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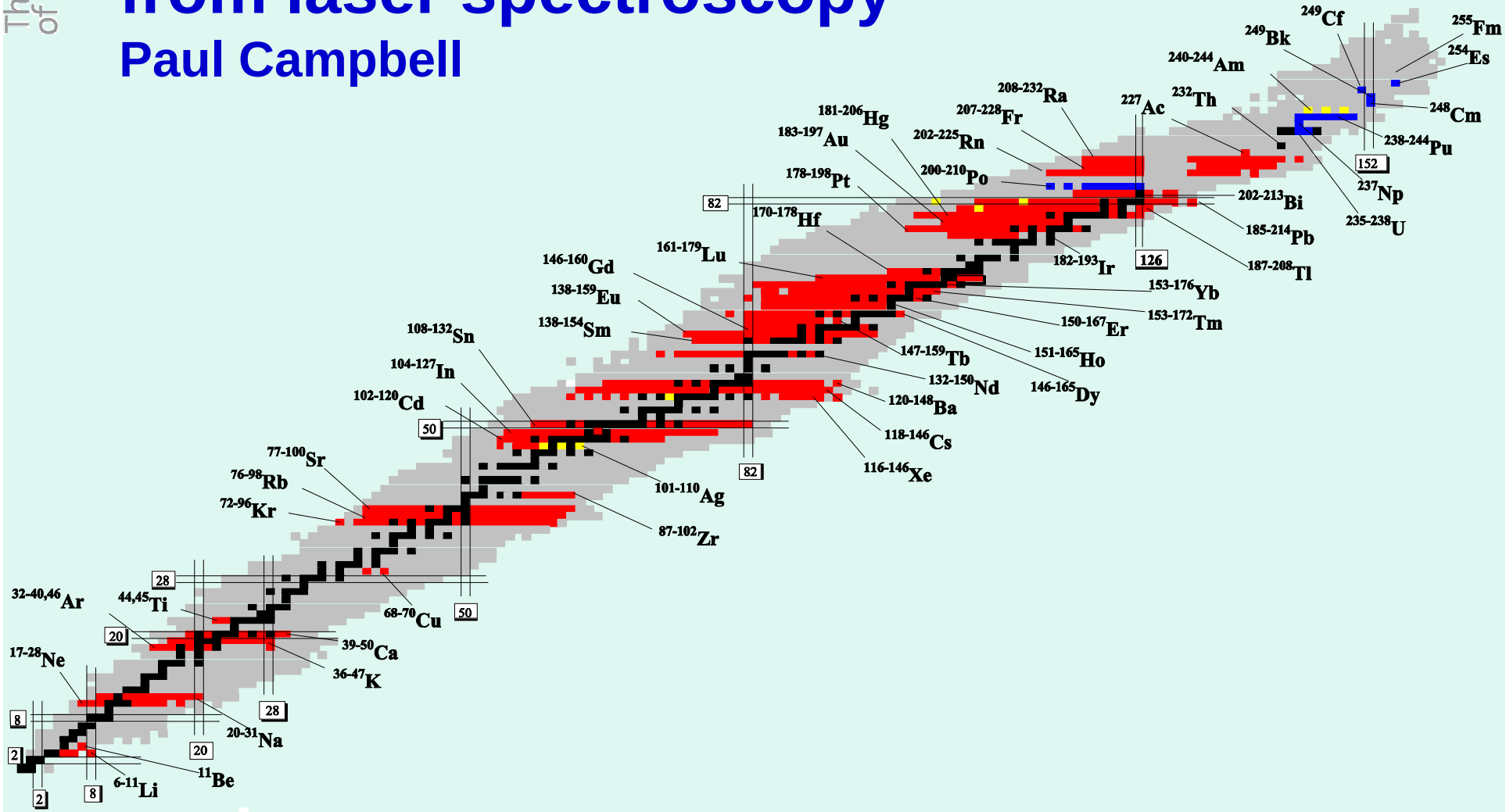
# High Spin Isomers: what we can learn from laser spectroscopy

Paul Campbell




(Kluge & Noerterhauser)

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# Laser Spectroscopy

Investigation of

- Hyperfine Structure
- Isotope Shifts
- Isomer Shifts

provides **model-independent** nuclear data…

Why OPTICAL??

provides **high-sensitivity…**

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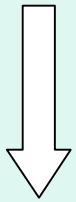
# Ground State Properties

## Isotope Shift (IS)



Mean Square Charge Radii

$$\delta\left\langle r^2\right\rangle^{AA'}$$

## Hyperfine Structure (HFS)

Nuclear Spin $I$

Magnetic Dipole Moment $\mu_I$

Electric Quadrupole Moment $Q_s$

Hyperfine Anomaly

**Charge radii affected by size, shape, rigidity and diffuseness….**

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# High spin isomers

## (spin-aligned isomers)

**Optical Data**

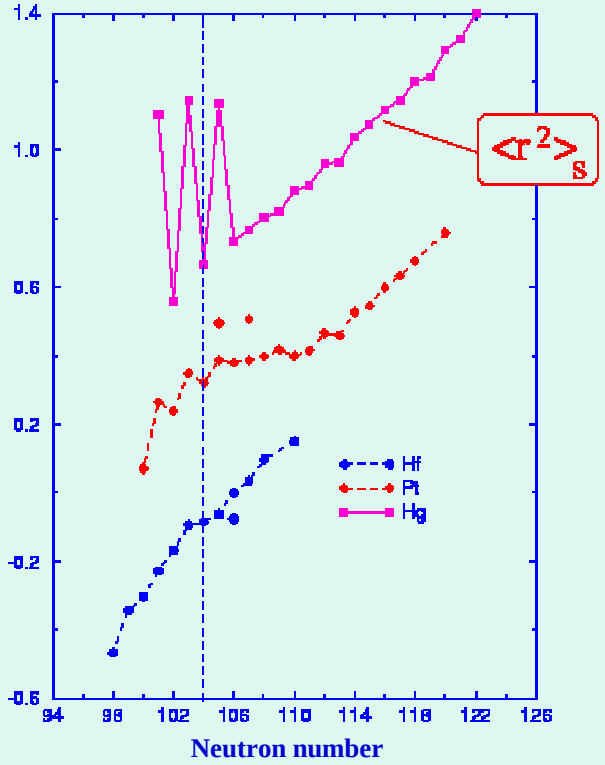
$\langle r^2 \rangle$ evaluation is model independent and provides a sensitive probe of the nuclear shape and size

**Deformed shape**

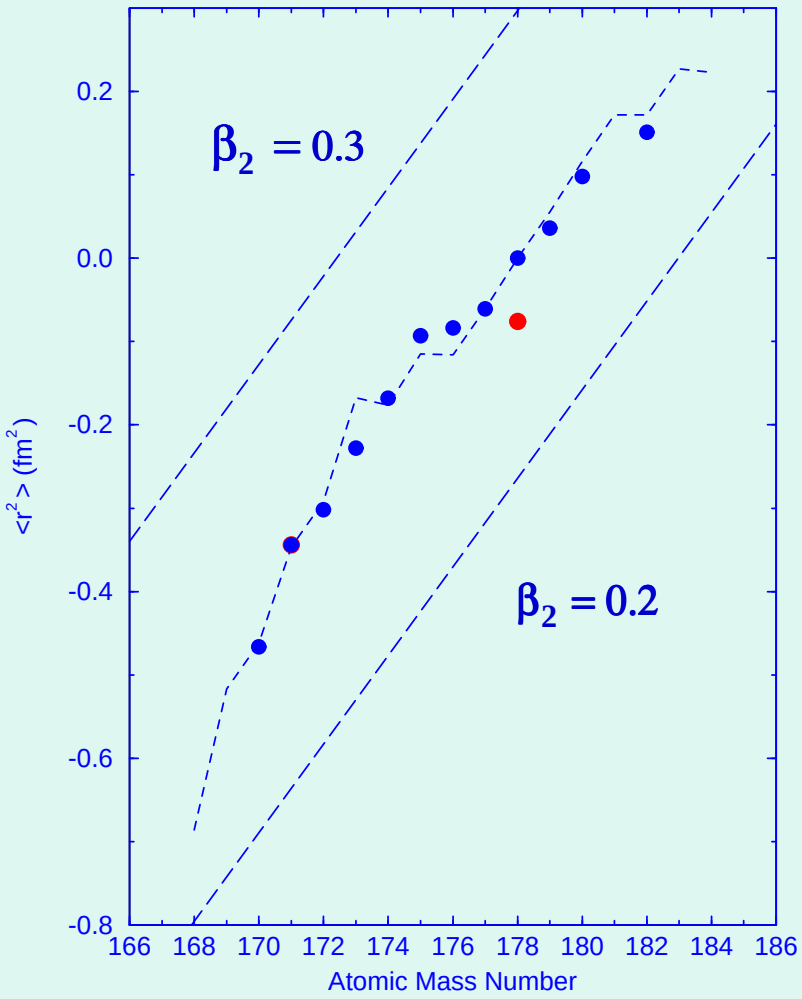
$$\langle r^2 \rangle_{defm} = \langle r^2 \rangle_s (1 + \alpha_2^2 + \ldots) + 3\sigma^2$$

Quadrupole deformation

Nuclear diffuseness



# Hafnium charge radii




Isomer measurement;
Boos et al.
Dubna, Orsay, Mainz, McGill
PRL **72** (1994) 2689

The isomer has a static quadrupole moment that is greater than the static + dynamic quadrupole moment of the gs

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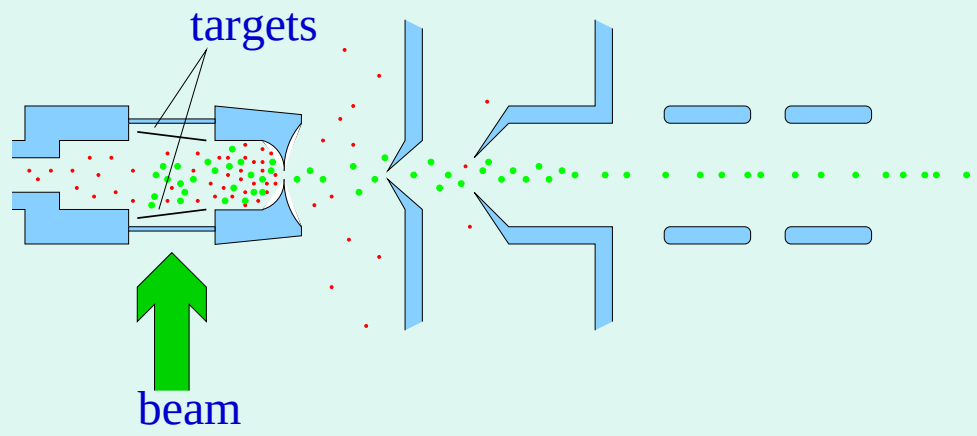
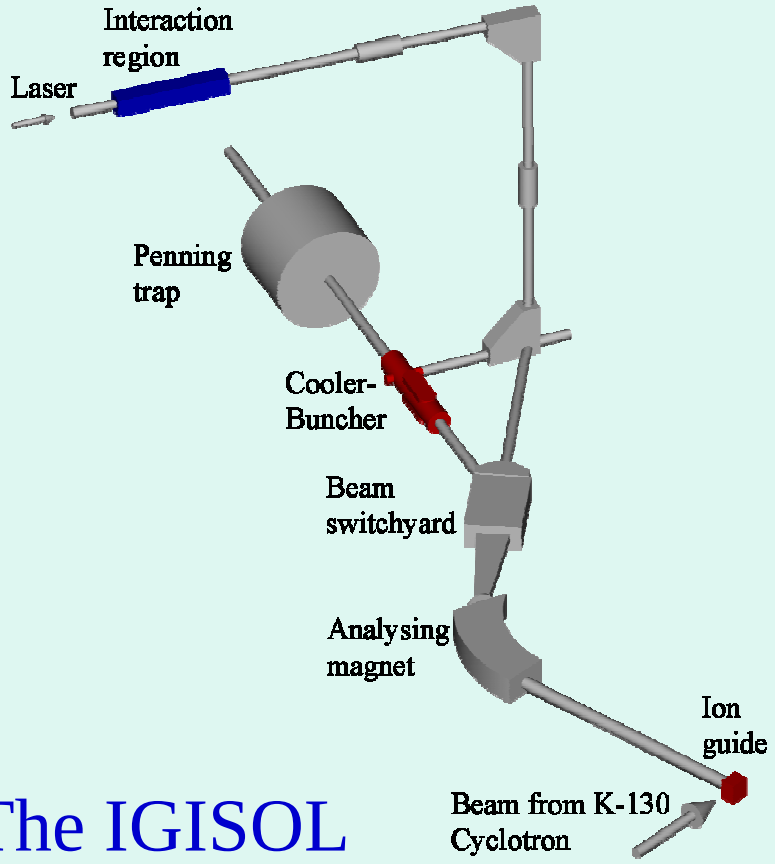
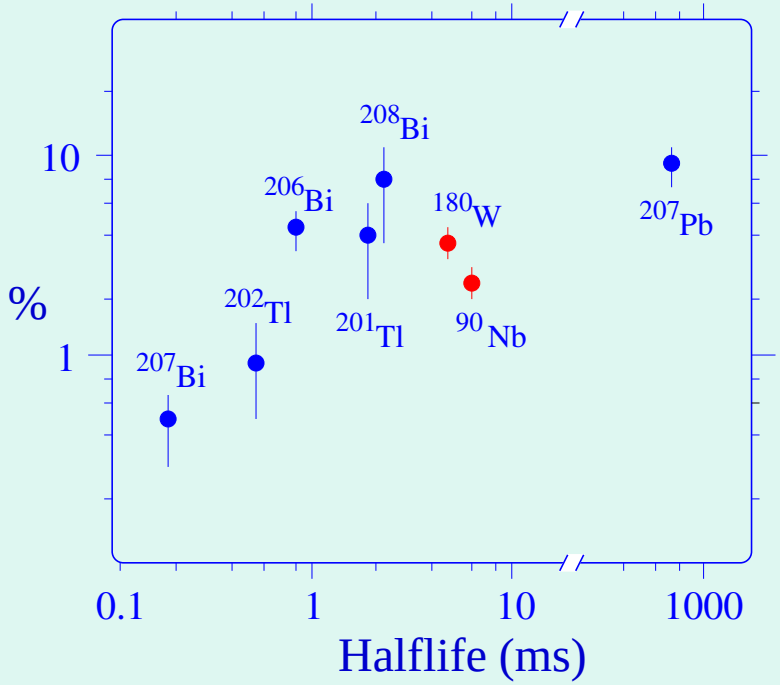



# The IGISOL facility, JYFL



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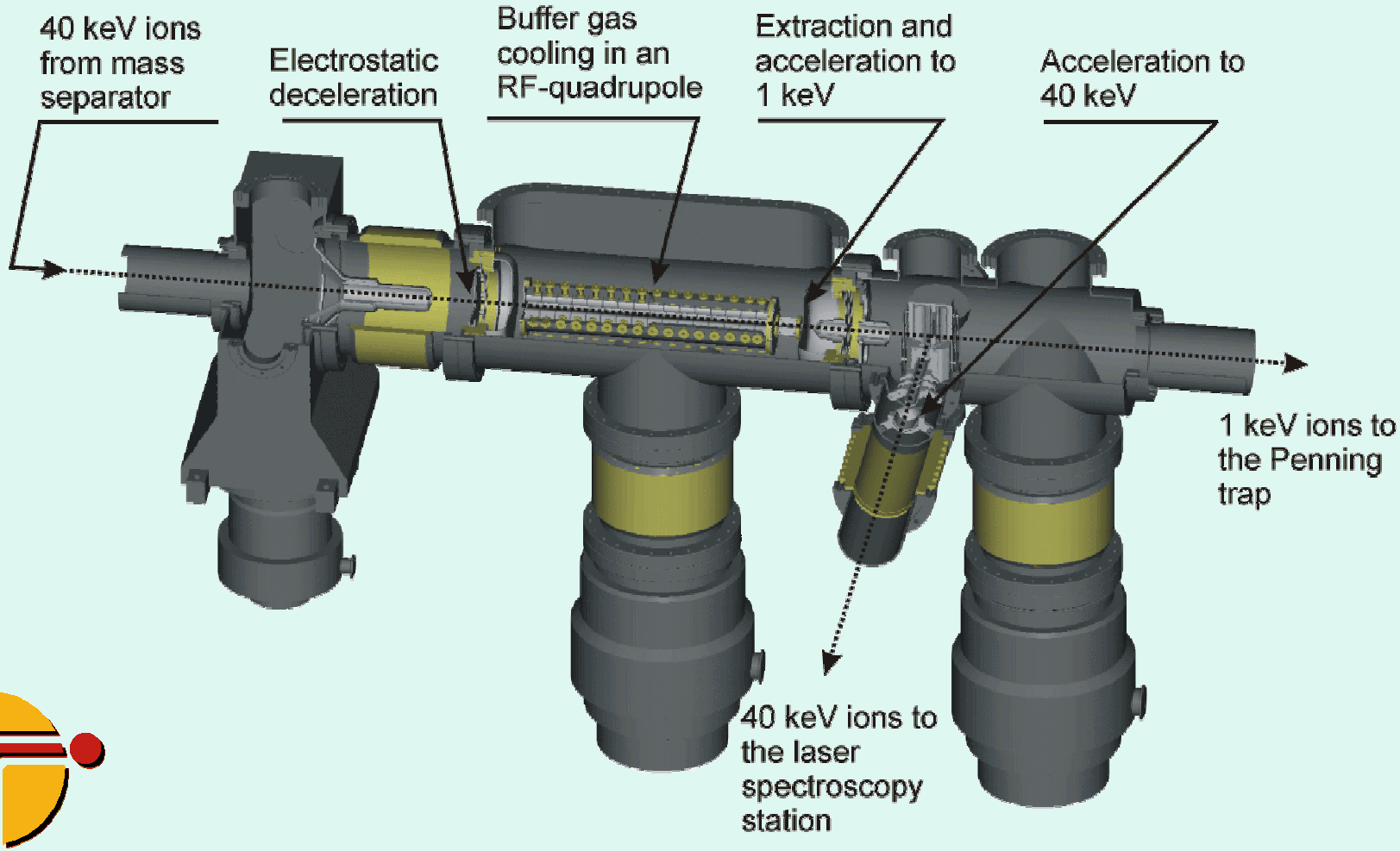
# Cooling and bunching:




JYFL

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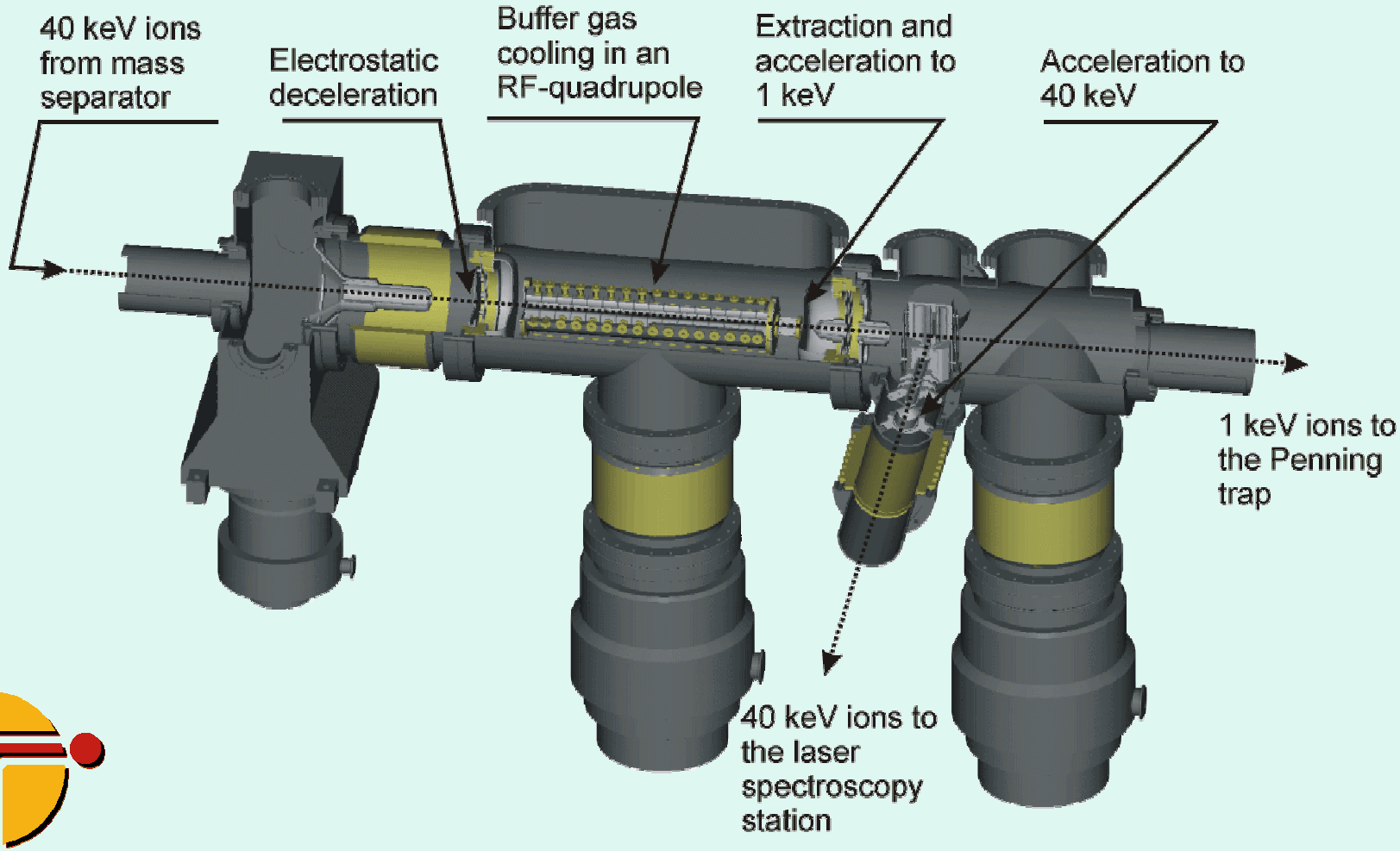
# Cooling ~~and bunching~~:




JYFL

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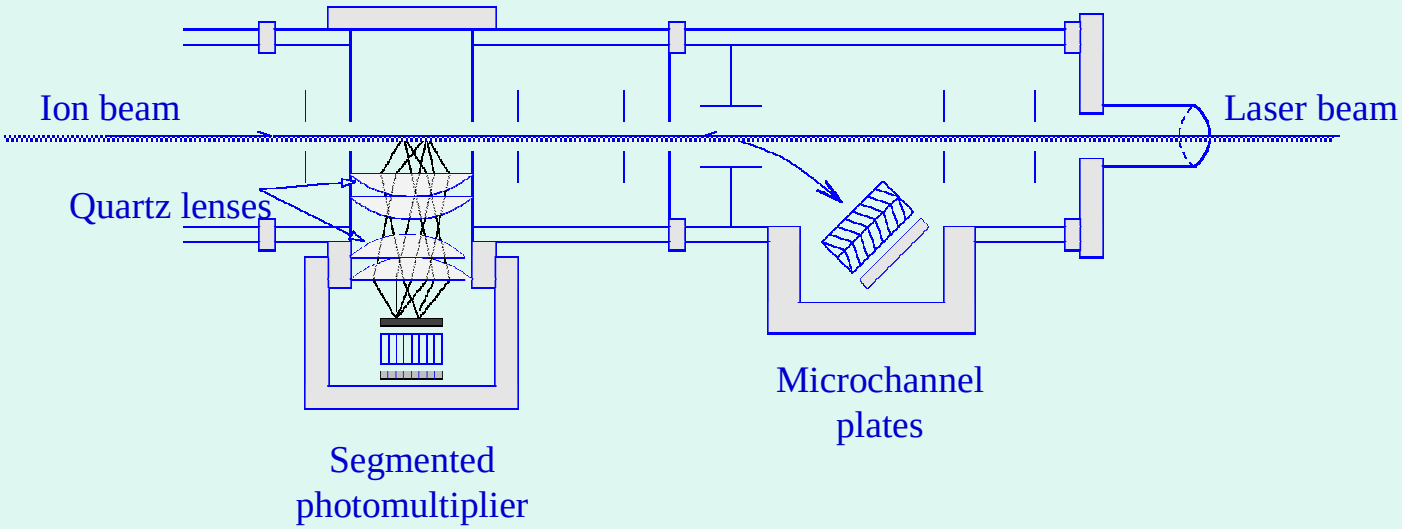
# Photon-ion coincidence spectroscopy



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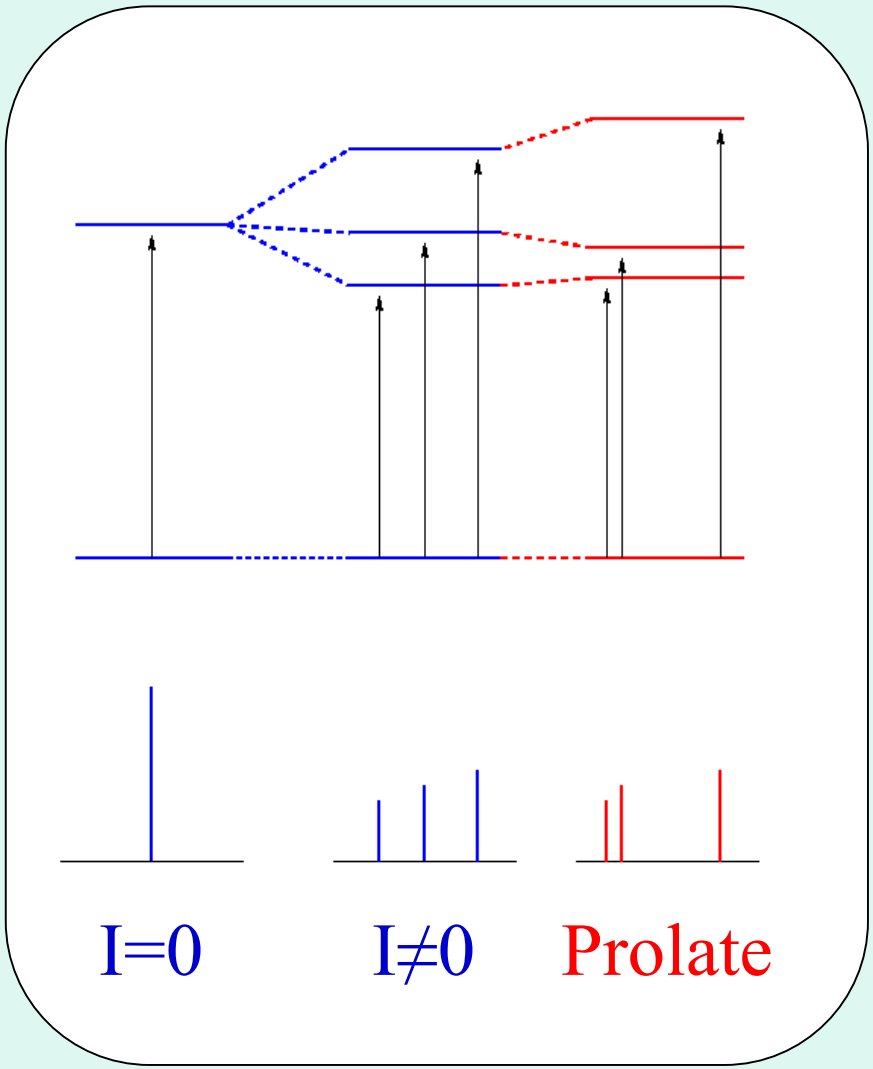
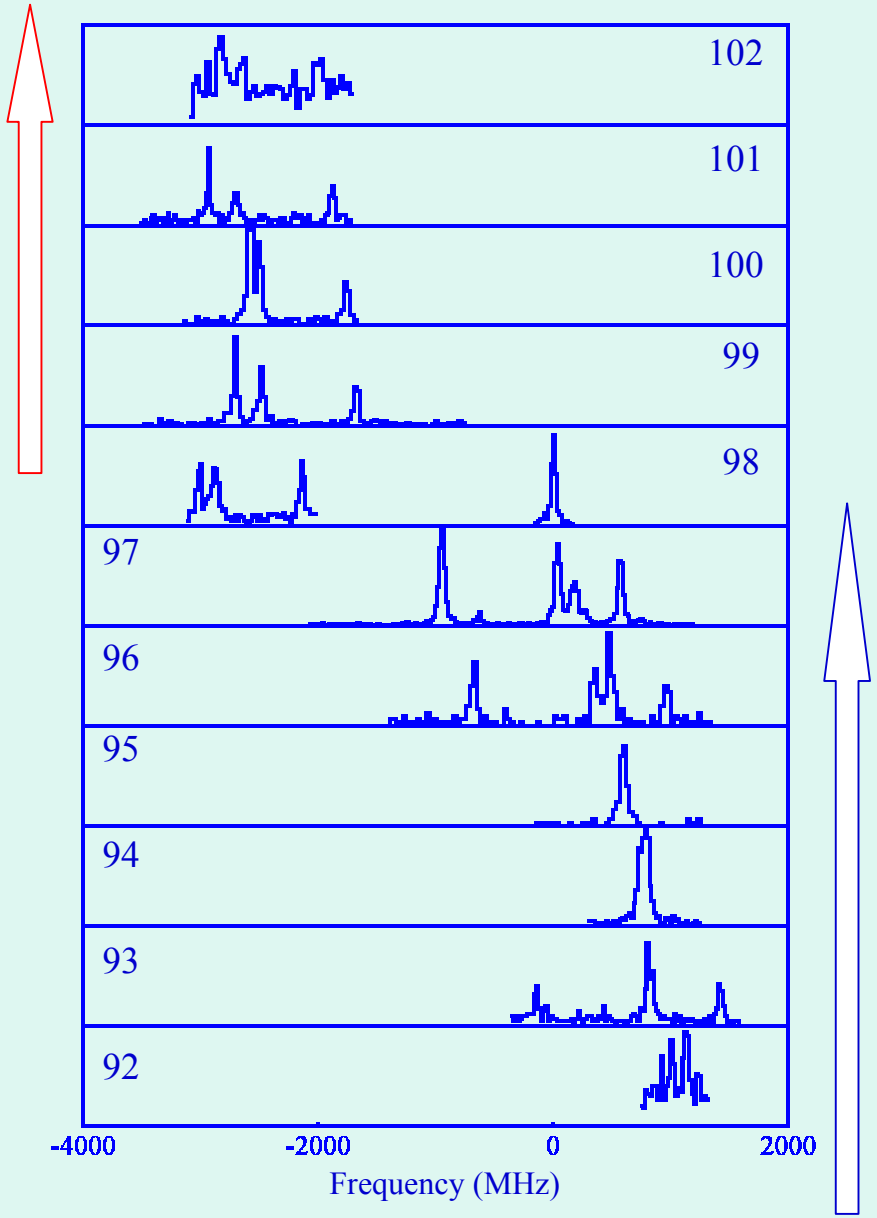
# Yttrium J=0 – J'=1




Decreasingly strong prolate




Increasingly oblate

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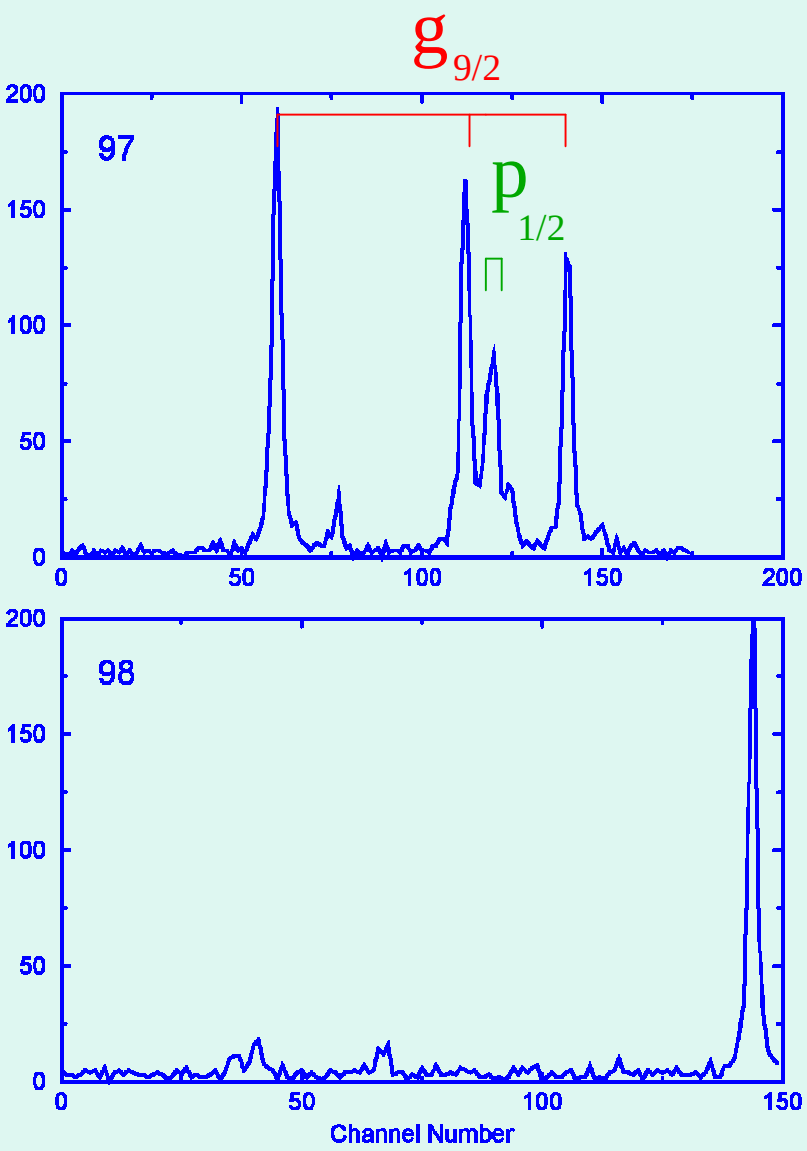
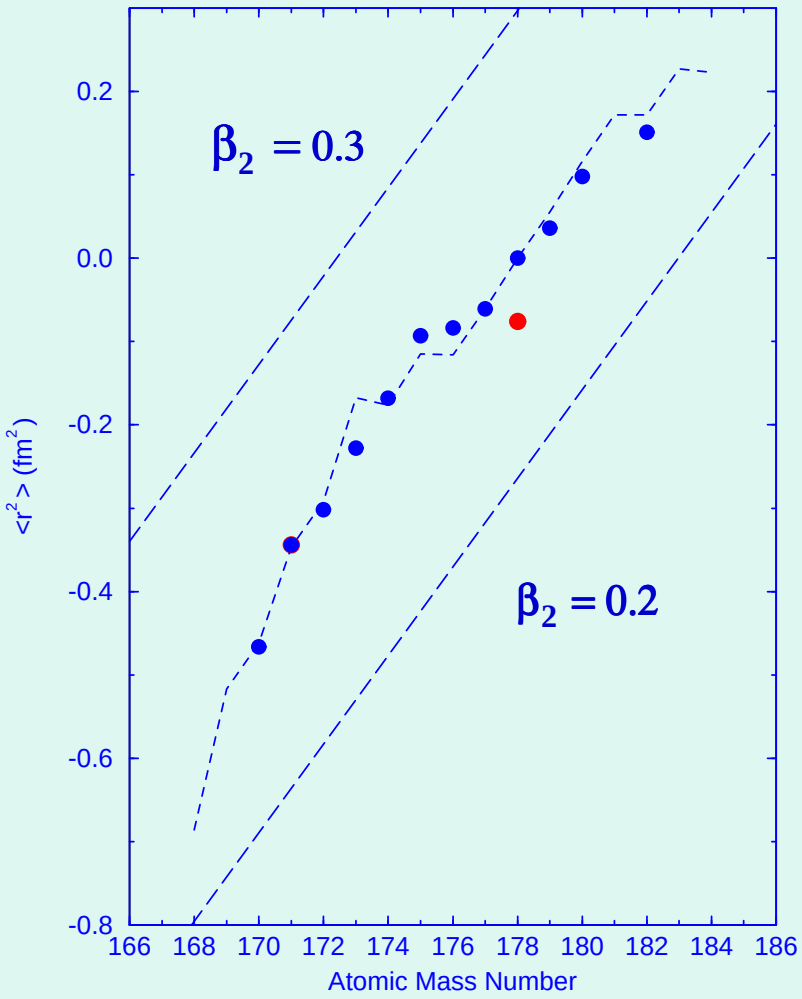
# Isomer results



# Hafnium charge radii

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The isomer has a static quadrupole moment that is greater than the static + dynamic quadrupole moment of the gs

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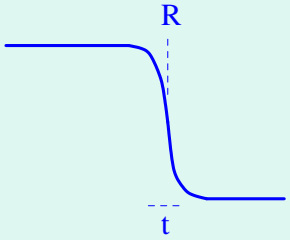
# Sensitivity to diffuseness??

$$\langle r^2 \rangle = \langle r^2 \rangle_{SCO} + 0.72\, t^2$$

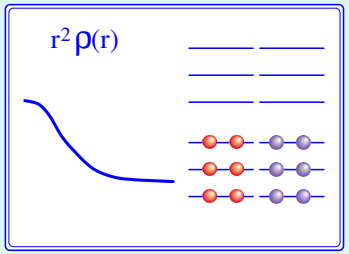


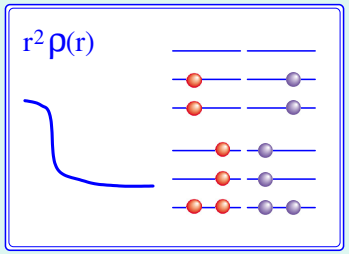

$$\rho(r) = \frac{\rho(0)}{1 + e^{\frac{4.39(r-R)}{t}}}$$

$e^{-\frac{r^2}{2\sigma^2}}$ Folded Gaussian

$$\rightarrow \langle r^2 \rangle = \langle r^2 \rangle_{SCO} + 3\sigma_g^2$$

Decrease pairing - $\sigma$ decreases??



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# Droplet model

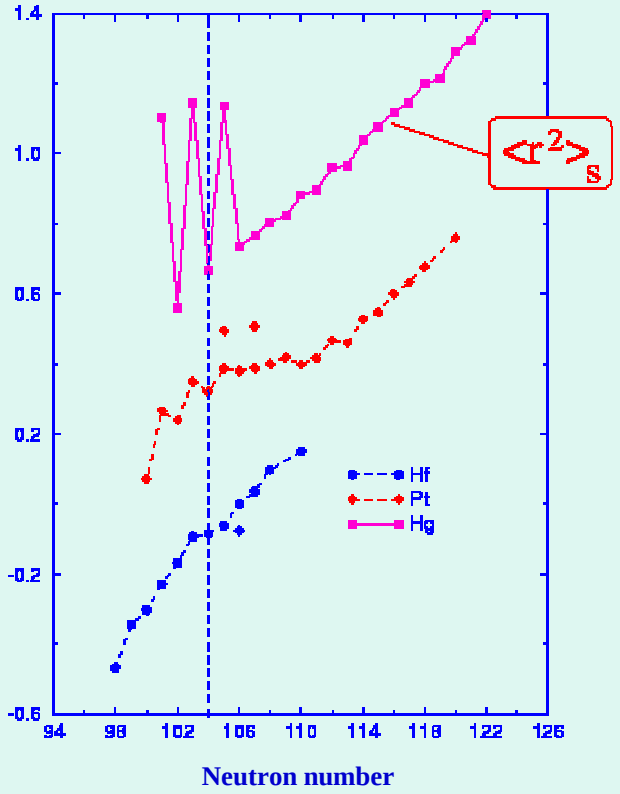
$$\langle r^2 \rangle_{defm} =$$

$$\langle r^2 \rangle_s \left(1 + \alpha_2^2 + \ldots\ldots\right)$$

$$+ C \langle r^2 \rangle_s \left(1 + \tfrac{14}{5} \alpha_2^2 + \ldots\ldots\right) \quad (2.6\%)$$

$$+ 3\,\sigma^2 \quad (12\%)$$

for a shape expansion in terms of Legendre polynomials



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# High-K isomer measurements

**Two reported (deformed) results were those on $^{178m2}$Hf and $^{177m}$Lu**

**Both show reductions in $<r^2>$ despite increases in $\beta_2$**

## JYFL measurements

- $^{130m}$Ba — Z=56 — N=74
- $^{176m}$Yb — Z=70 — N=106
- $^{178m1}$Hf — Z=72 — N=106
- $^{97m1,m2}$Y — Oblate

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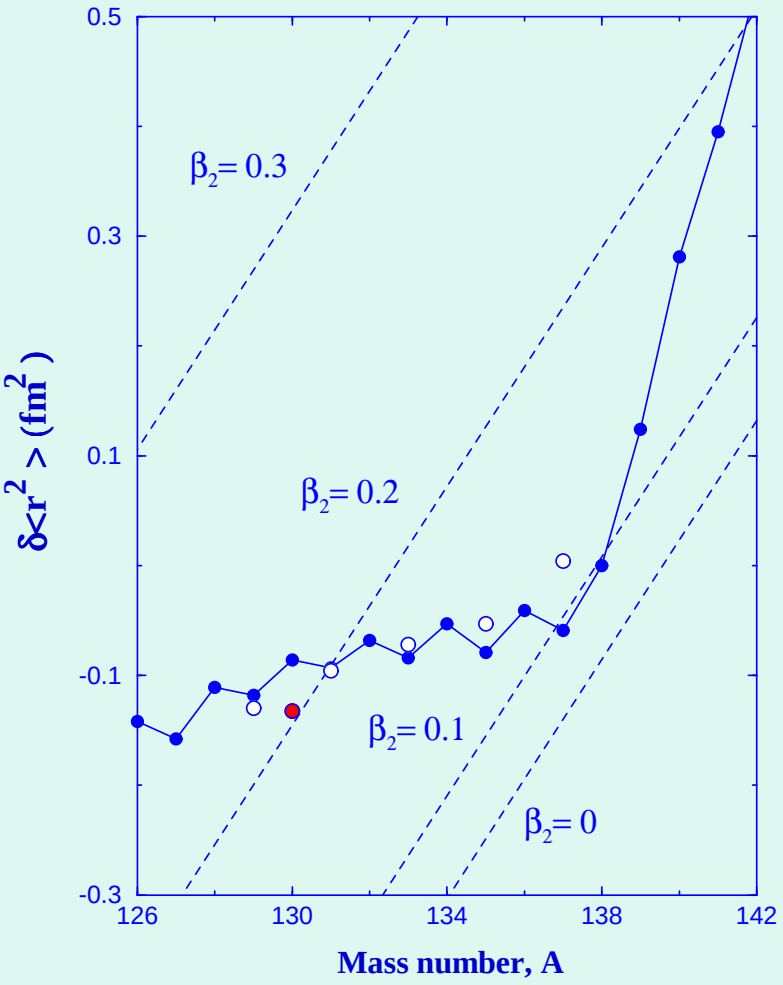
# Barium mean square charge radii

**(in collaboration with A Bruce)**

**$^{130m}$Ba isomer**

**(9.5ms)**



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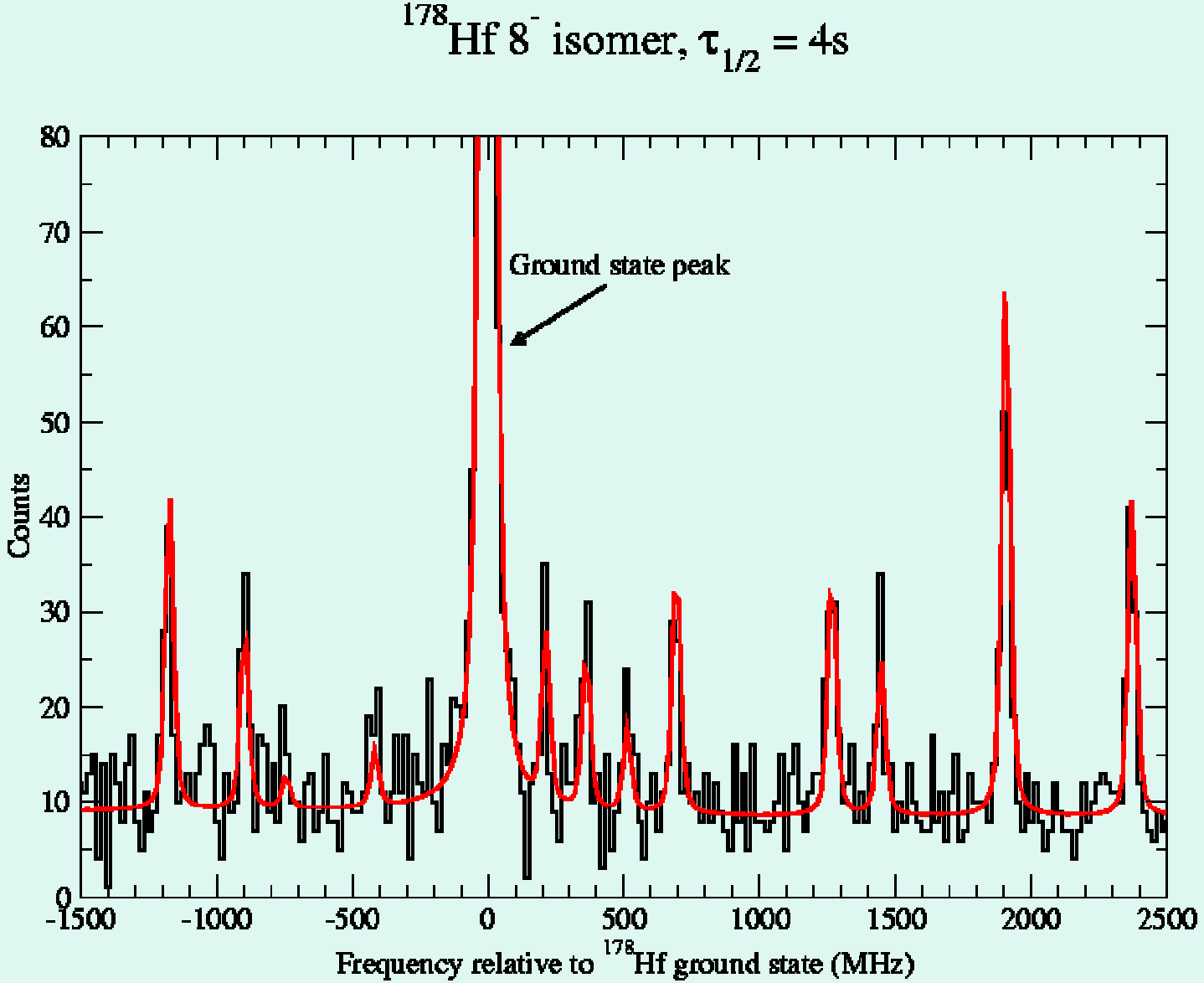

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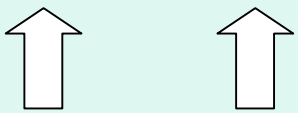
# All results:

| Y | $I$ | $\mu$ ($\mu_N$) | $Q_s$ (b) | $Q_0$ (b) | $\delta\langle r^2\rangle^{97m1,A}$ |
|---|---|---|---|---|---|
| 97m1 | $\frac{9}{2}$ | +5.87(5) | −0.76(8) | −1.40(15) | |
| 97m2 | $\frac{27}{2}$ | +5.64(5) | −1.21(14) | −1.50(17) | −0.101(1) |
| **Ba** | $I$ | $\mu$ ($\mu_N$) | $Q_s$ (b) | $Q_0$ (b) | $\delta\langle r^2\rangle^{130g,A}$ |
| 130g | 0 | — | — | +3.419(24) | |
| 130m1 | 8 | −0.043(28) | +2.77(30) | +3.95(43) | −0.0473(30) |
| **Yb** | $I$ | $\mu$ ($\mu_N$) | $Q_s$ (b) | $Q_0$ (b) | $\delta\langle r^2\rangle^{170g,A}$ |
| 176g | 0 | — | — | +7.30(13) | |
| 176m1 | 8 | −0.151(15) | +5.30(8) | +7.55(11) | −0.0224(1) |
| **Lu** | $I$ | $\mu$ ($\mu_N$) | $Q_s$(b) | $Q_0$ (b) | $\delta\langle r^2\rangle^{177g,A}$ |
| 177g | $\frac{7}{2}$ | +2.239(7) | +3.39(3) | +7.26(6) | |
| 177m1 | $\frac{23}{2}$ | +2.308(11) | +5.71(5) | +7.33(6) | −0.035 |
| **Hf** | $I$ | $\mu$ ($\mu_N$) | $Q_s$ (b) | $Q_0$ (b) | $\delta\langle r^2\rangle^{179g,A}$ |
| 178g | 0 | — | — | +6.961(43) | |
| 178m1 | 8 | +3.10(1) | +4.99(4) | +7.11(6) | −0.0394(1) |
| 178m2 | 16 | +8.16(4) | +6.00(7) | +7.20(8) | −0.0946(22) |



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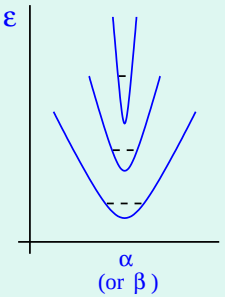
# All the spin-aligned isomers measured show decreases in mean square charge radii despite increases in Qo

**Why?**

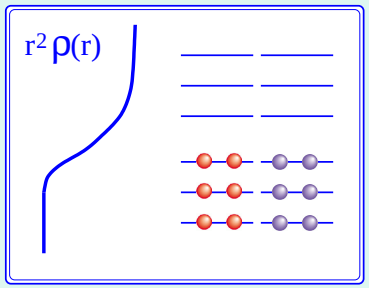
$\Rightarrow$ $\langle\beta^2\rangle - \langle\beta\rangle^2$ reduction?

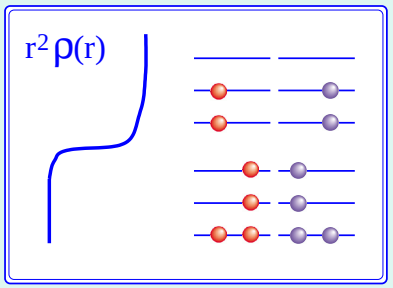
**IS, B(E2)** **Qs**

**178g,m1,m2 Hf**




$\Rightarrow$ Loss of pairing?



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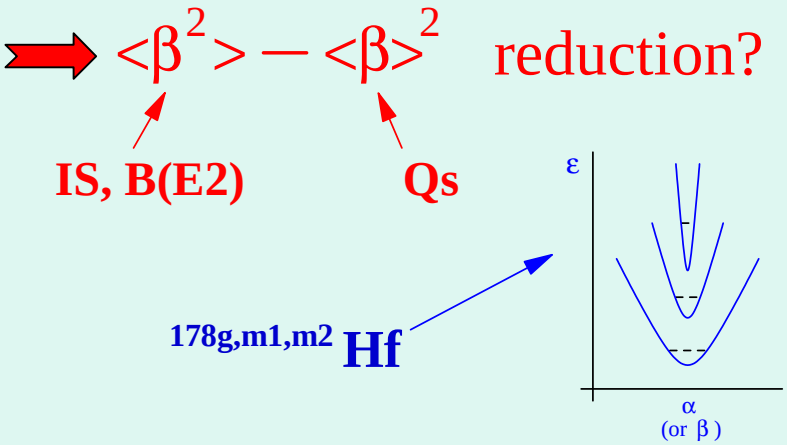
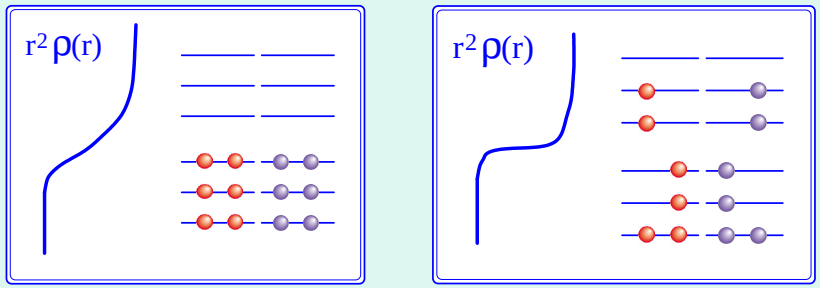
# Can you tell them apart??




Loss of pairing?



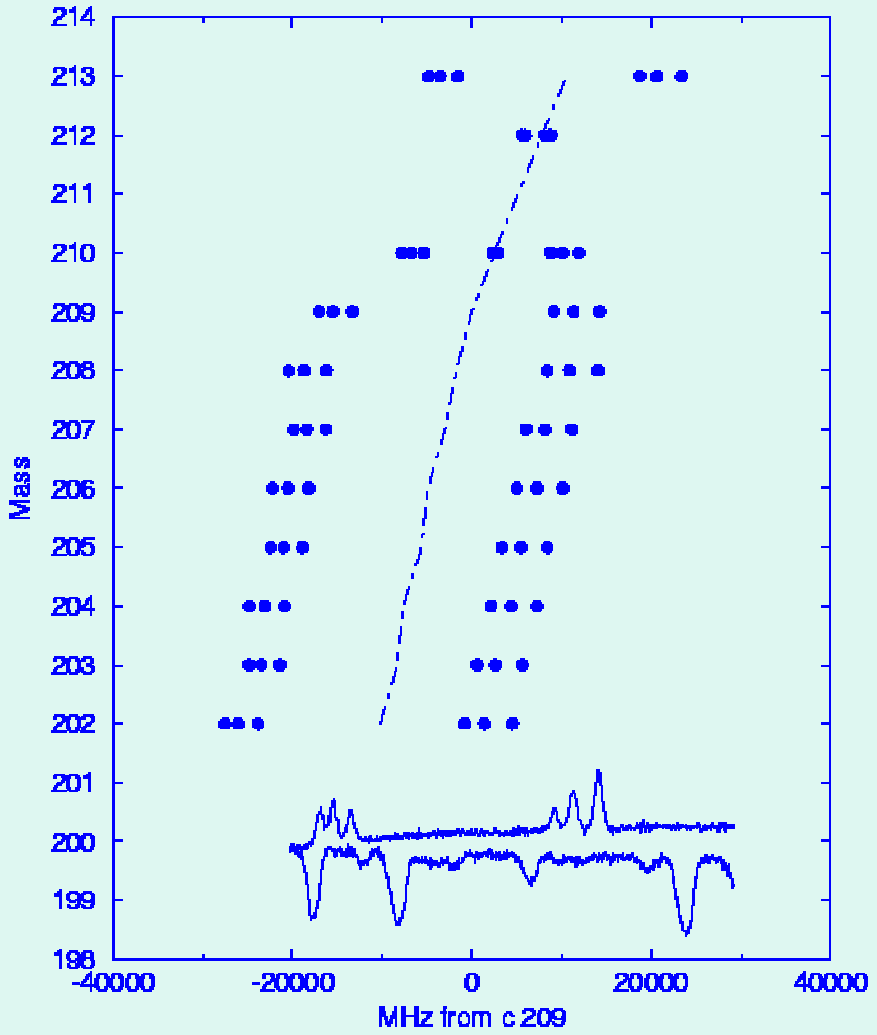

**Yes – spherical spin-aligned isomers**

# Next – Bismuth

**November 20th – 24th**
**JYFL**

**$^{209}$Bi(p,pxn)**

$^{204}$Bi ($10^{-}$, 13 ms)
$^{204}$Bi ($17^{+}$, 1.07 ms)
$^{204}$Bi (gs, 12hrs)
$^{203}$Bi (1/2, 300 ms)
$^{203}$Bi (gs, 2hrs)



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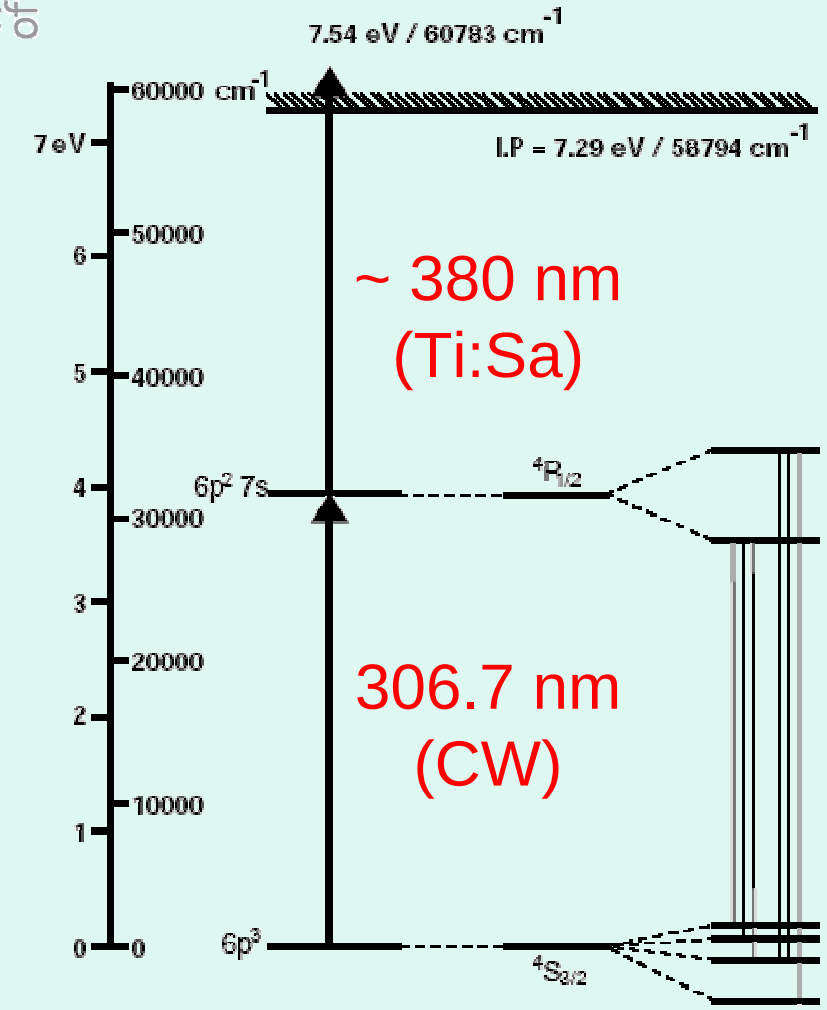
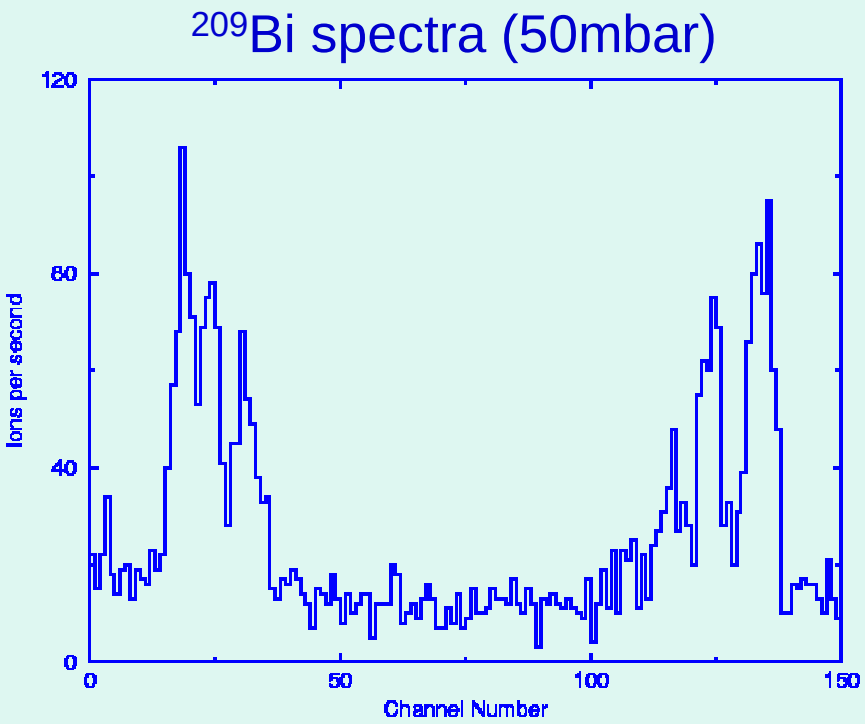
# CW + Ti:Sa intra-guide



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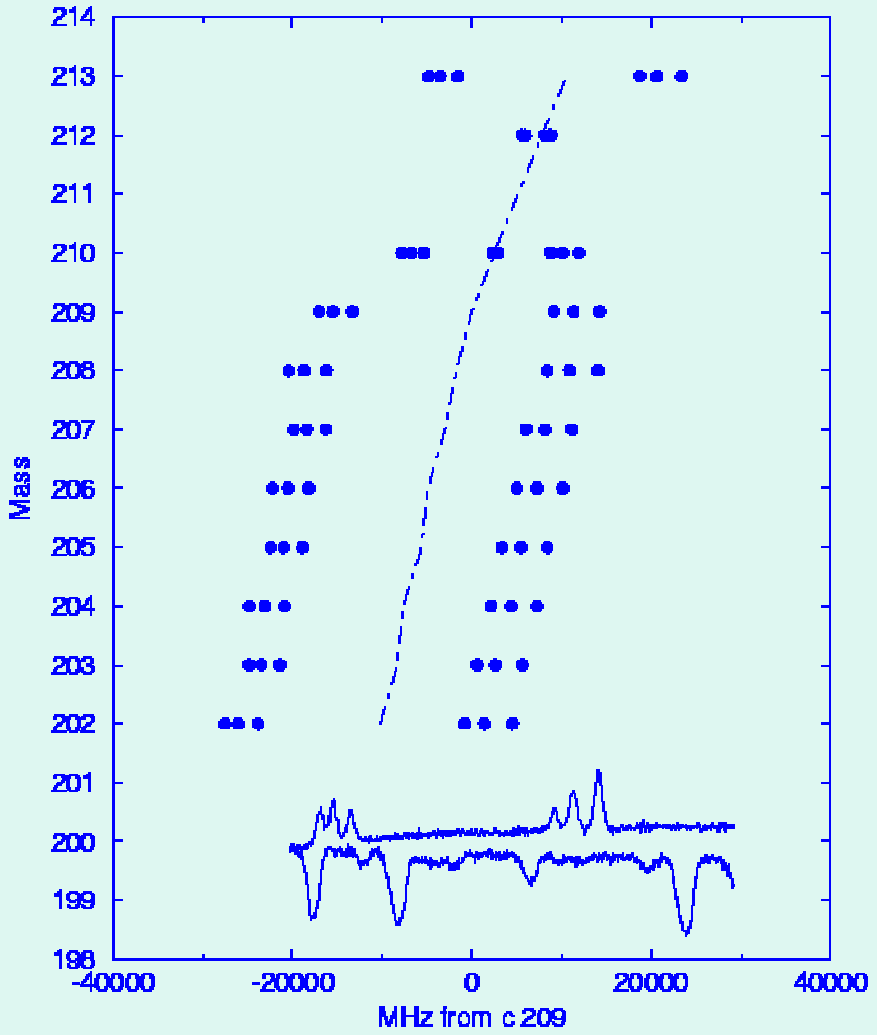
# November 20th – 24th

# $^{209}$Bi(p,pxn)

**We can have substantial partial pressures of $^{209}$Bi in the gas..**

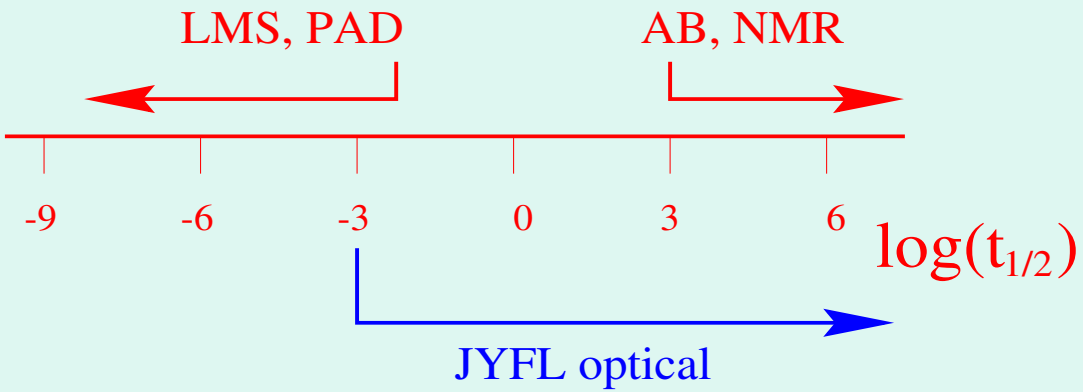
**…and a collinear RIS back-up**




JOHANNES GUTENBERG UNIVERSITÄT MAINZ

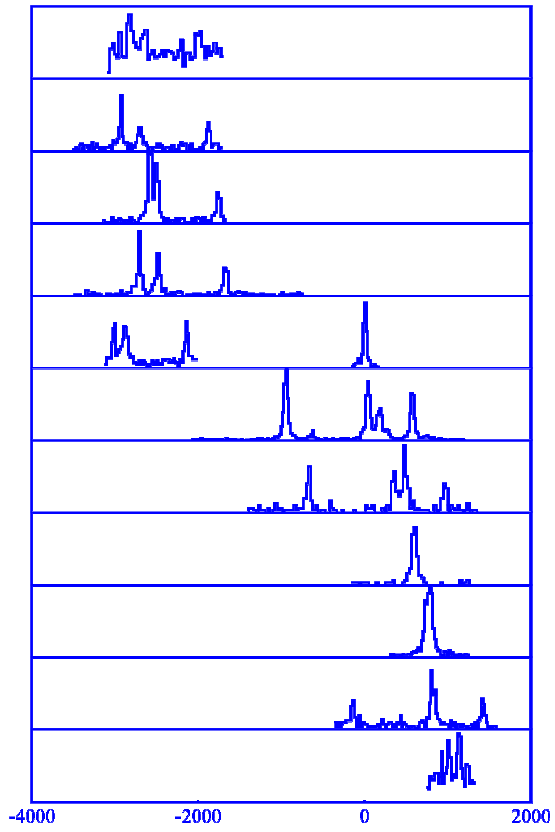
# For LaSpec…

- **Direct measurements on high-K isomers…**
- **Calibration of non-optical results;**
  **B-fields in LMS etc**

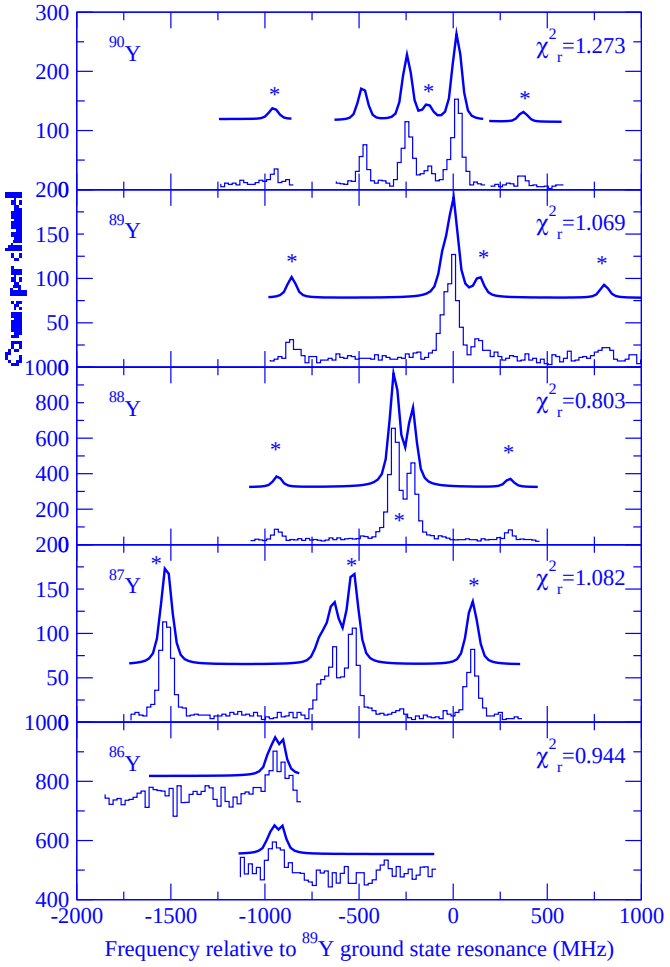


# (Yttrium)

## Fission fragments




## ..and neutron deficient



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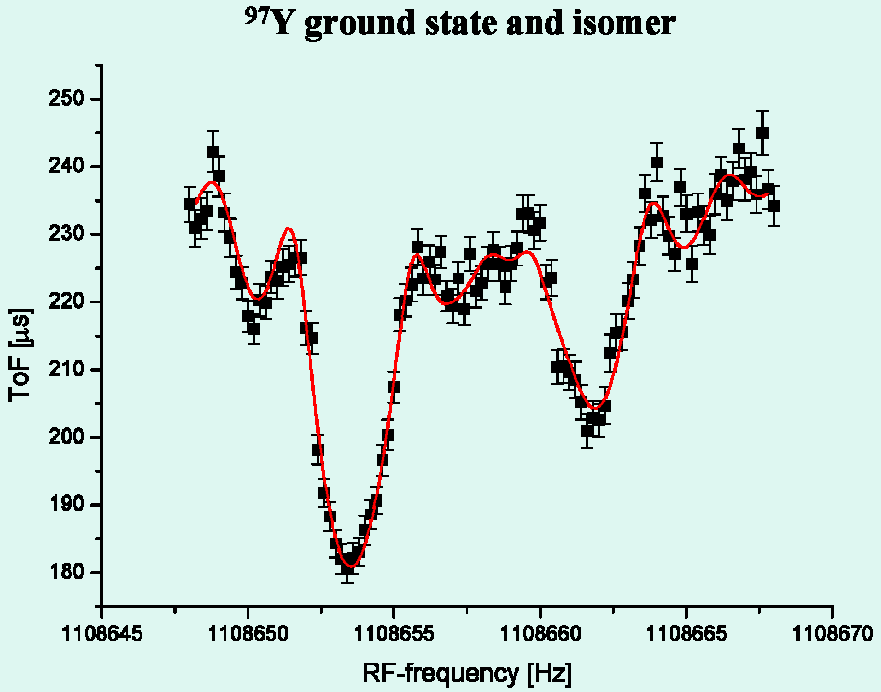
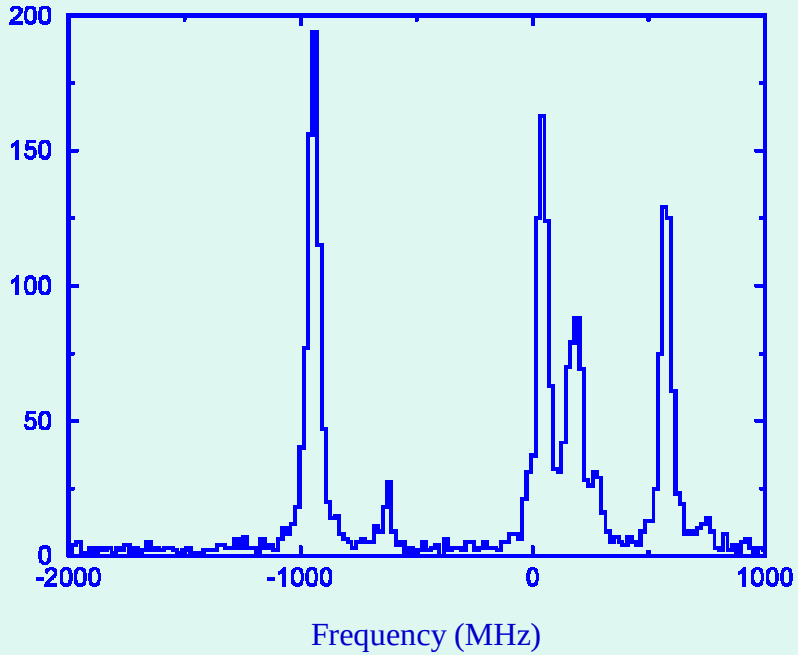
# "Complete" spectroscopy:

Trap time of flight measurement of ground and isomer state masses

+

Laser measurement of hyperfine structures of ground and isomeric states

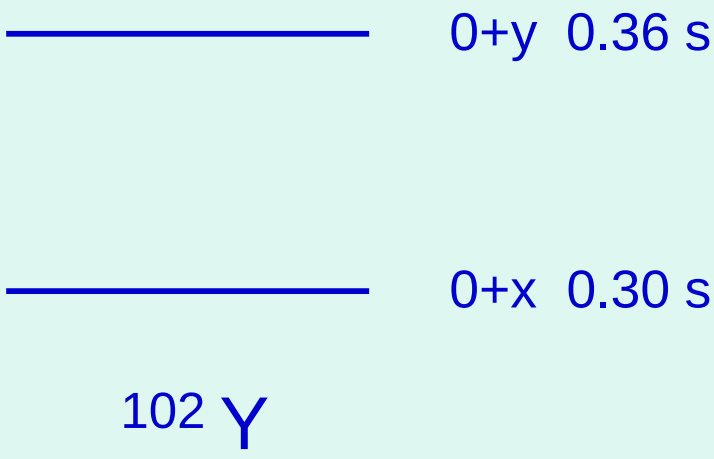


Trap time of flight measurement of ground and isomer state masses

+

Laser measurement of hyperfine structures of ground and isomeric states



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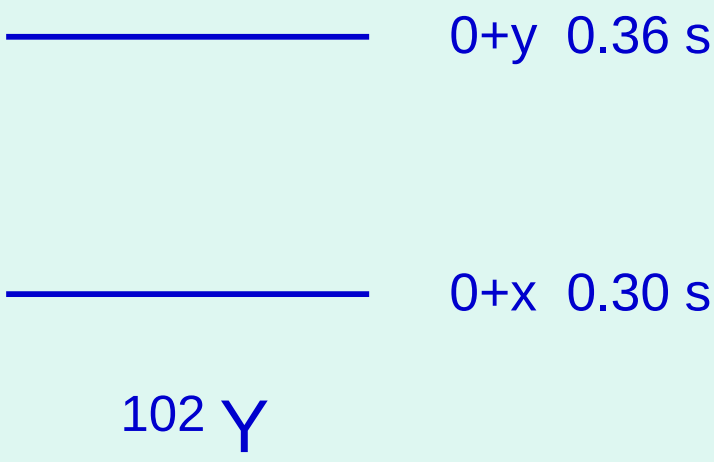
Mass measurement

+

Laser measurement

+

Trap assisted spectroscopy




**Vital if identification of the ground state is the goal**

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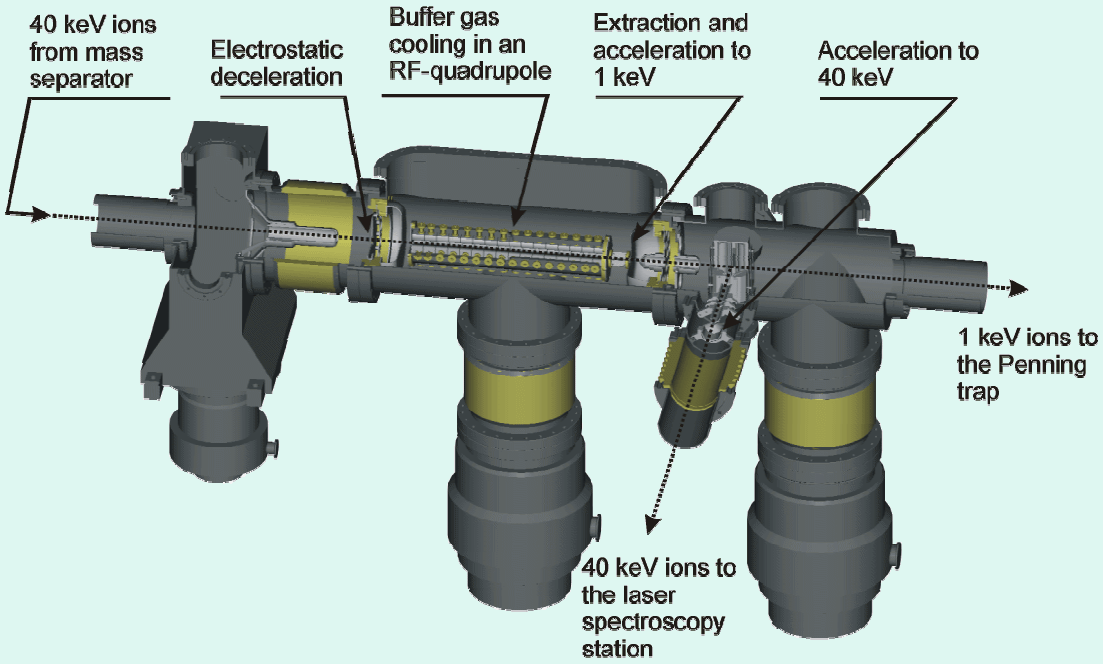
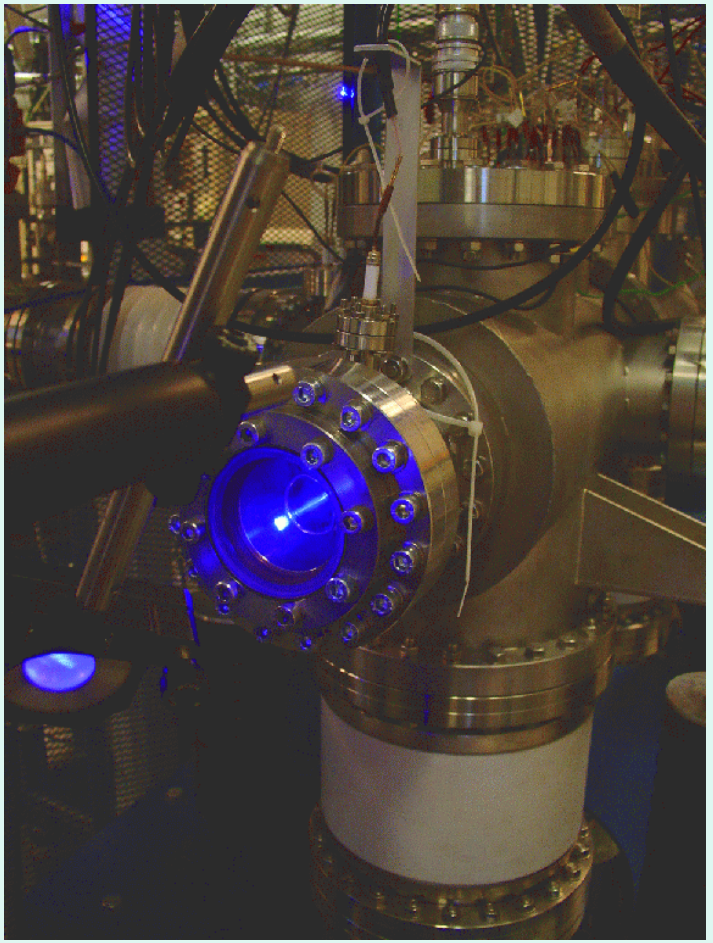
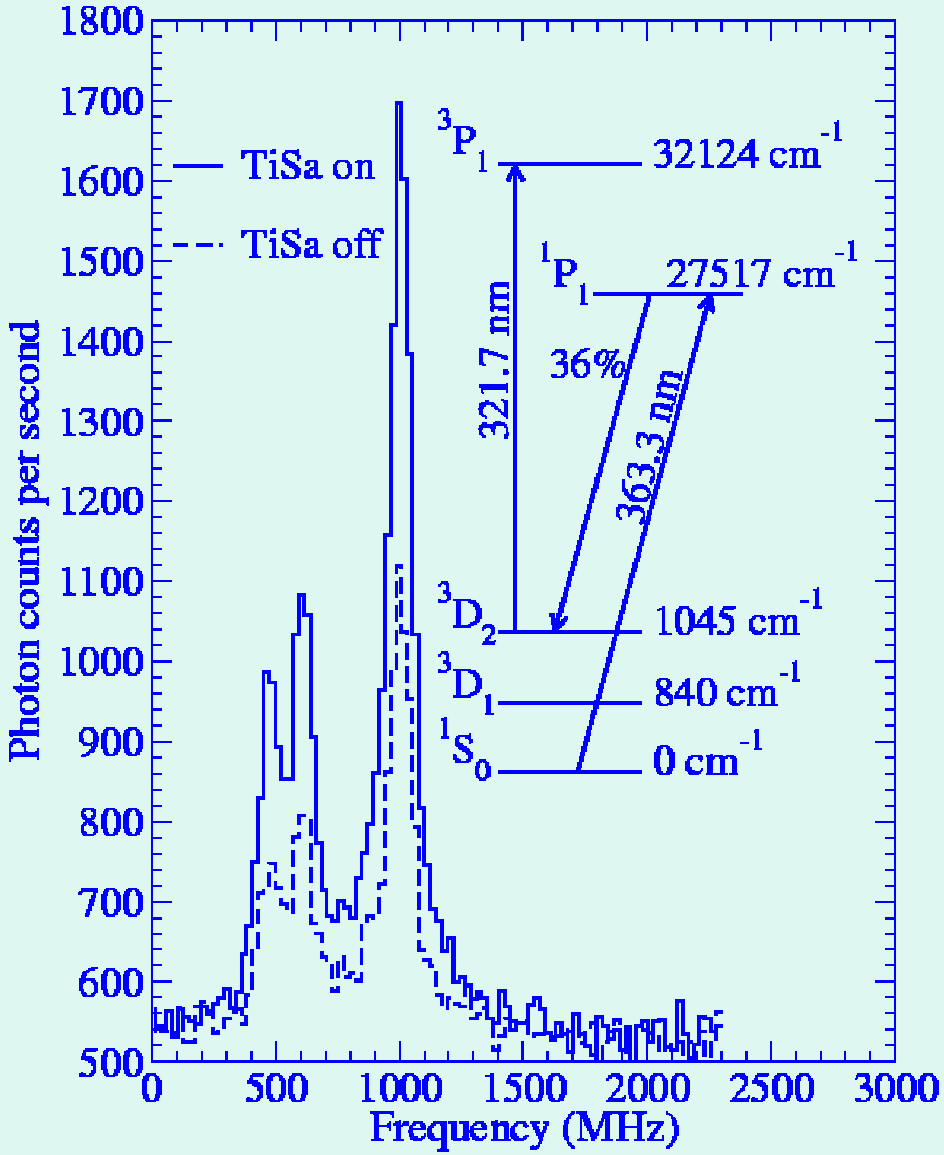
# Pumping in the cooler:






**363.3nm pumping (40% transfer)**

**1pA of $^{89}$Y continuous beam**

**University of Manchester**

**J Billowes, P Campbell, B Cheal, B A Marsh and B W Tordoff**

**University of Birmingham**

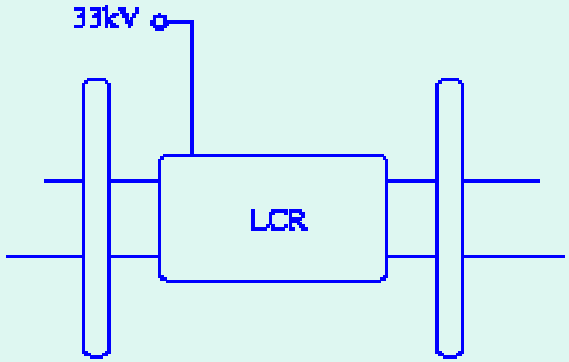
**G Tungate, D H Forest, M D Gardner and M Bissell**

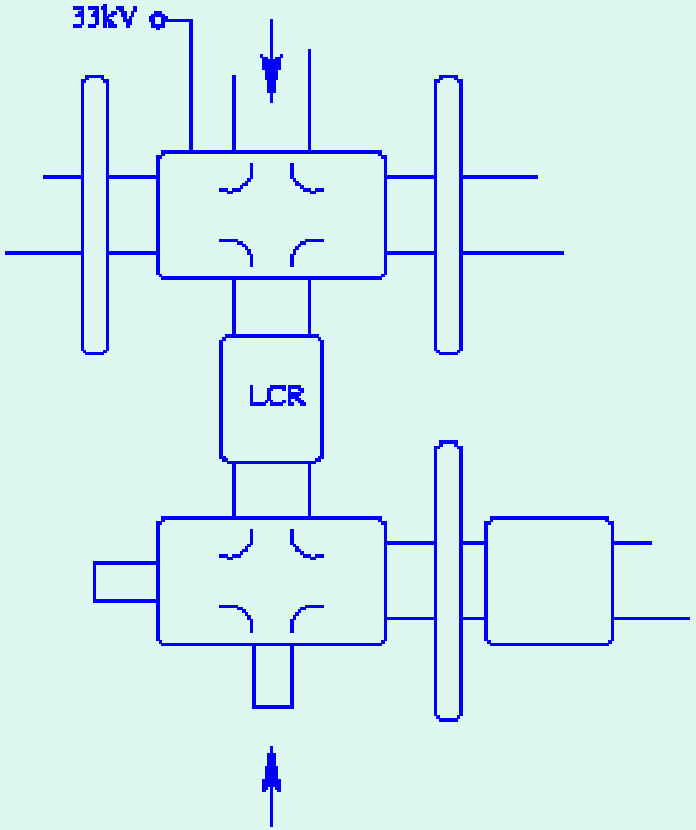
**University of Jyvaskyla**

**J Aysto, A Jokinen, ID Moore, H Penttila, T Eronen, S Rinta-Antila and T Kessler**

**(KT Flanagan, J Huikari, R Moore, A Nieminen)**

# ‘Slow’ fast beams



MANCHESTER 1824
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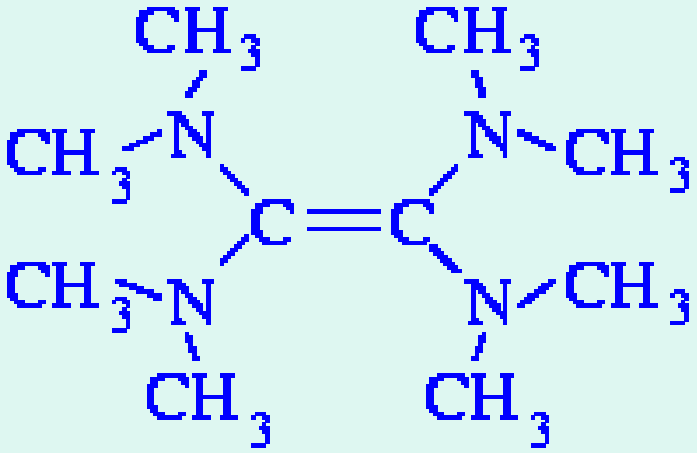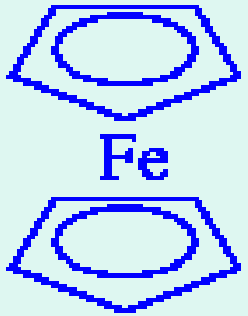
# Charge exchange alternatives?