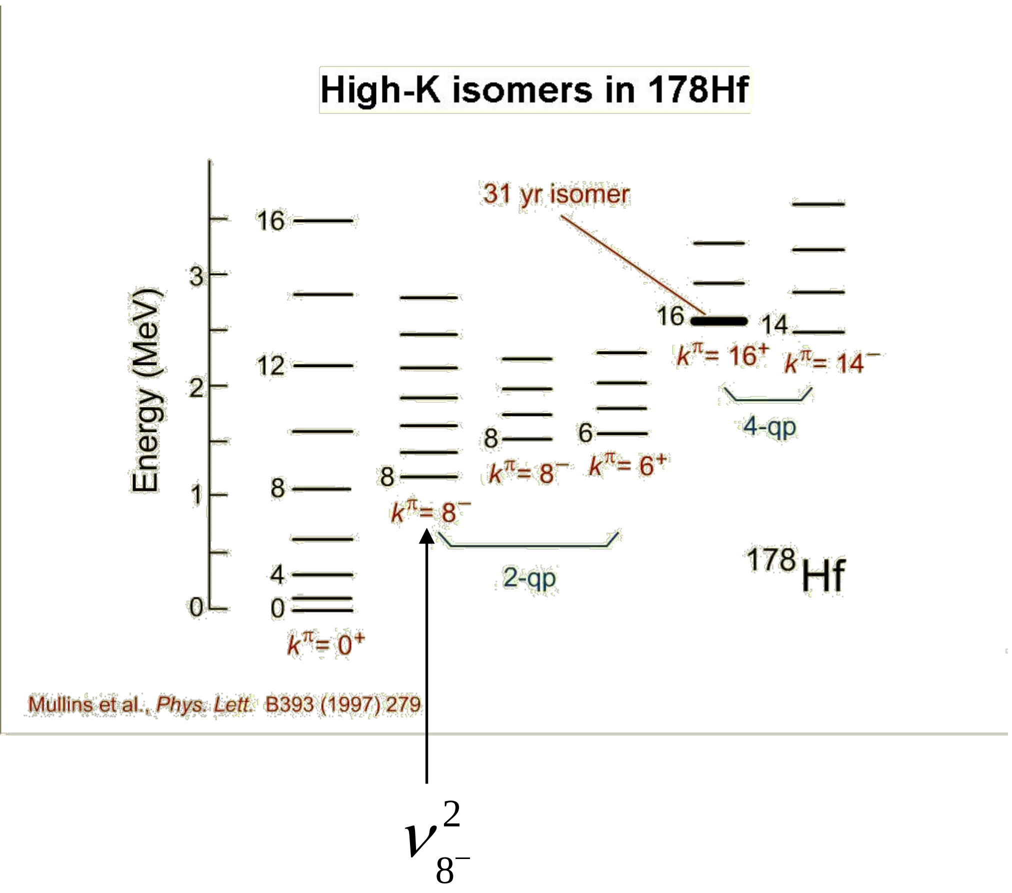

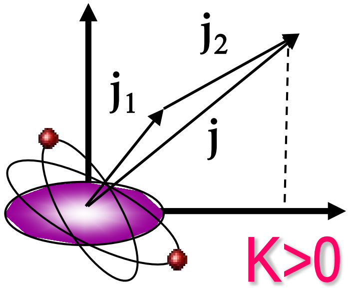

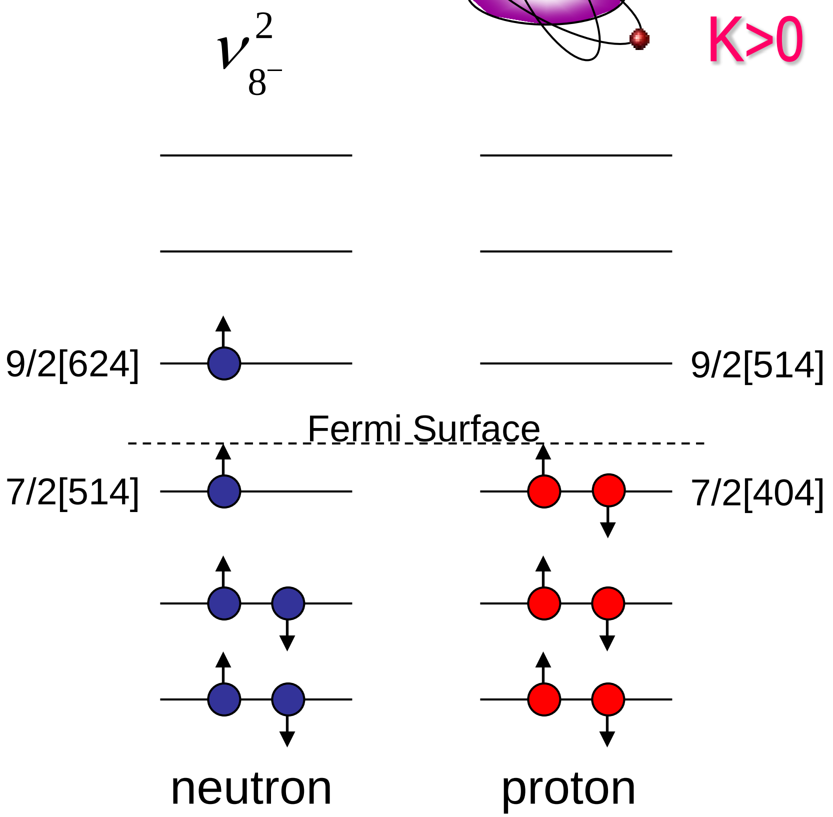

Investigation of ^{178}Hf – K-isomers

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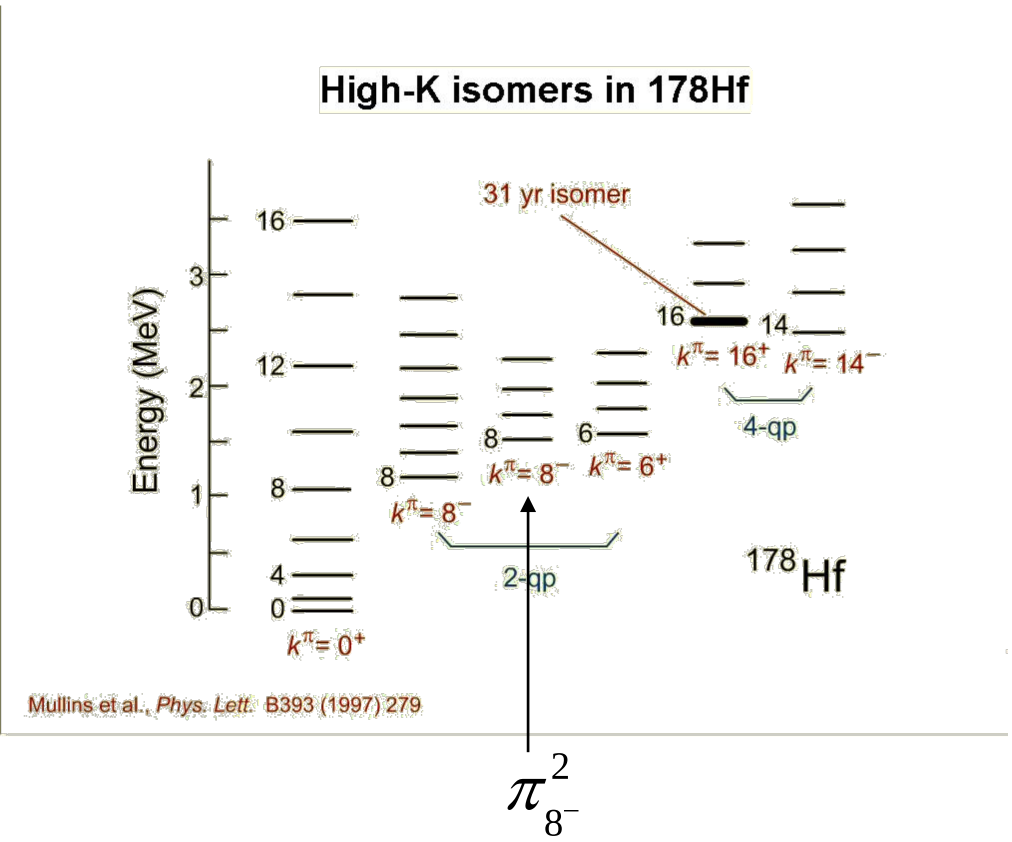
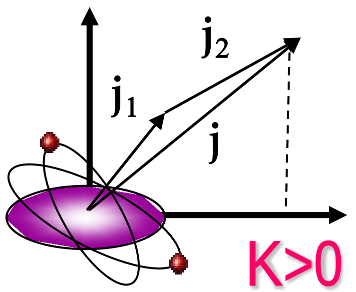
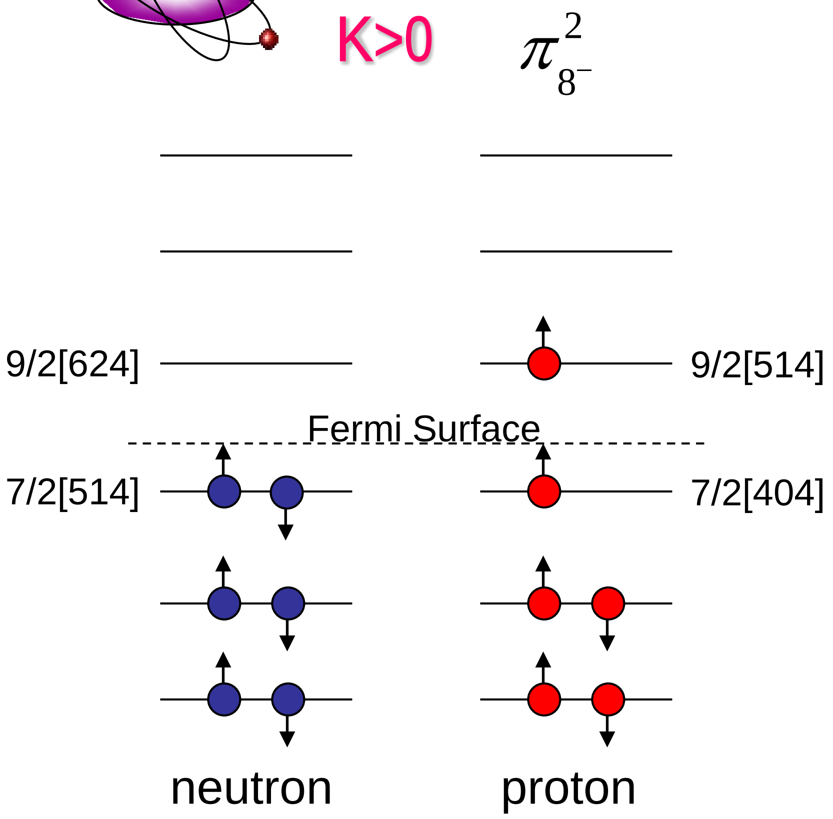


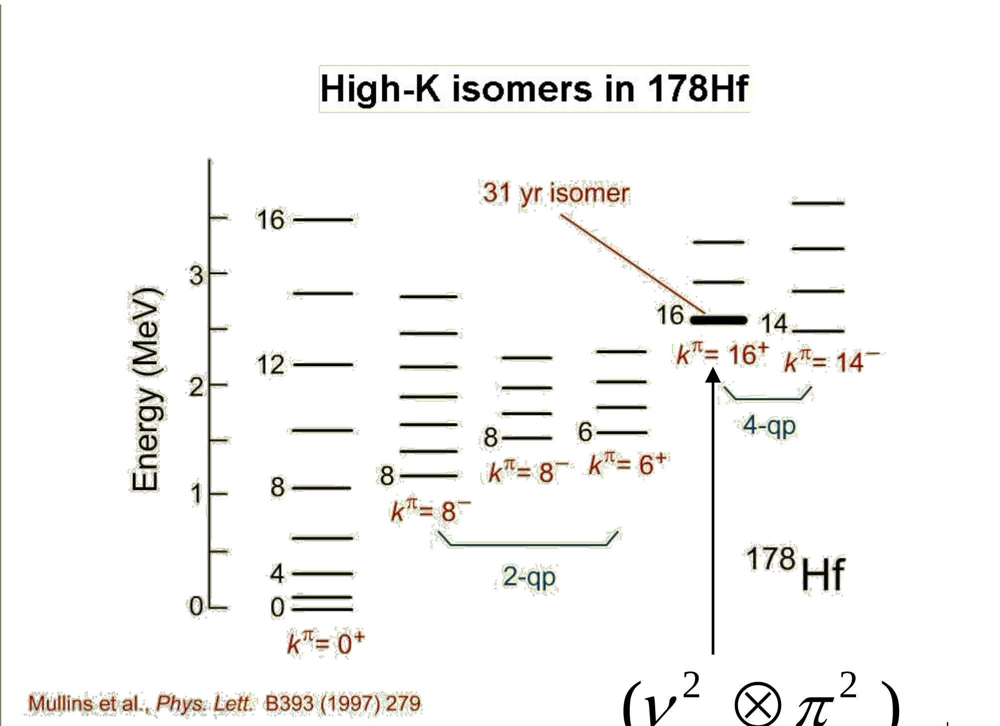




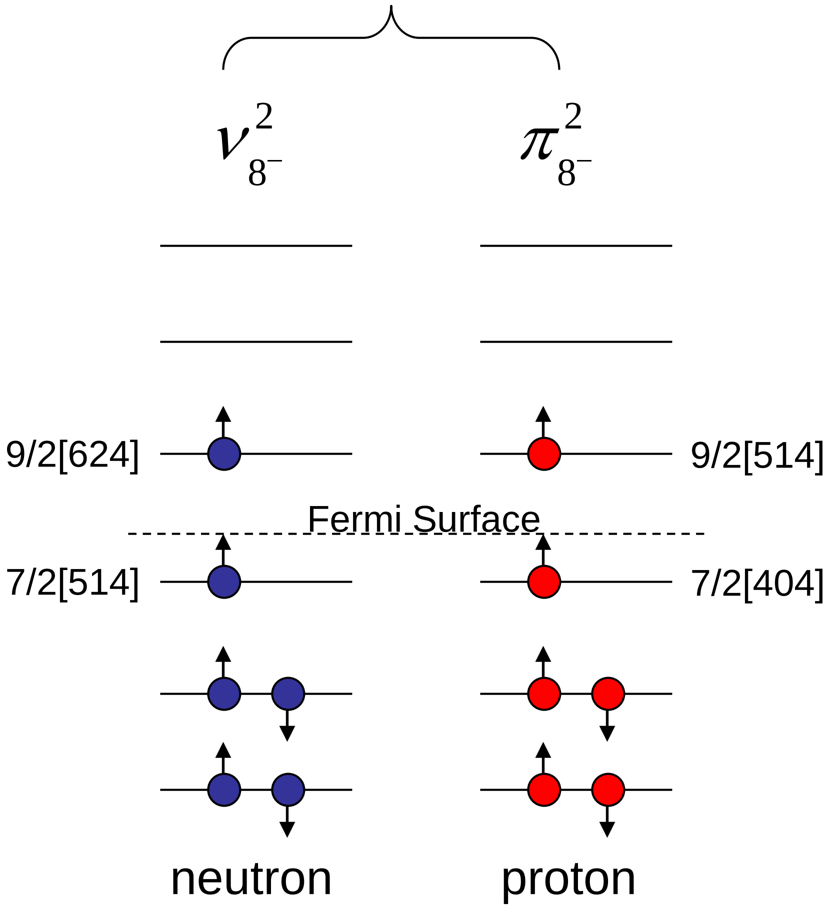
Investigation of ^{178}Hf – K-isomers

- A well-known example:

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



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



Magnetic moments in ^{178}Hf

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

proton	$g_\ell = 1$	$g_s = 5.59$
neutron	$g_\ell = 0$	$g_s = -3.83$

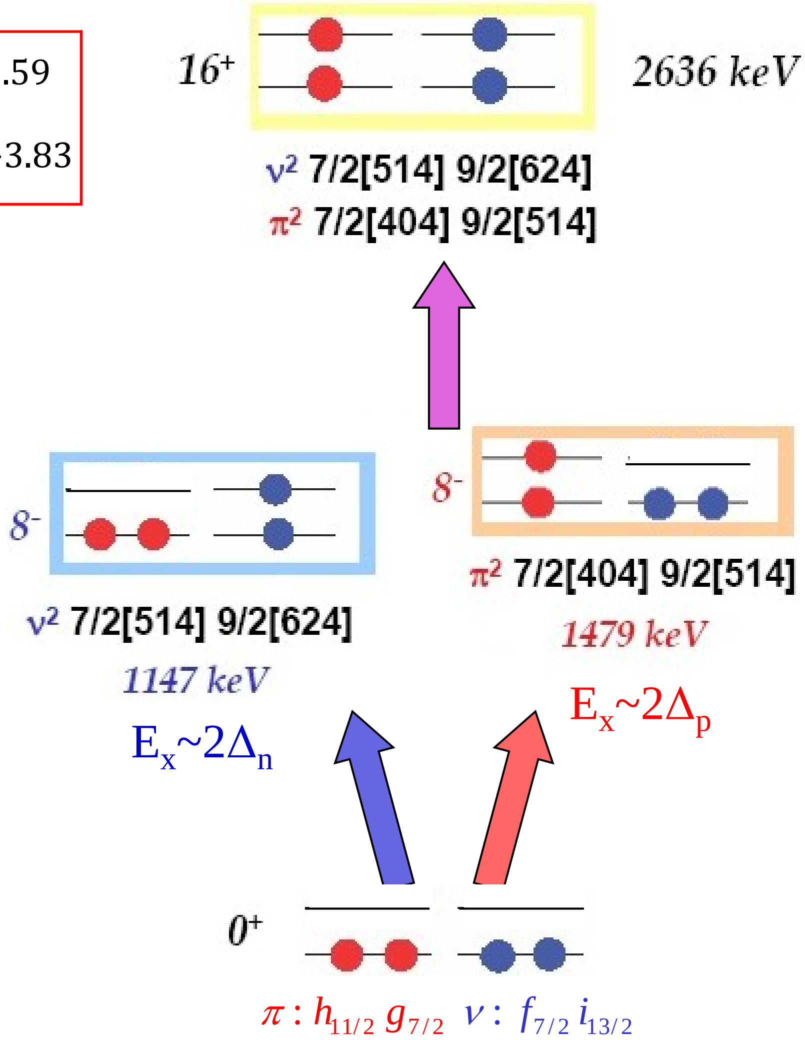
$g(h_{11/2}) = 1.42$ $g(g_{7/2}) = 0.49$ $g(f_{7/2}) = -0.55$ $g(i_{13/2}) = -0.29$

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

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

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

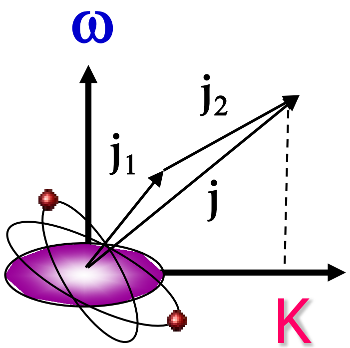
7.26±0.16 nm

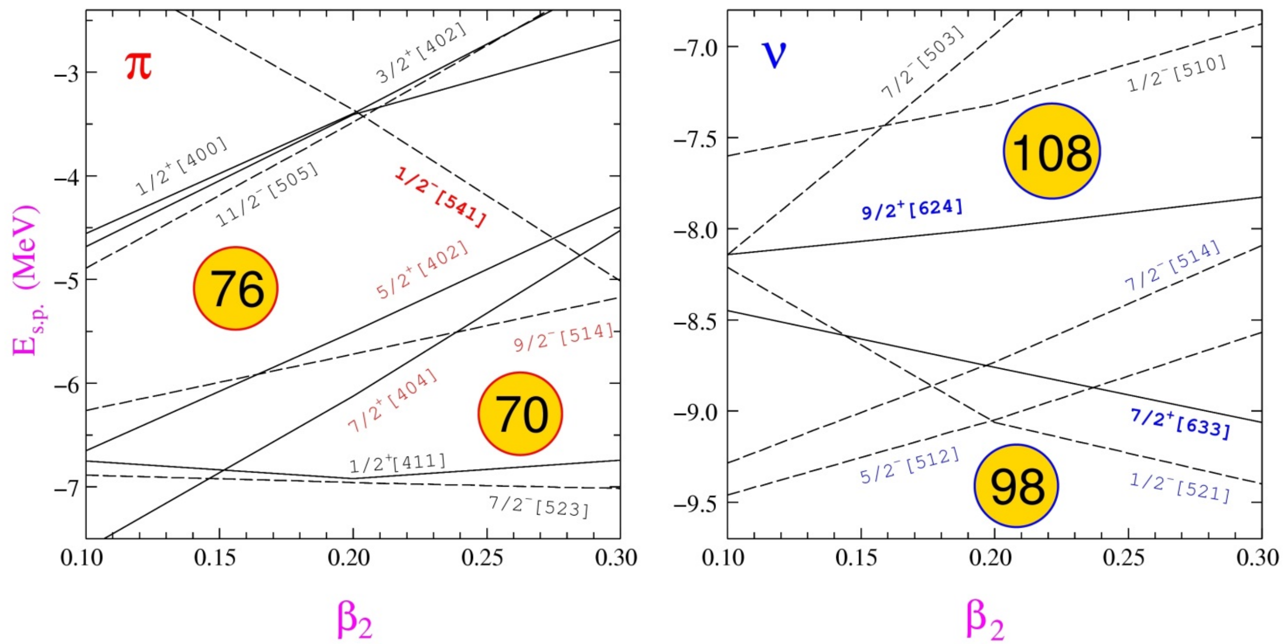


Helmer & Reich; Nucl. Phys. A114 (1968), 649

- Deformed nuclei with axially-symmetric shape

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



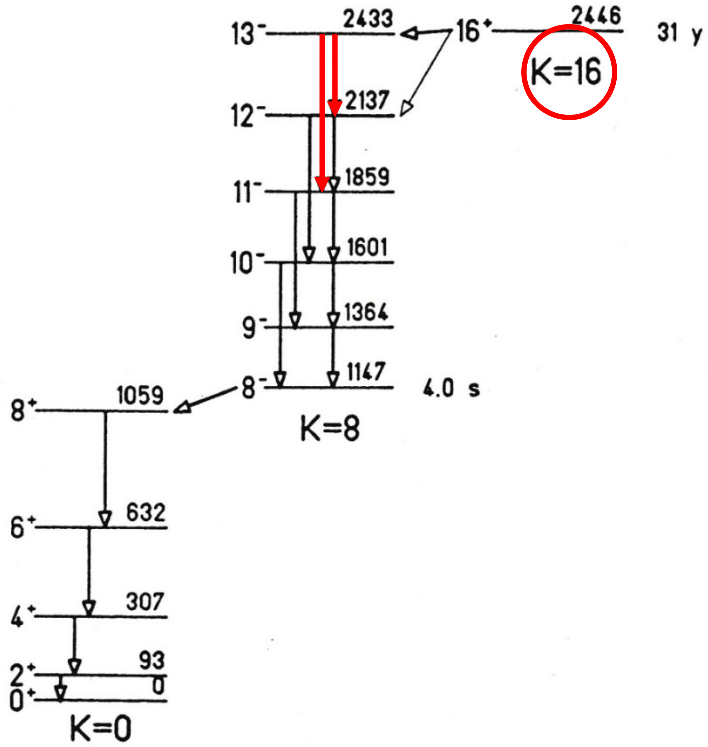


- High-K orbitals near the Fermi surface

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



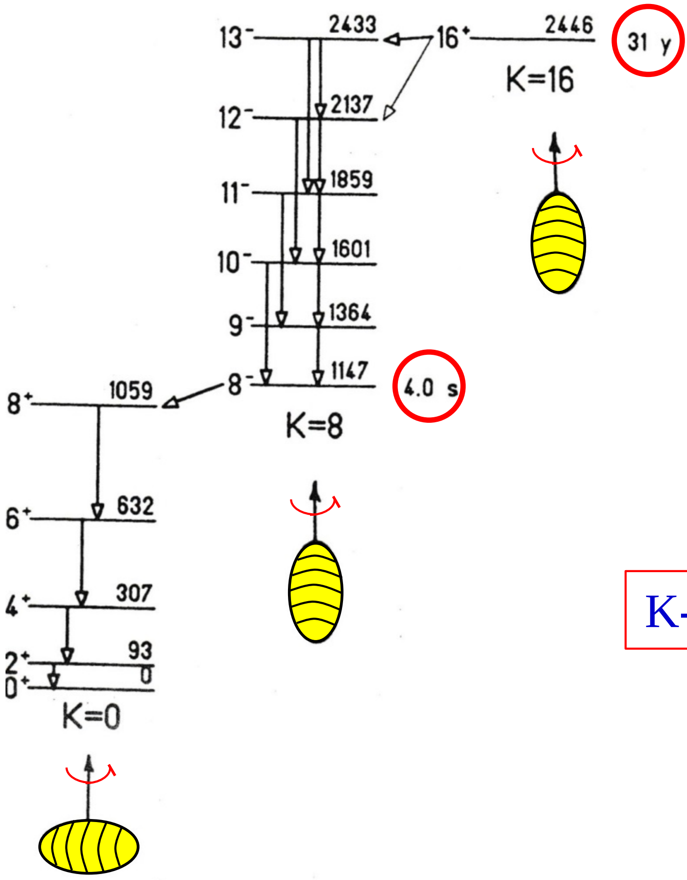
	$\frac{B(E2, I \to I-2)}{B(E2, I \to I-1)}$	rigid rotor K=8
10^-	0.104±0.012	0.0769
11^-	0.171±0.009	0.1607
12^-	0.230±0.017	0.2517
13^-	0.313±0.016	0.3500

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

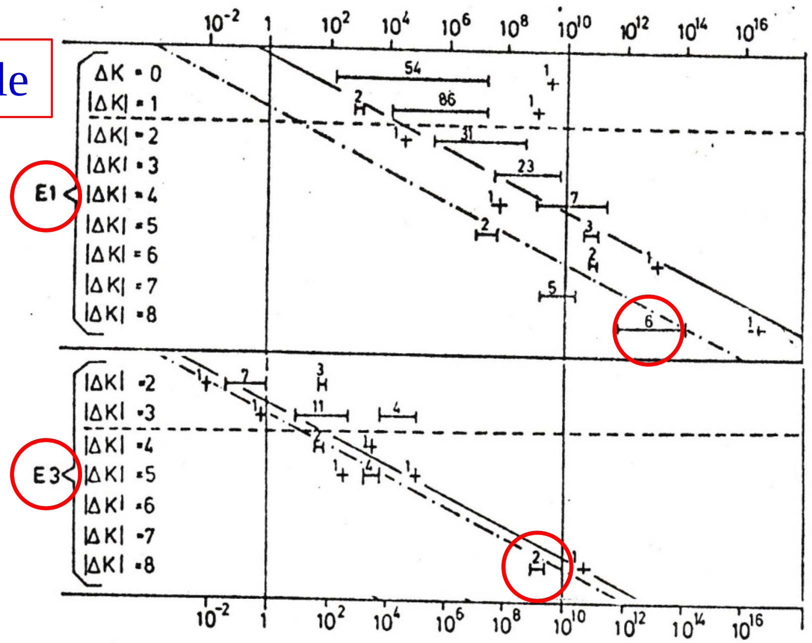


H = 10^9

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

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

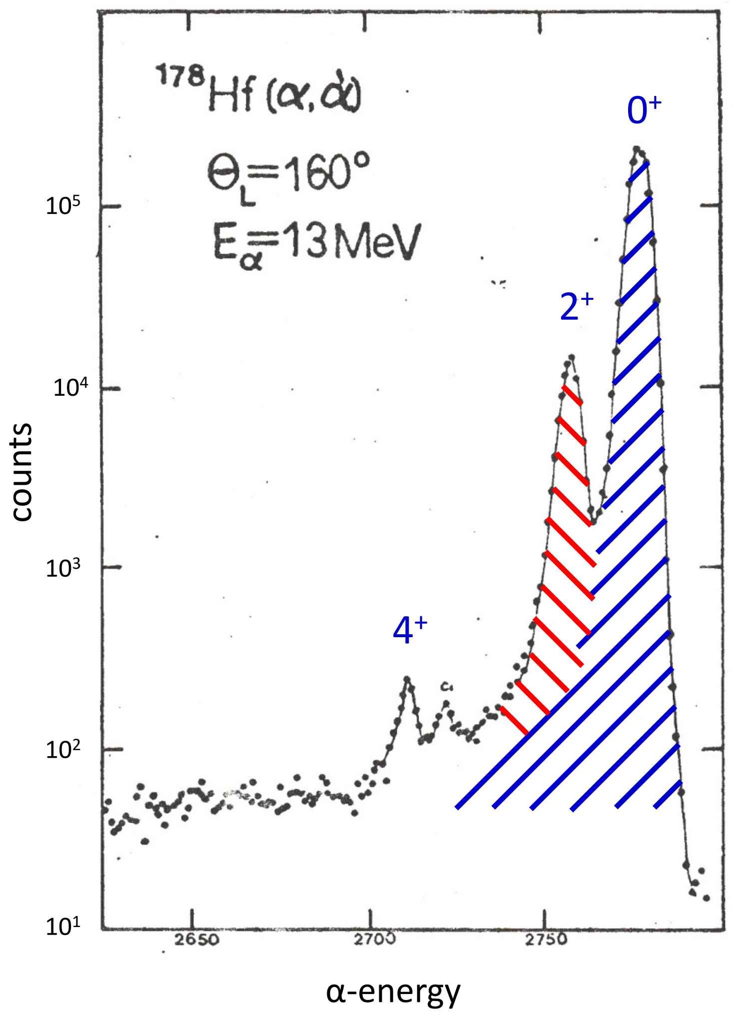
K-selection rule

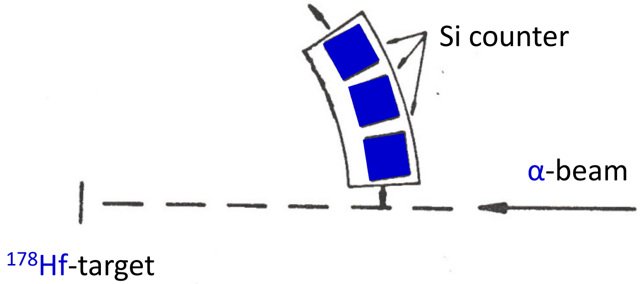


Helmer & Reich; Nucl. Phys. A114 (1968), 649

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

^{178}Hf: particle spectroscopy





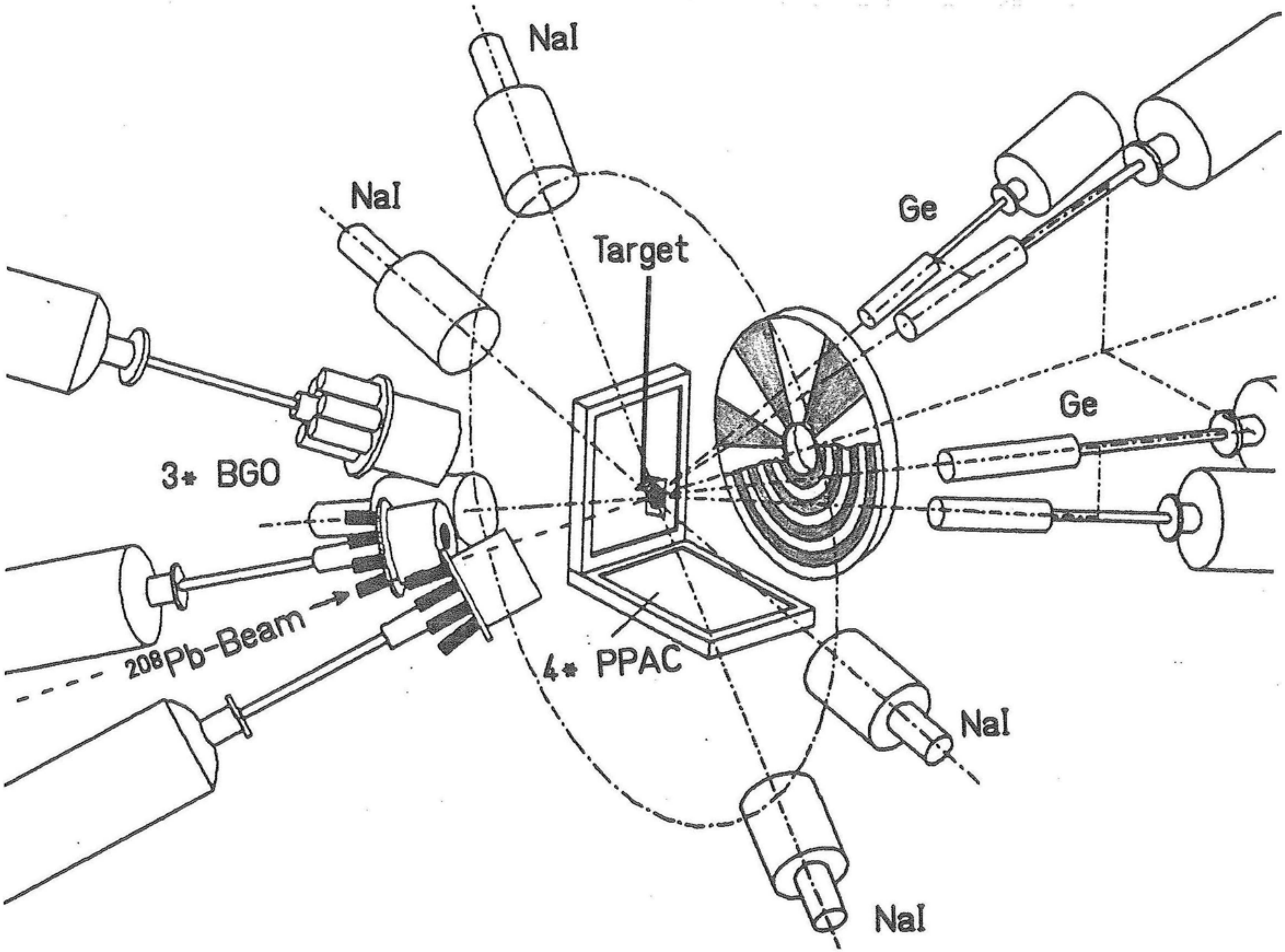
$$d\sigma_{C.E.}(E,\theta_{cm}) = P_I(E,\theta_{cm}) \cdot d\sigma_{Ruth}(E,\theta_{cm})$$

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

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



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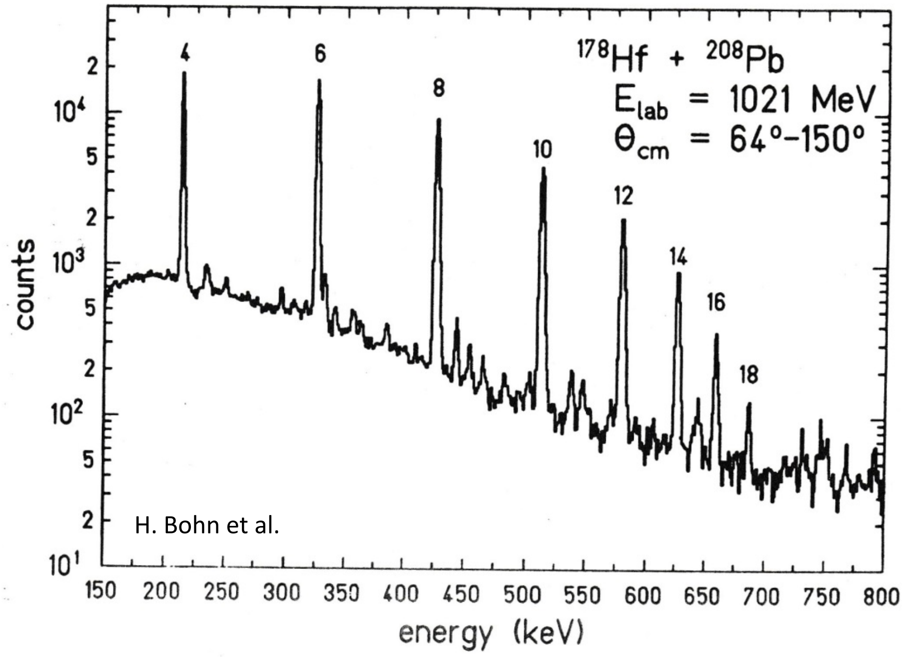


E2, E3 excitation of collective states:

ground state band K = 0

γ-vibrational band K = 2

determination of K-quantum number:

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

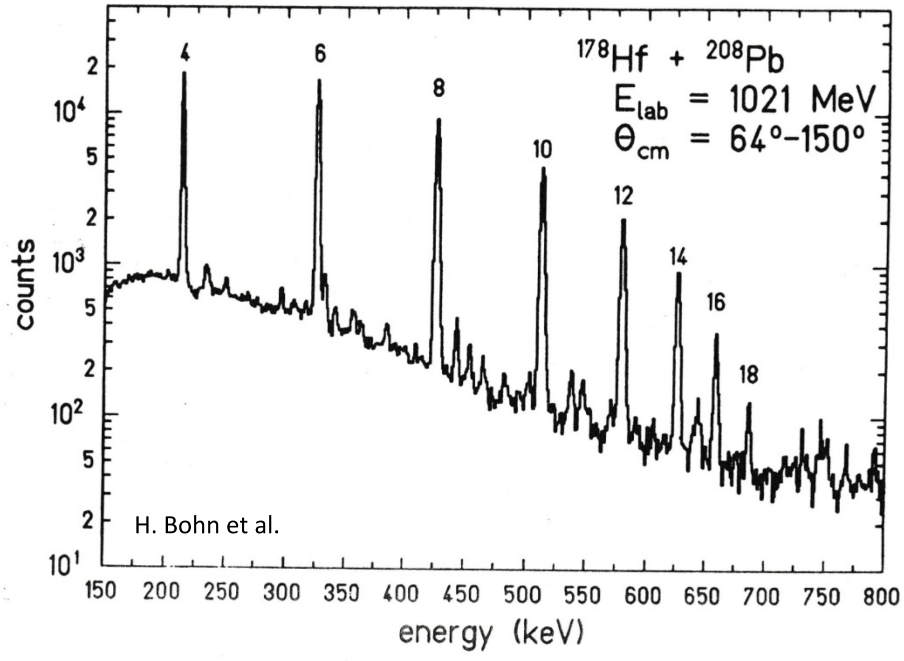
$$Q_{20} = 6.99(4)\ b \qquad Q_{40} = 0.54\binom{26}{47}\ b^2\ or\ -1.58(48)\ b^2$$

$\beta_2 = 0.29(1)$ $\beta_4 = -0.20(4)$

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

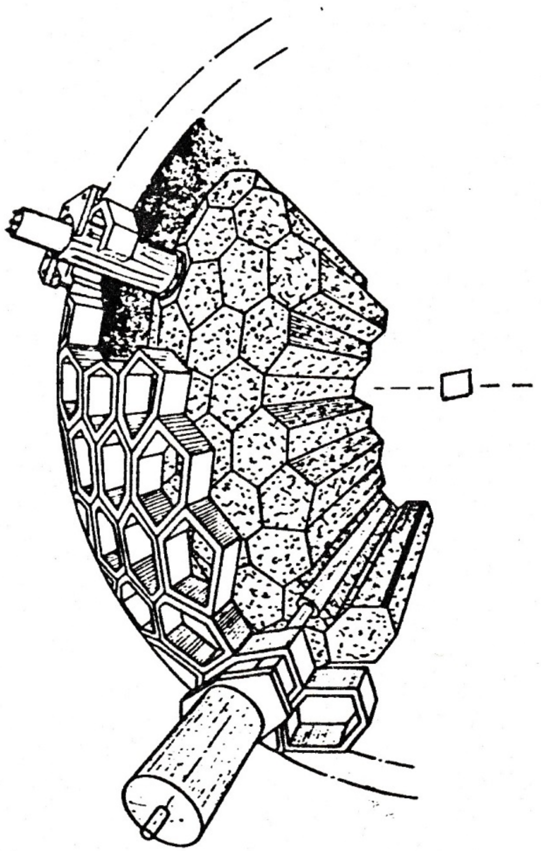
- excitation of the K = 8 isomeric state !

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

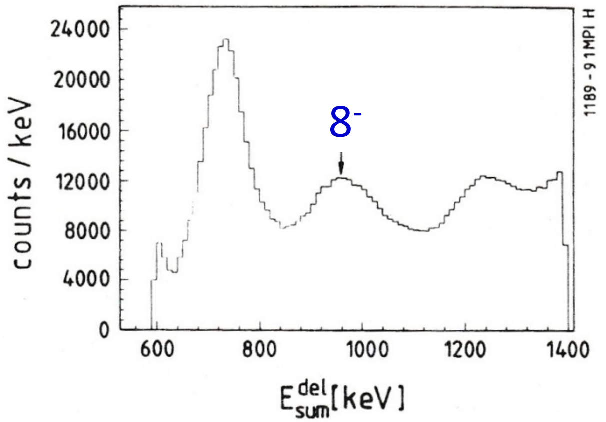
H. Xie et al.; Phys. Rev. C48 (1993), 2517

parameters and resolutions FWHM

E_i	5.5% at 1332 keV
t_i	2.8 ns
$W(\theta)$	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**.

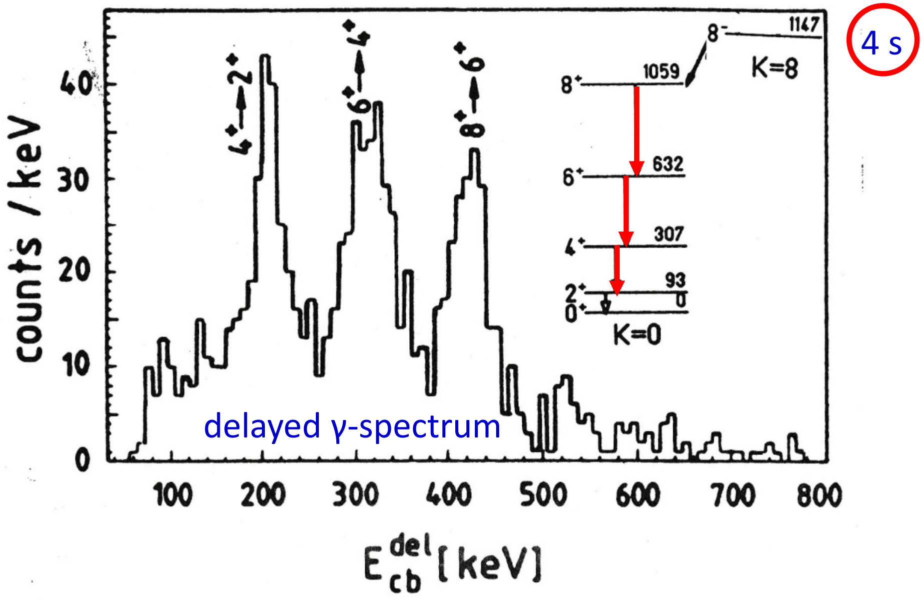
- ^{178}Hf + ^{130}Te at 560, 590, 620 MeV
  particle detection at ~180^0, Pb catcher (0.5 mm thickness) was positioned 1cm downstream to stop the recoiling ^{178}Hf ions.



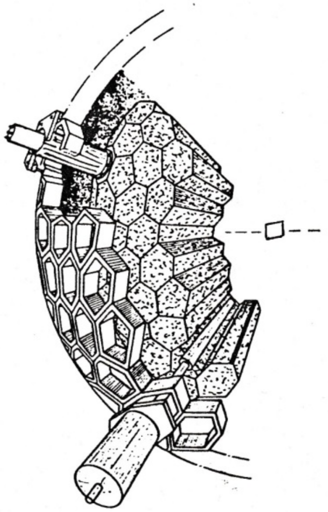
Delayed sum-energy spectrum taken at 590 MeV. (delayed time window 20-65ns with respect to beam pulse) A peak associated to the $K^\pi=8^-$ shows up.
The other peaks correspond to isomers of fusion products from target contaminants and β-decay.

Coulomb excitation of the K = 8 isomer in ^{178}Hf

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



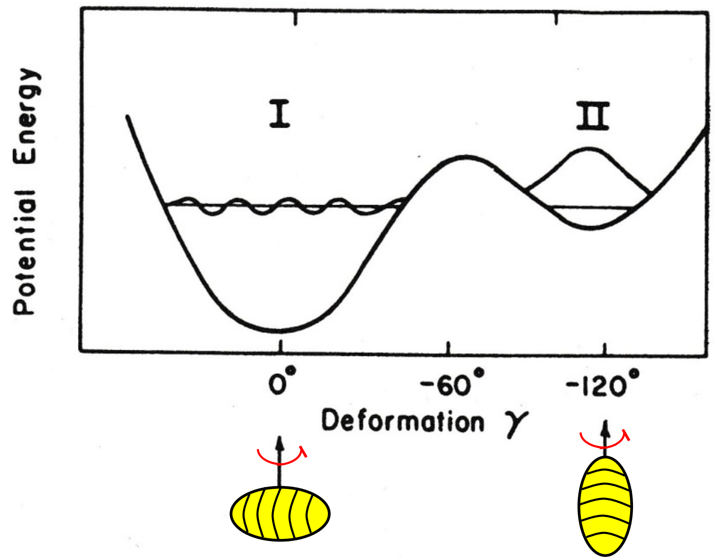
→ $M_{30}\ (E3) \leq 0.01$



Delayed γ-ray spectrum of the Crystal Ball with $850 keV \leq E_{sum}^{del} \leq 1100 keV$ 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

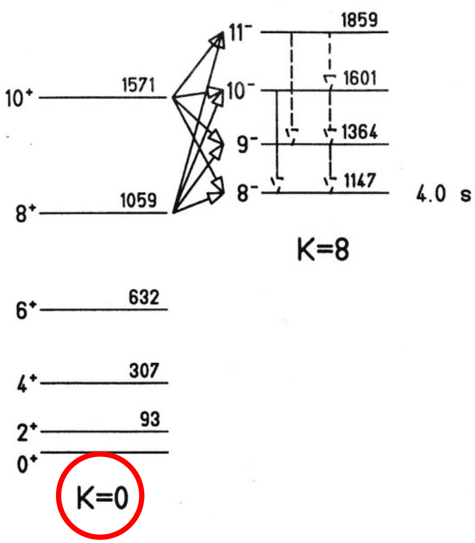
Decay of the isomer by barrier penetration



rigid rotor model:

$$\langle I_f \| M(E2) \| I_i \rangle = \sqrt{2I_i + 1} \cdot \left(I_i 3K0 | I_f K \right) \cdot M_{30}$$

+ small K=8 admixture



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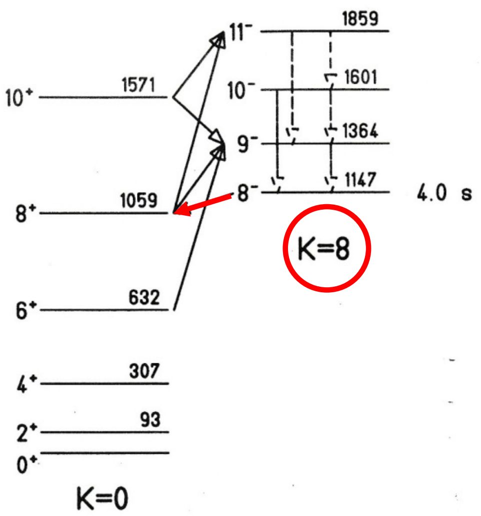
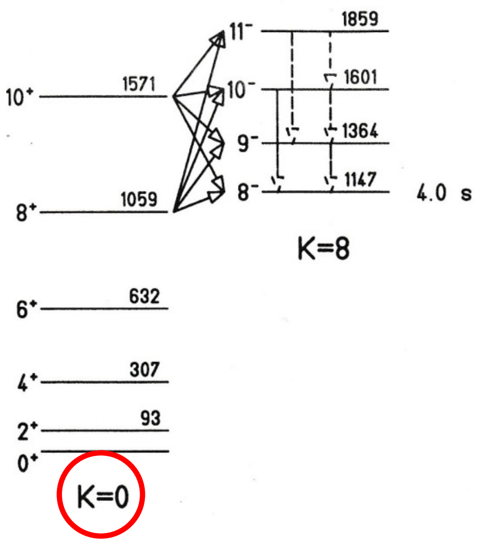


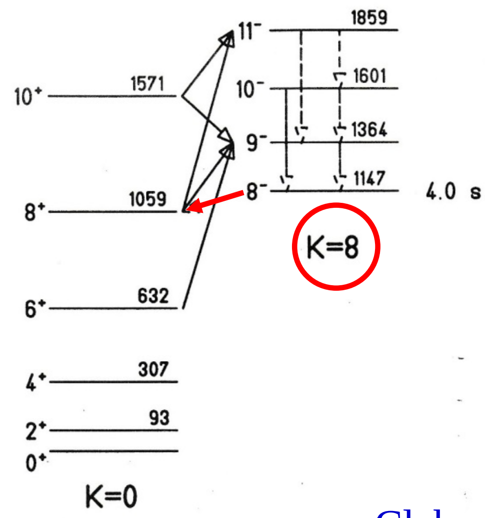
8^- lifetime is independent from excitation

2-band K-mixing model

+ small K=8 admixture



+ small K=0 admixture



8^- lifetime is independent from excitation

rigid rotor model:

$$\langle I_f \| M(E3) \| I_i \rangle = \sqrt{2I_i + 1} \cdot \left(I_i 3K0 | I_f K \right) \cdot M_{30}$$

Clebsch Gordan coefficient:

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

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

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

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

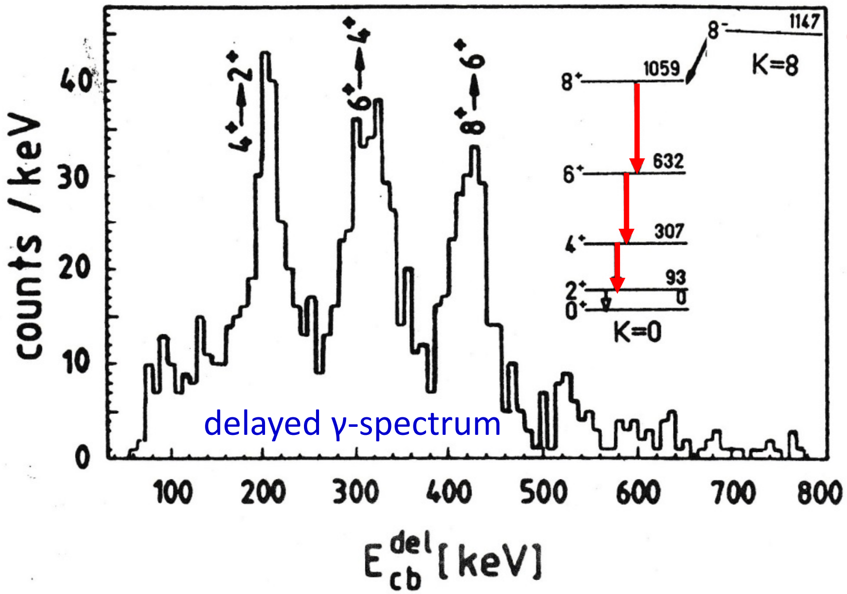
$$< I3K0|(I+1)K > = \sqrt{\frac{3(I+K+1)(I-K+1)}{I(I+1)(2I-1)(2I+1)(2I+4)(2I+5)}} * (5K^2 - I^2 - 2I)$$

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

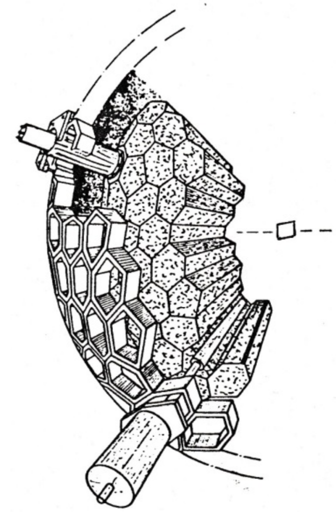
$$< I3K0|(I+3)K > = \sqrt{\frac{5(I+K+1)(I+K+2)(I+K+3)(I-K+1)(I-K+2)(I-K+3)}{2(I+1)(I+2)(I+3)(2I+1)(2I+3)(2I+5)}}$$

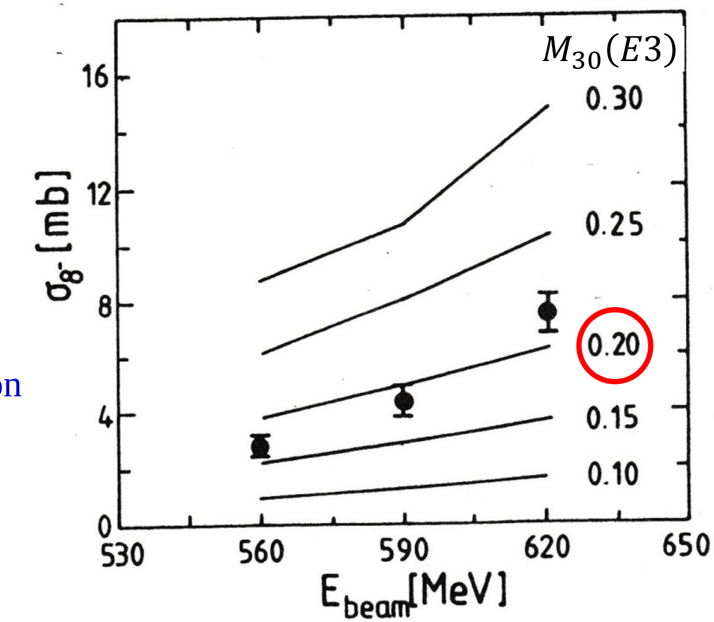
Coulomb excitation of the K = 8 isomer in ^{178}Hf

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



4 s → $M_{30}\,(E3) \leq 0.01$





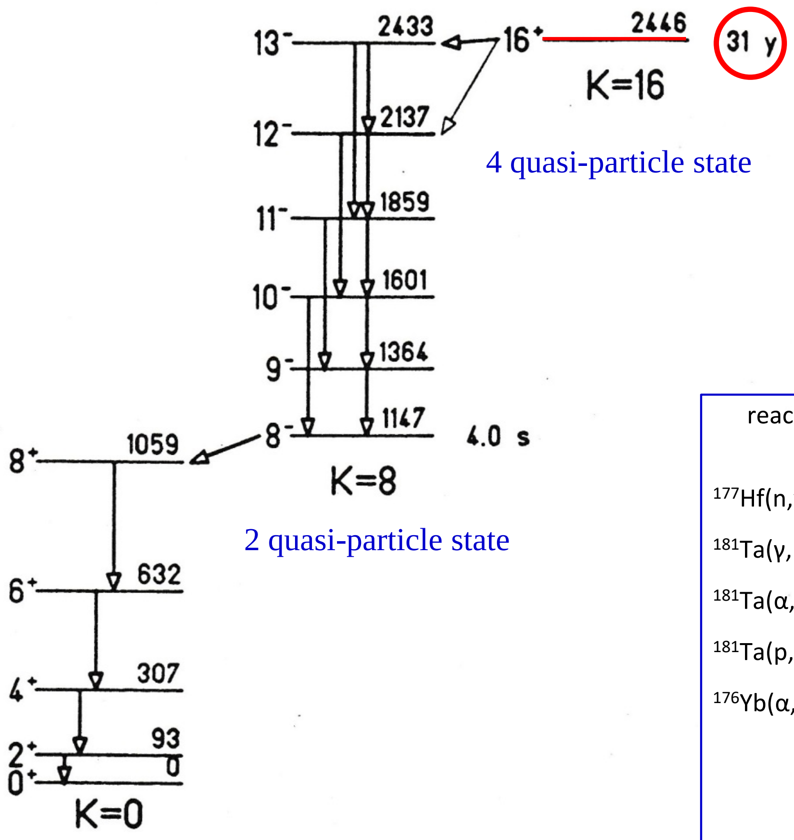
coupling between rotational motion
and single particle excitation

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

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

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

decay scheme of ^{178m2}Hf



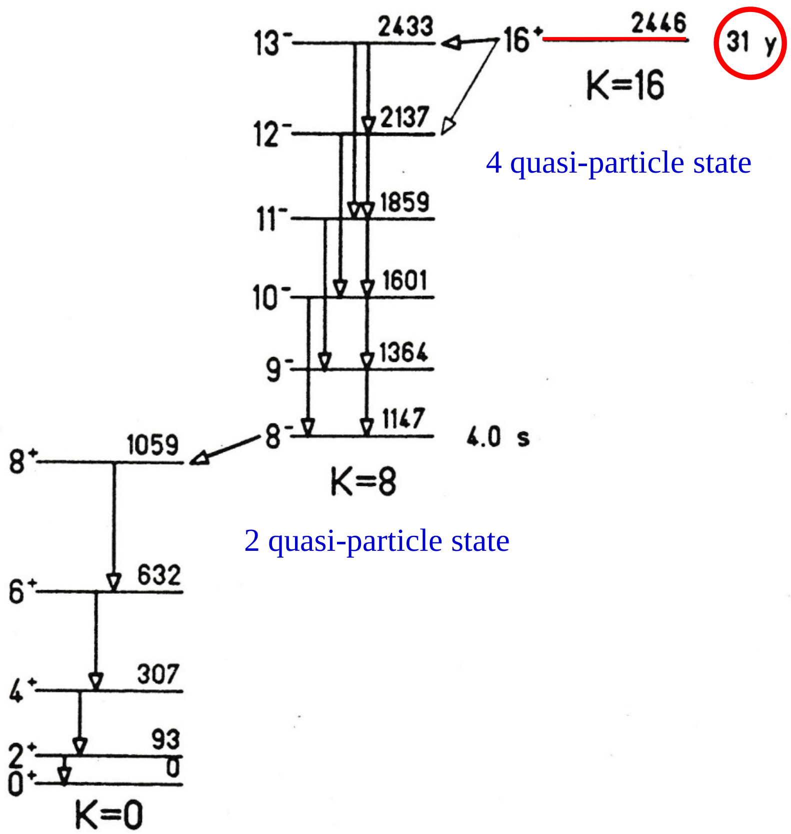
Production of ^{178m2}Hf in the past

reaction	projectile energy (MeV)	σ_m/σ_g	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	

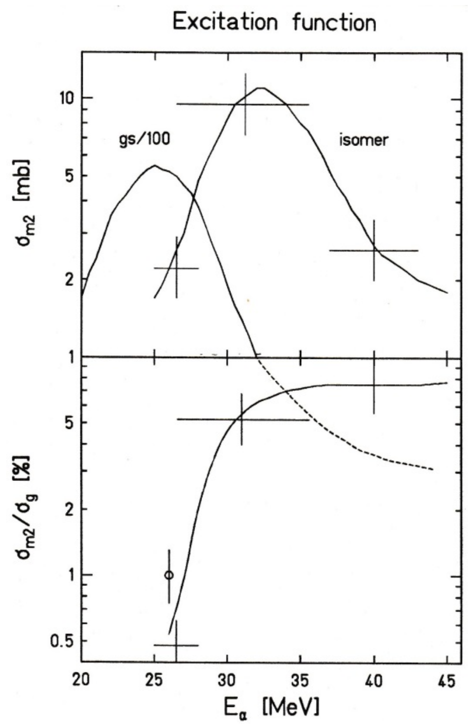
Helmer & Reich; Nucl. Phys. A114 (1968), 649

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

decay scheme of ^{178m2}Hf



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



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

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

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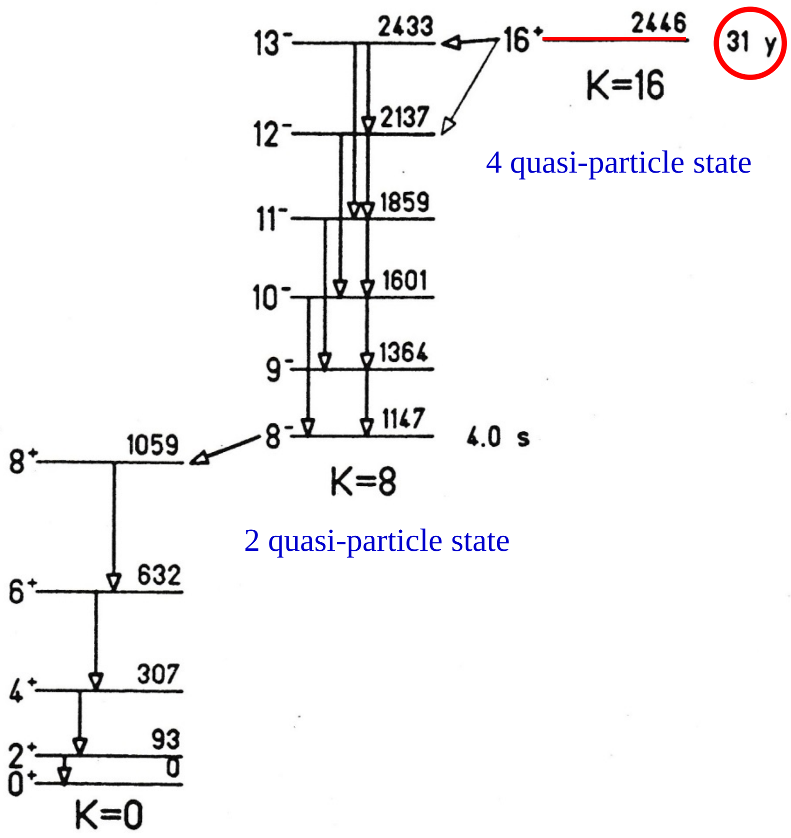


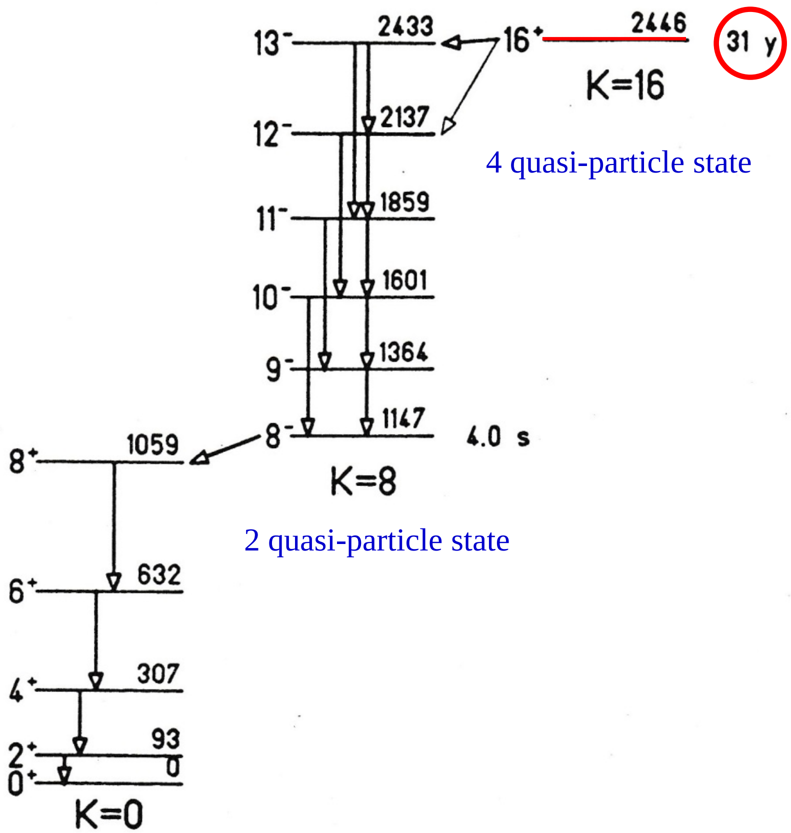
The isotopic distribution of radioactive Hf nuclei produced in the irradiation $^{4}He + ^{176}Yb$

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 μ(16^+) = 7.3±0.2 nm
- 4-qp state: π[514]9/2+π[404]7/2 + ν[514]7/2+ν[624]9/2

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

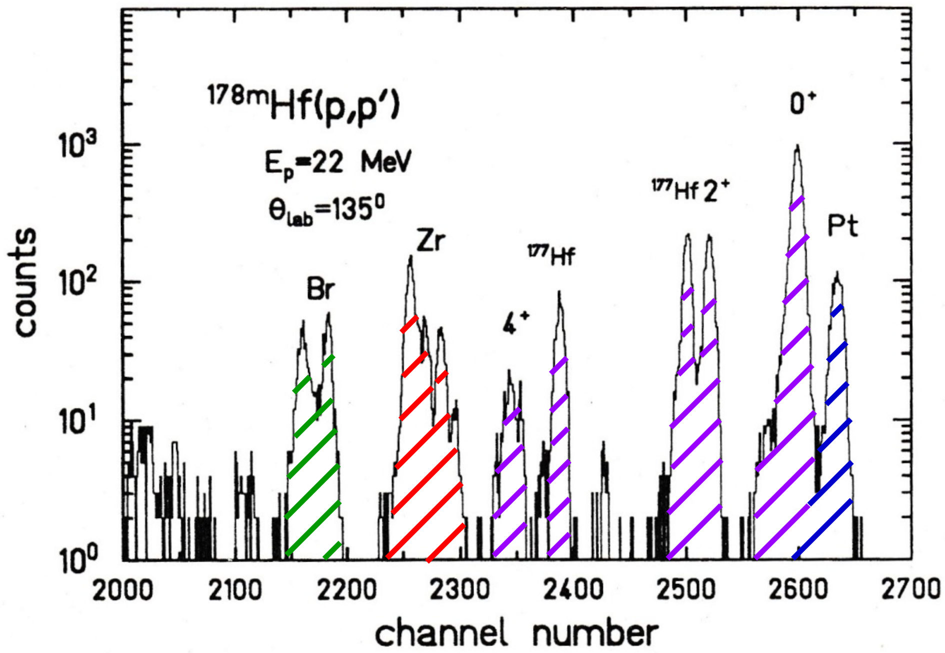
chemistry by M. Hussonnois (IN2P3-CNRS Orsay, France)

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

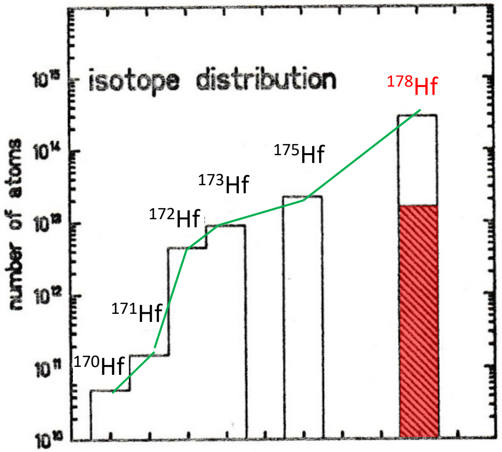


- X-ray analysis

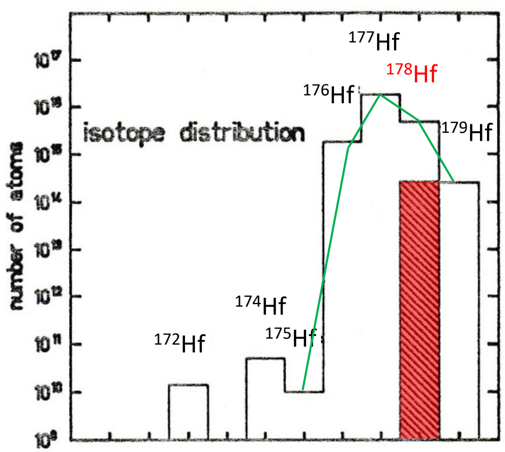
		Br	Zr	Hf	Pt	
^{178m2}Hf	15µg	**107**	**320**	**1278**	**33**	counts/s
^{nat}Hf	40µg	**-**	**223**	**3645**	**-**	counts/s

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

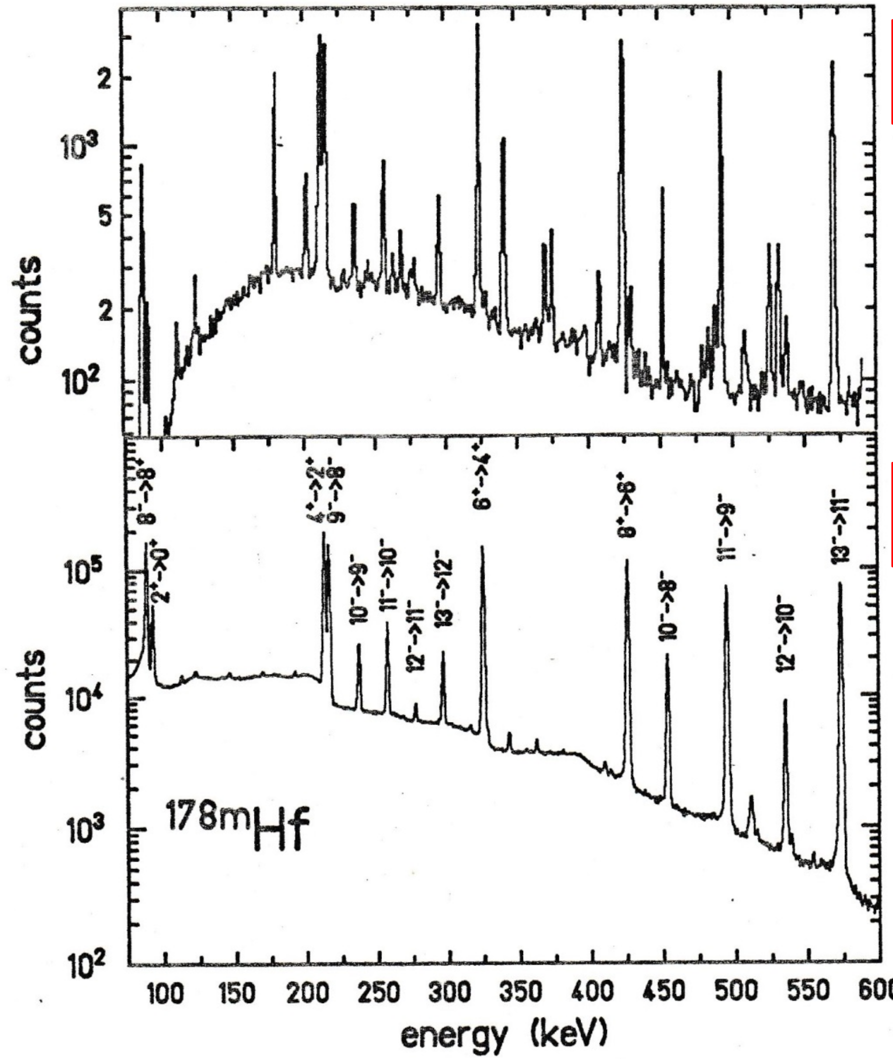
The $^{176}Yb(\alpha,2n)$ reaction



96% enriched ^{176}Yb



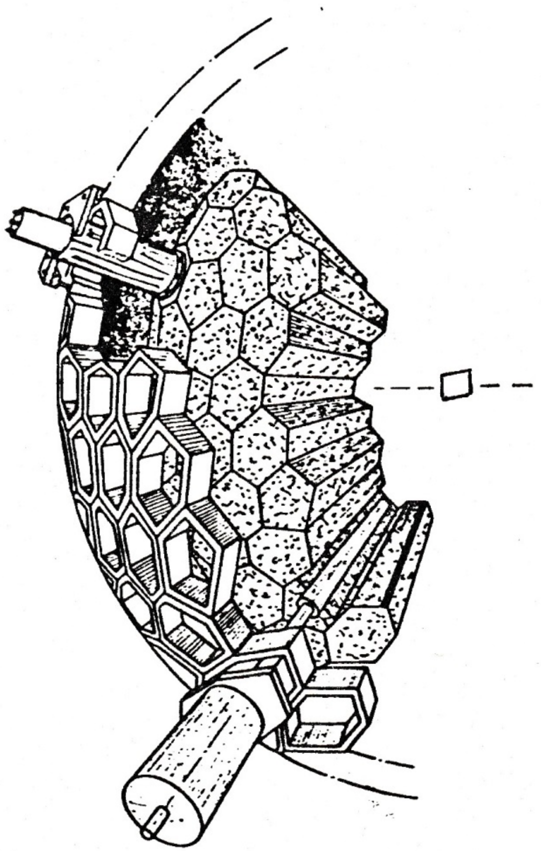
99.998% enriched ^{176}Yb



96% enriched ^{176}Yb

99.998% enriched ^{176}Yb

Decay study with the GSI-MPI Crystal Ball

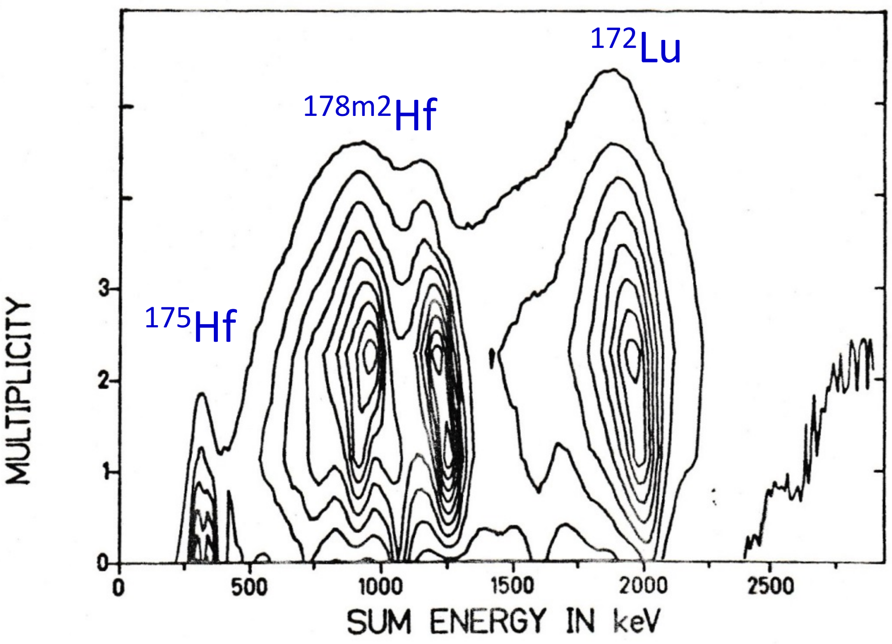


162 **NaI** detectors
1 **Ge** detector

parameters and resolutions FWHM

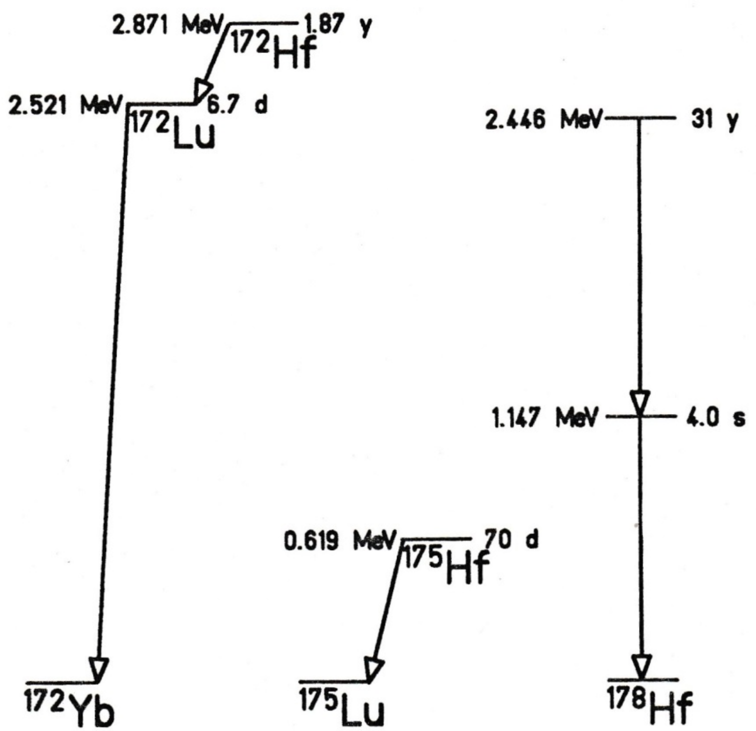
E_i	5.5% at 1332 keV
t_i	2.8 ns
$W(\theta)$	14^0
E_{total}	18-22% for M_γ=20
M_γ	25-30% for M_γ=20

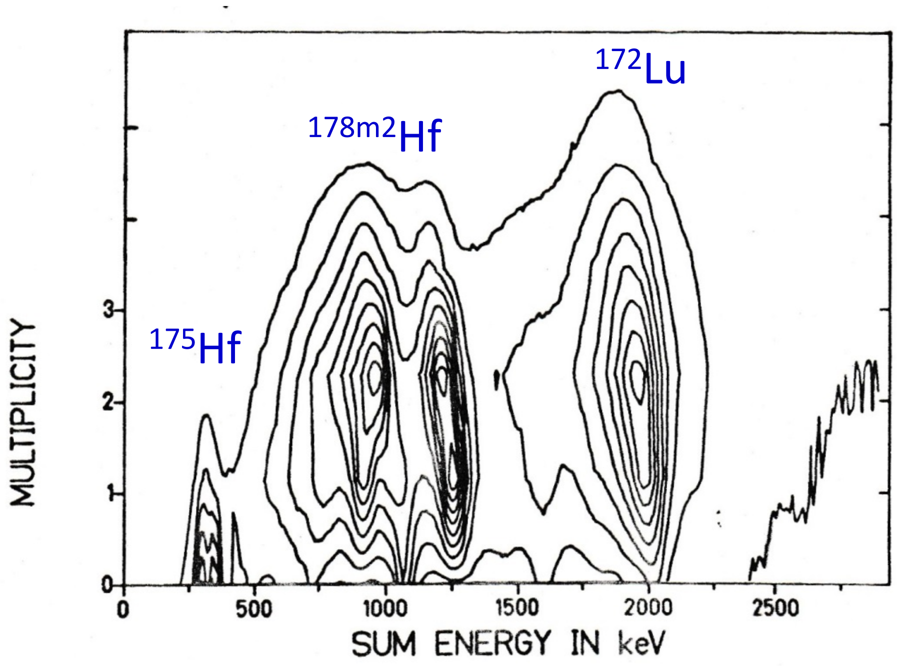
The two basic observables which can be measured for the resulting γ-ray shower are the **total energy** emitted as γ-radiation and the **number of γ-rays**.



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

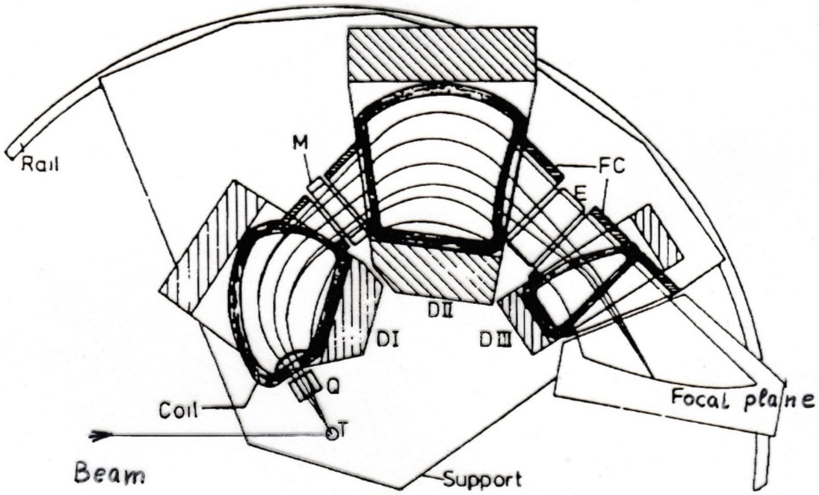
Decay scheme of ^{175,178m2}Hf, ^{172}Lu





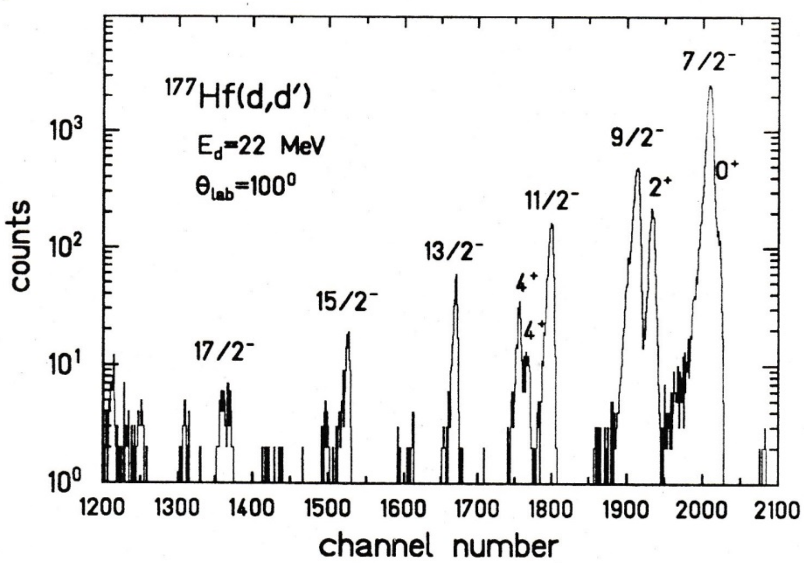
H. Xie et al.; Phys. Rev. C48 (1993), 2517

Inelastic Deuteron scattering experiment



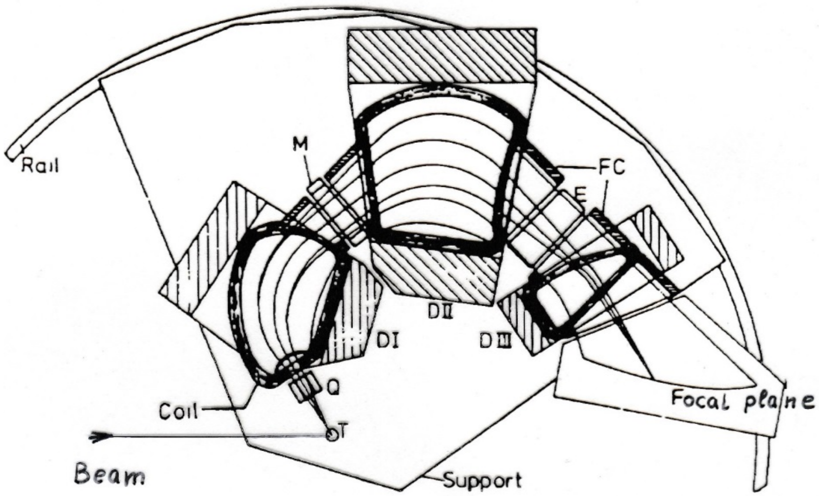
Q3D measurement at the Munich tandem

energy resolution: 12 keV

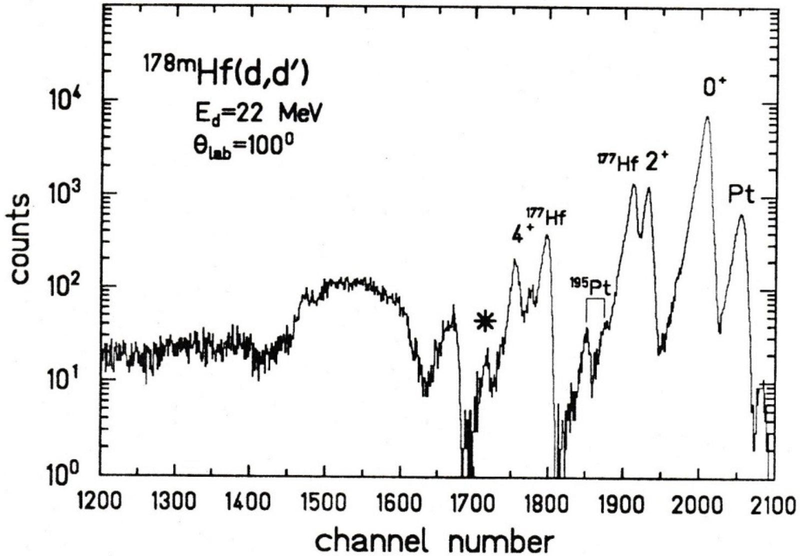


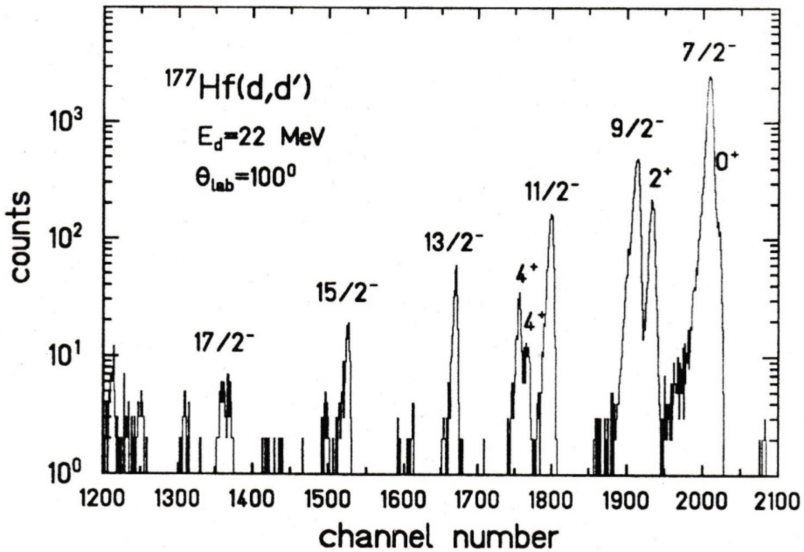
S. Deylitz et al. Phys. Rev. C53 (1996), 1266

Inelastic Deuteron scattering experiment



isomeric ^{178}Hf target





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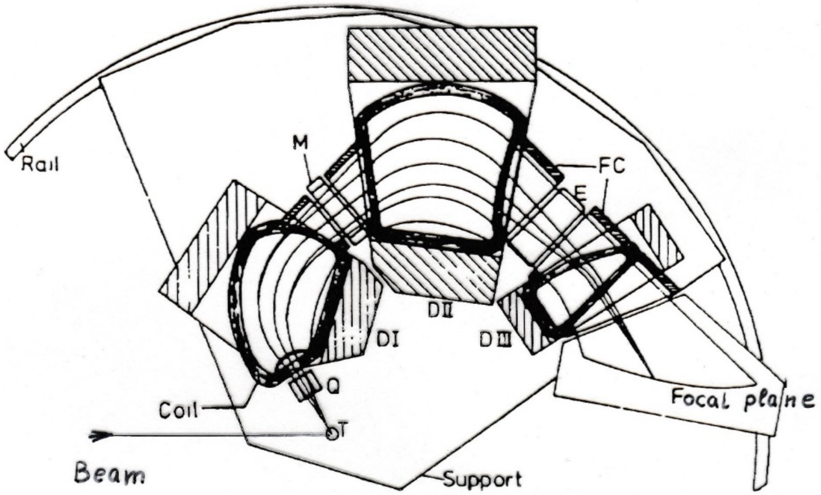

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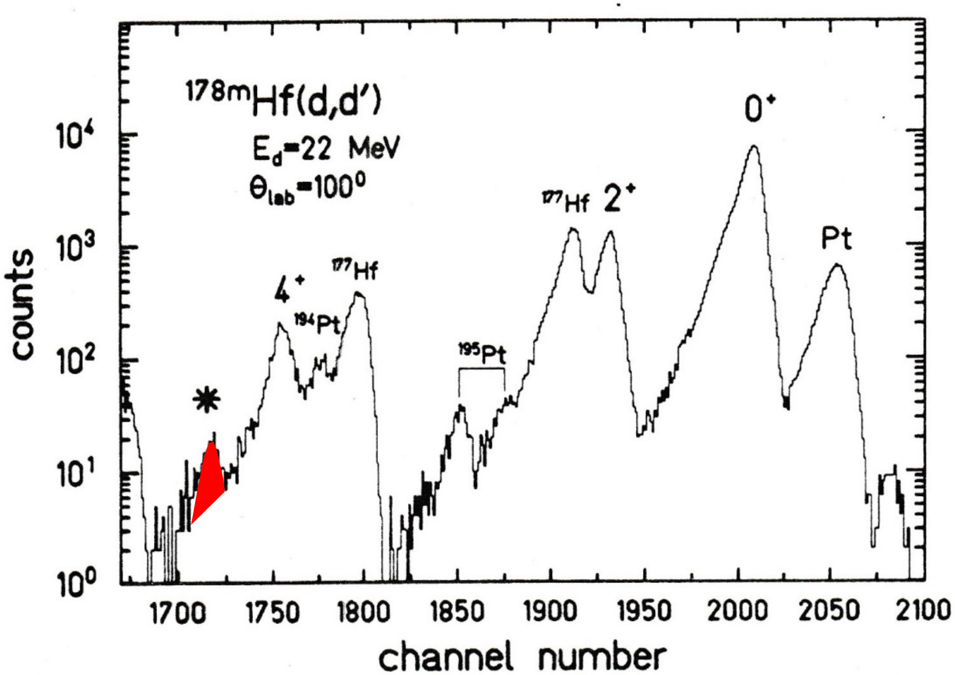
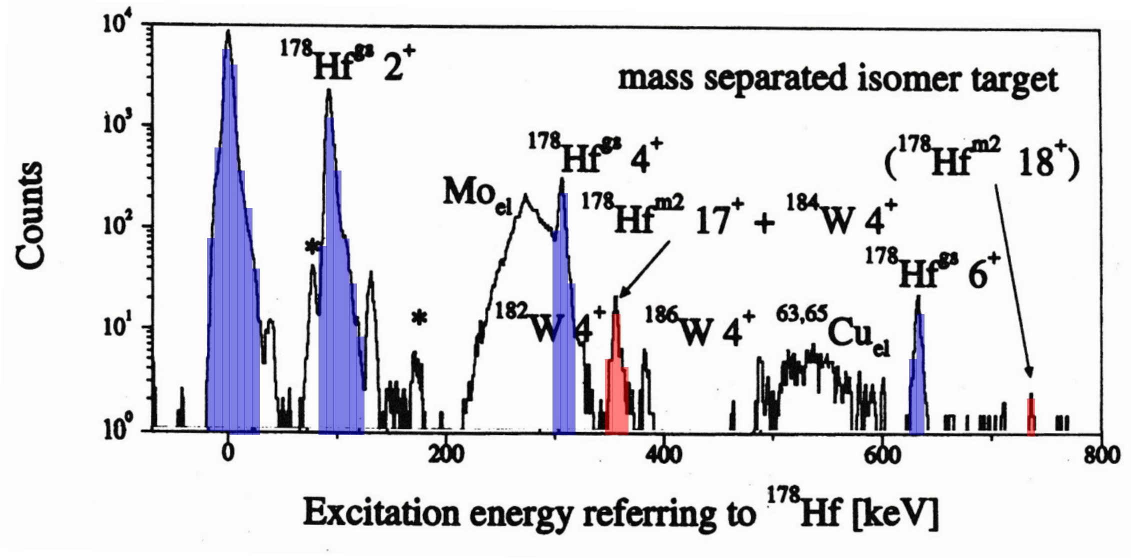


S. Deylitz et al. Phys. Rev. C53 (1996), 1266

Inelastic Deuteron scattering from K=16 isomer



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

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

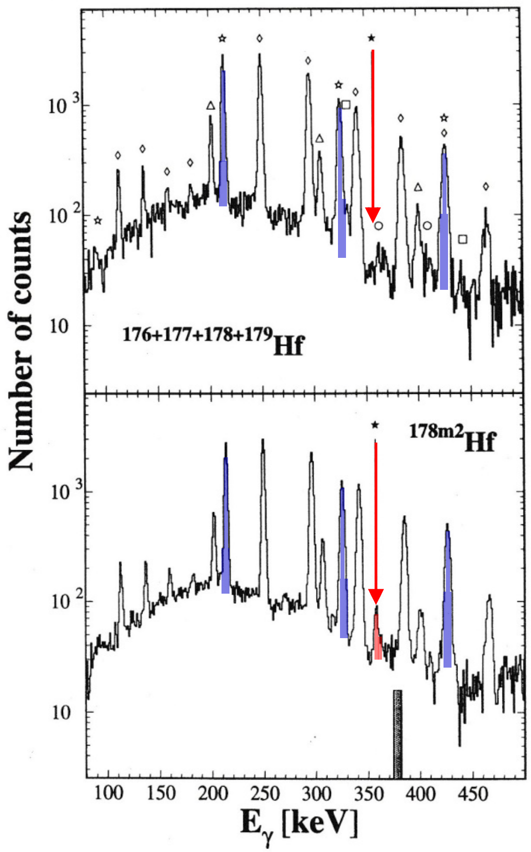
W, Ta, Mo, Cu result from sputtering and migration process in the mass-separator facility

- $E_x = 356.5 \pm 0.4$ 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 → Hf; 4.8 MeV/u

"artificial" γ-spectrum

γ-spectrum with isomeric target

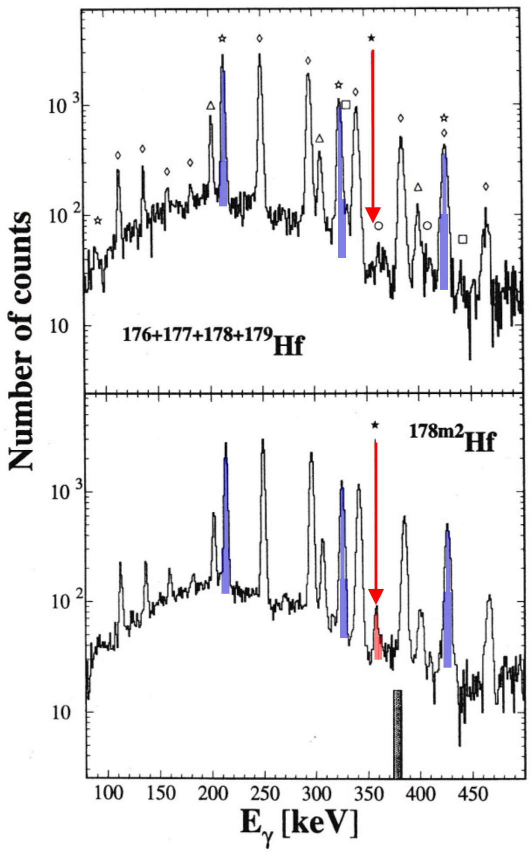
$$\frac{^{178m2}Hf}{Hf} = 0.6\% \qquad \mathbf{10^{14}}\ {}^{178m2}Hf\ atoms$$

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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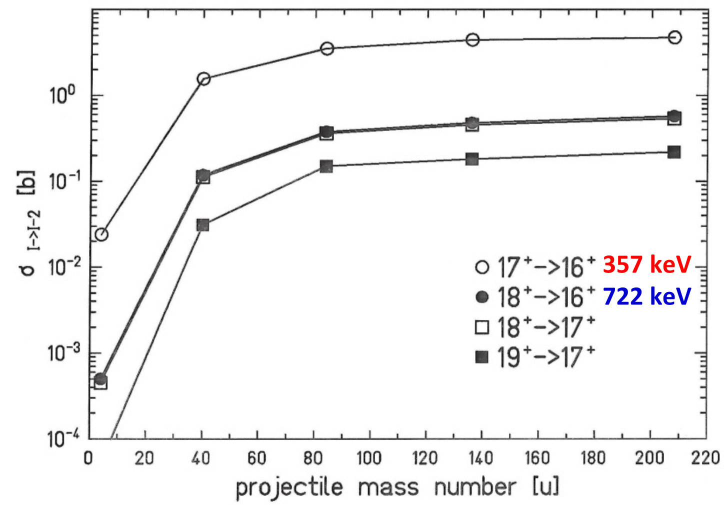

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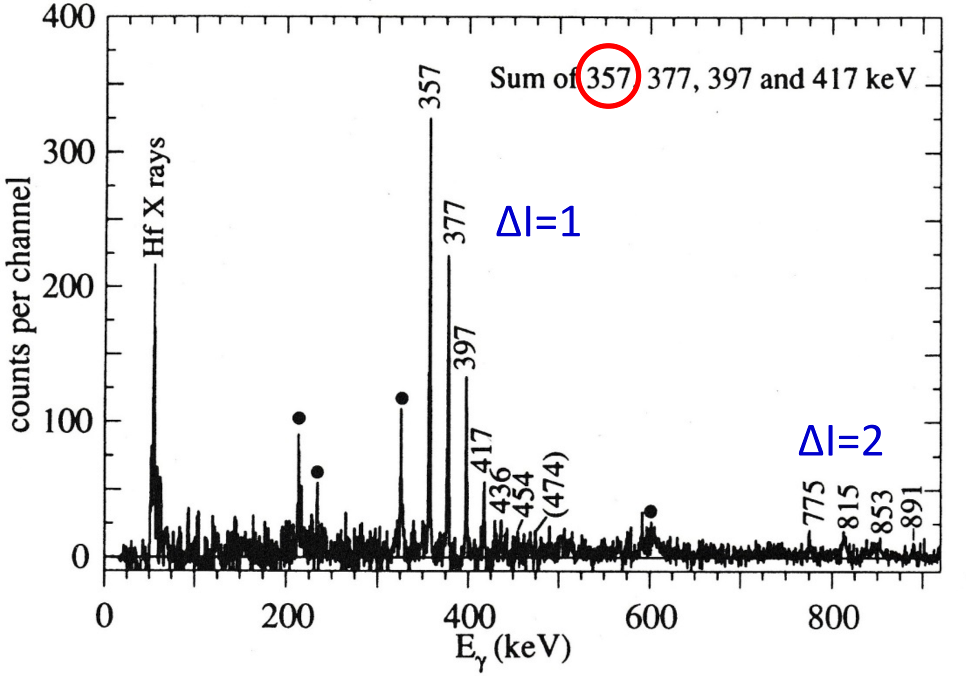
E. Lubkiewicz et al.; Z. Phys. A355 (1996), 377

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.

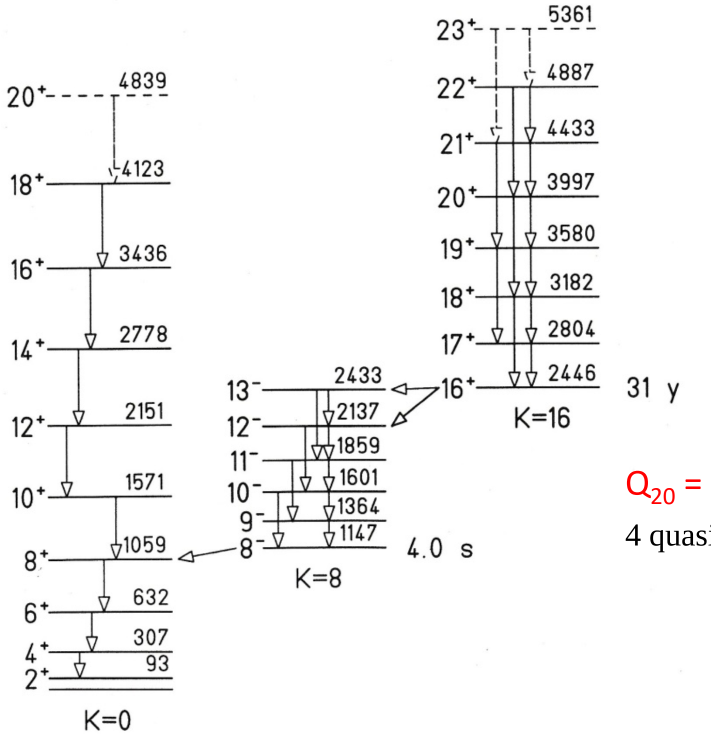
^{176}Yb(^{9}Be,α3n) ^{178}Hf   55, 60 MeV

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



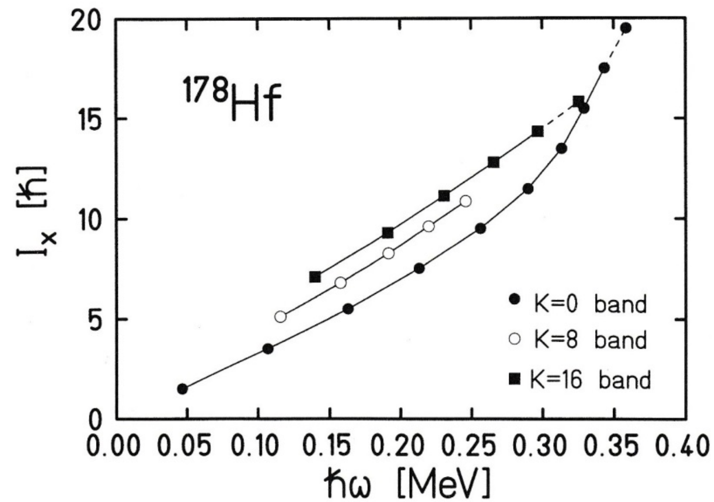
Q_{20} = 8.2±1.1 b

4 quasi-particle state

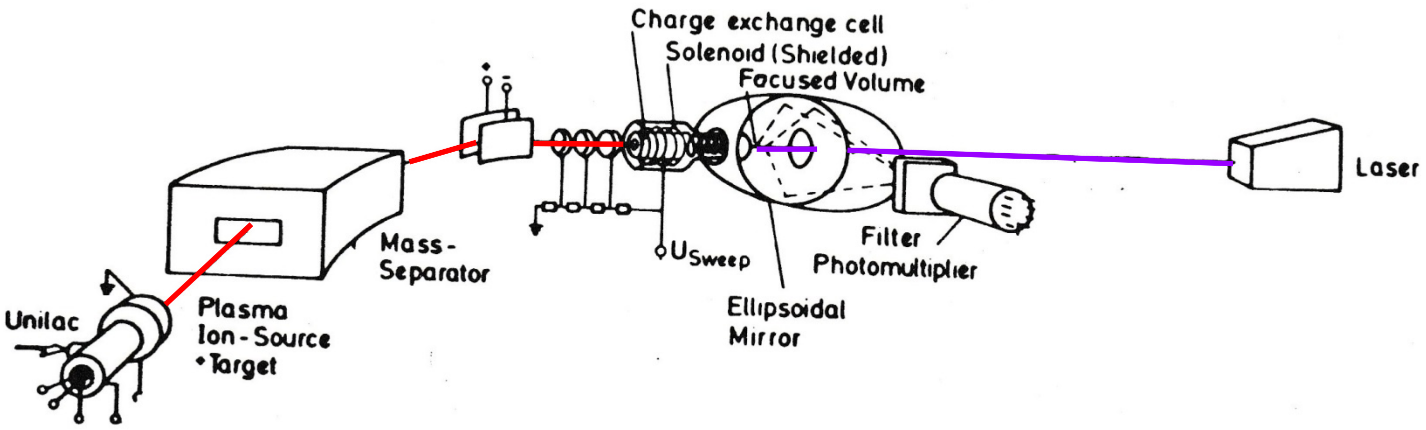
Q_{20} = 7.0 b

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

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

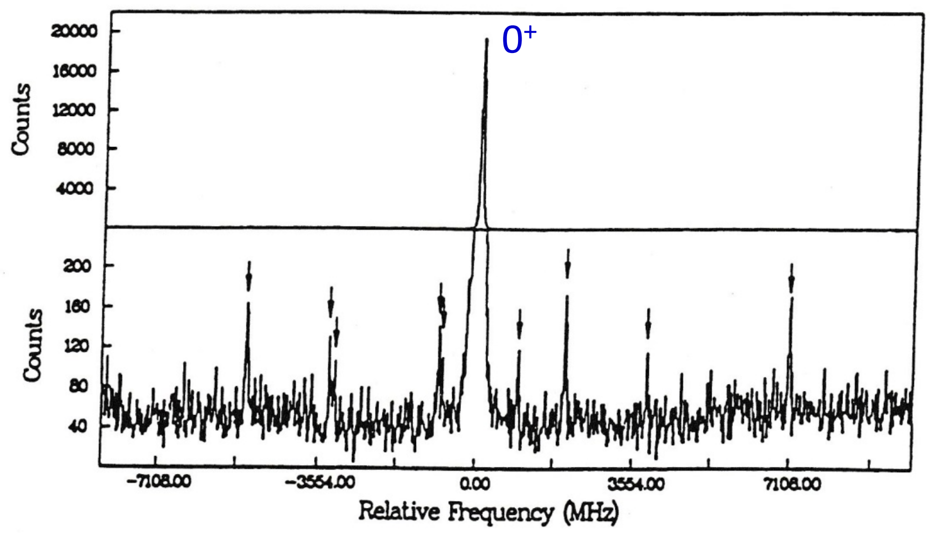


Collinear laser spectroscopy



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



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

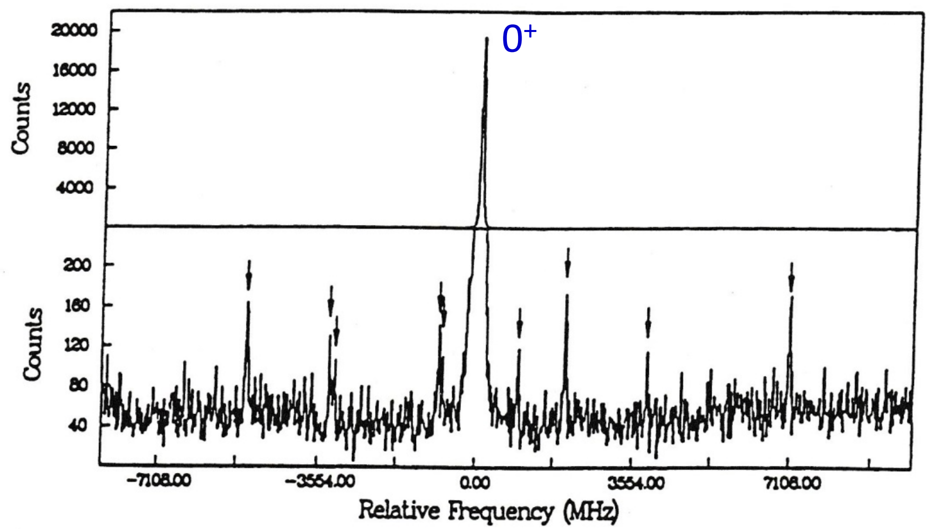
$$K = F(F+1) - I(I+1) - J(J+1)$$

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

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

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.

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

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

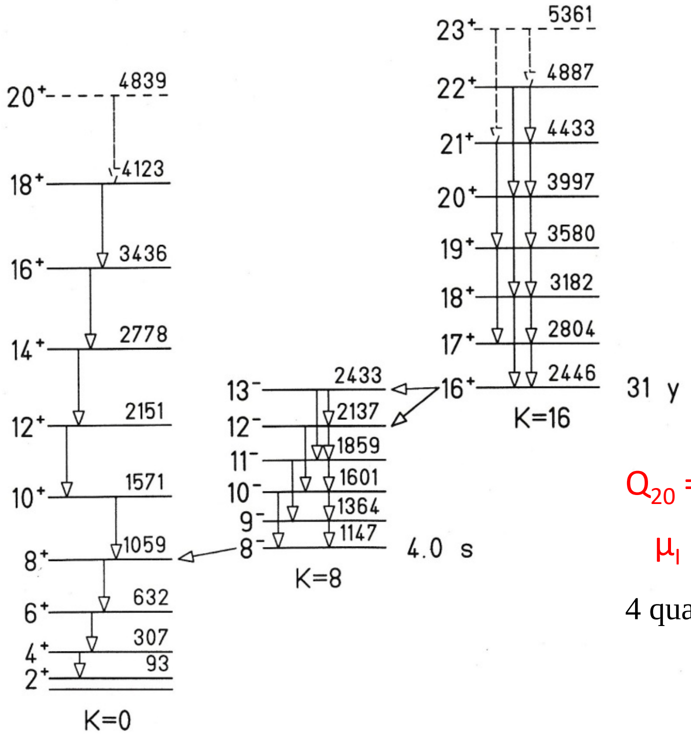
$$\delta\langle r^2\rangle^{178,178m2} = -0.059(9)\ \ fm^2$$

strong coupling scheme:

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

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

Partial level scheme of ^{178}Hf



Q_{20} = 7.2±0.1 b

μ_I = +8.16(4) n.m.

4 quasi-particle state

Q_{20} = 8.2±1.1 b (Coulomb excitation)

Q_{20} = 7.0 b

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

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