

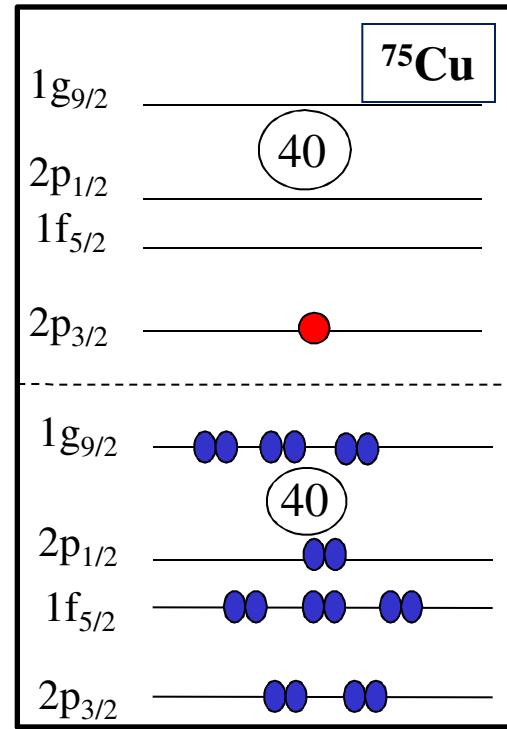
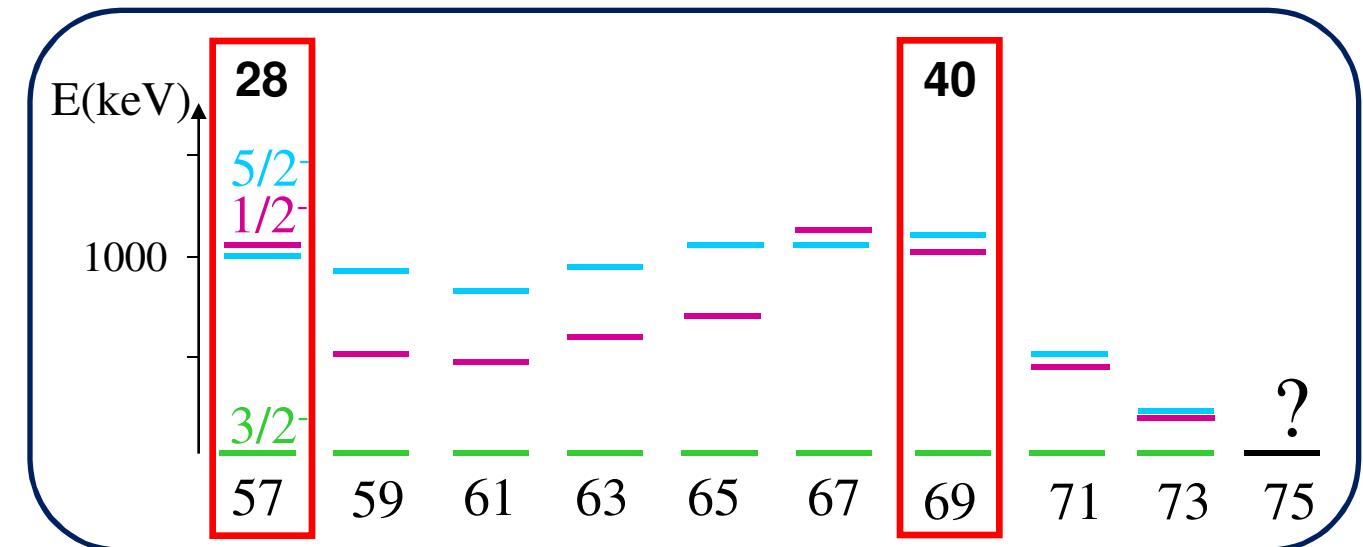
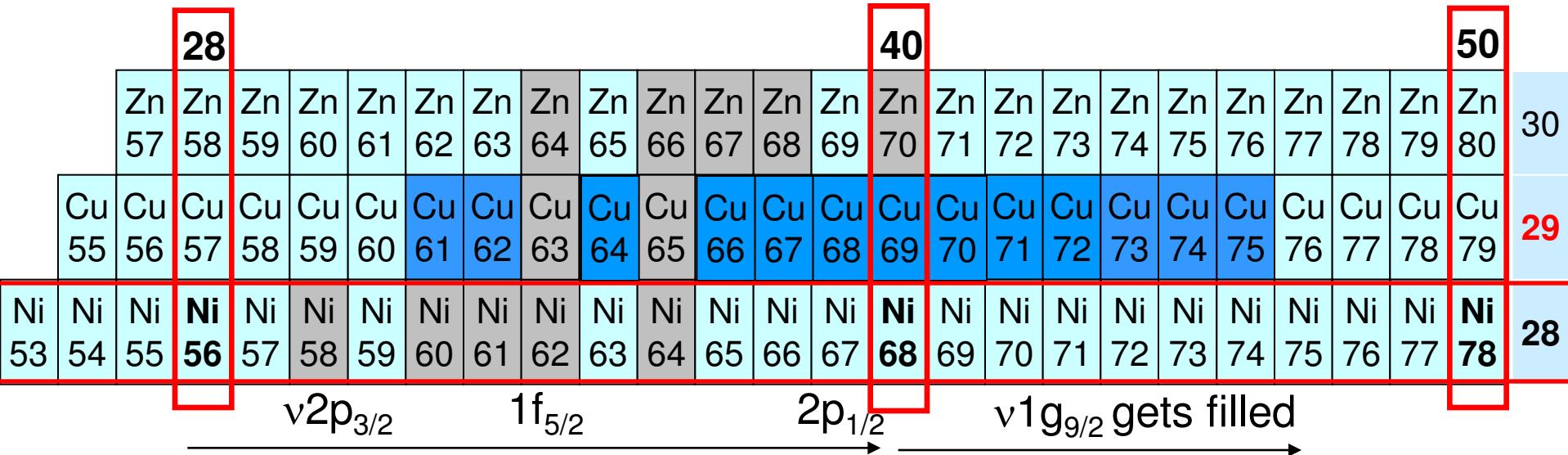


# Magnetic and Quadrupole moments of Cu isotopes With collinear laser spectroscopy

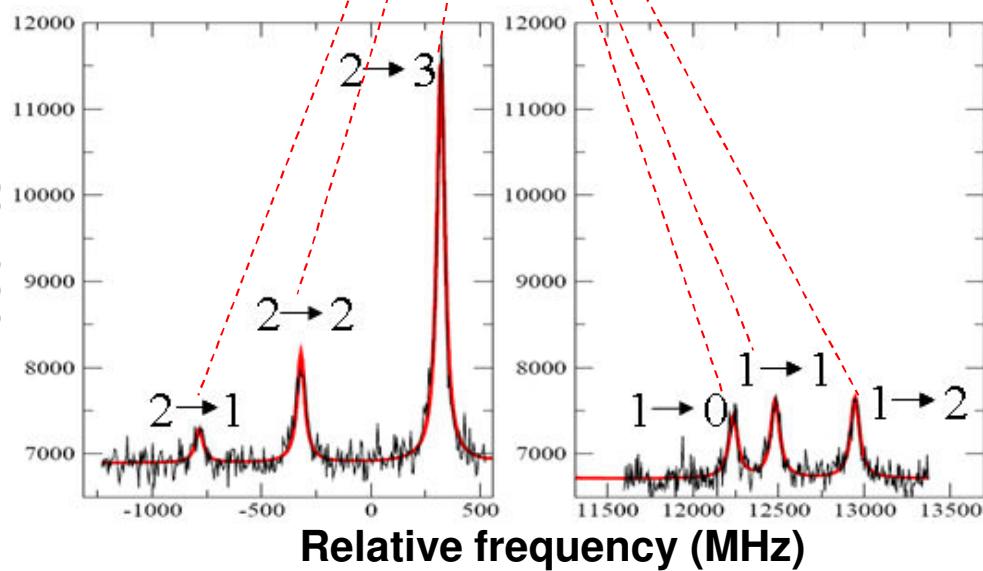
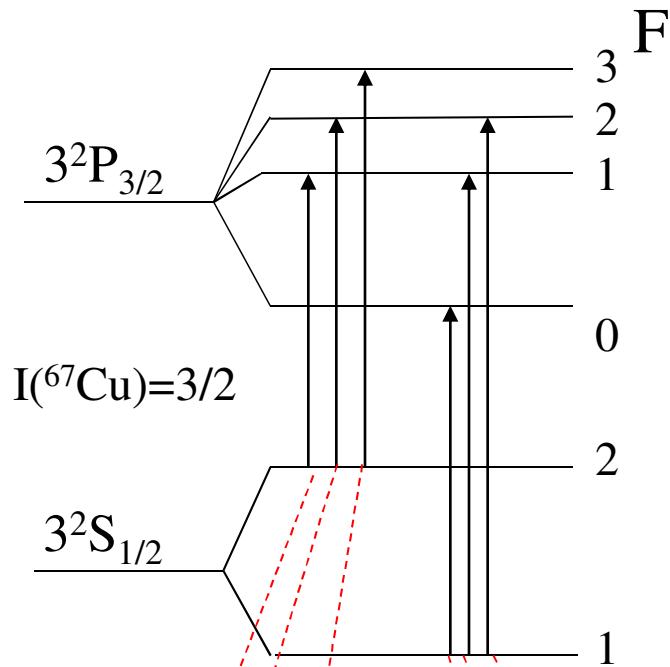
Pieter Vingerhoets  
18/11/2009



# Motivation: The region of the nuclear chart



# Laser spectroscopy: experimental technique



$$F = I + J$$

$$\Delta E = \frac{1}{2} AC + B \frac{(3/4)C(C+1) - I(I+1)J(J+1)}{2I(2I-1)J(2J-1)}$$

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

$$\mu_I = \frac{AI}{A_{ref} I_{ref}} \mu_{ref}$$

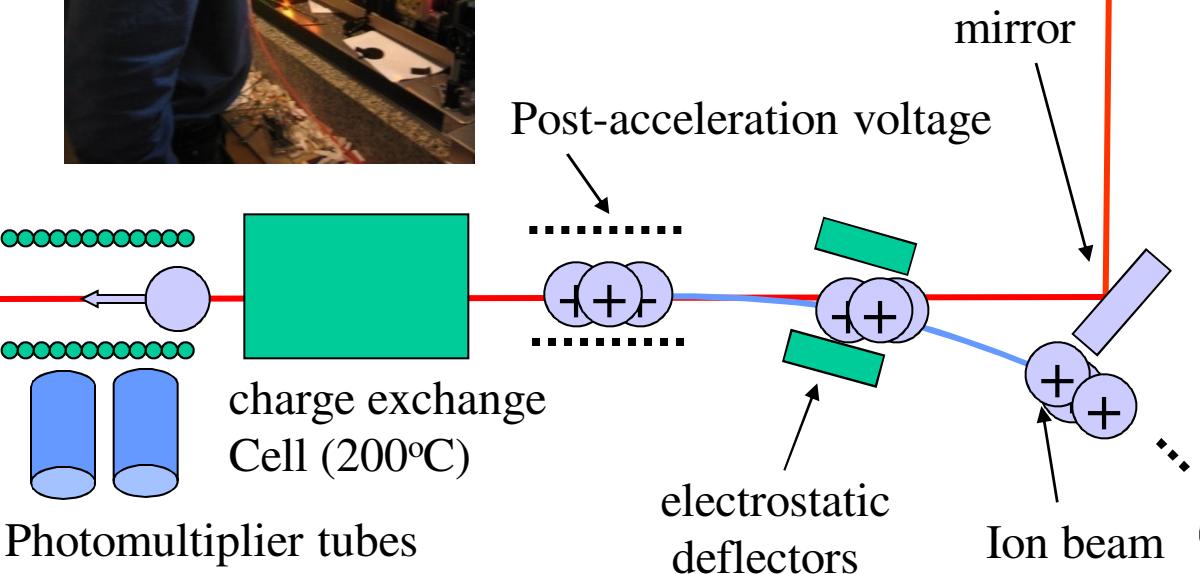
$$Q = \frac{B}{B_{ref}} Q_{ref}$$

# Laser spectroscopy: experimental setup

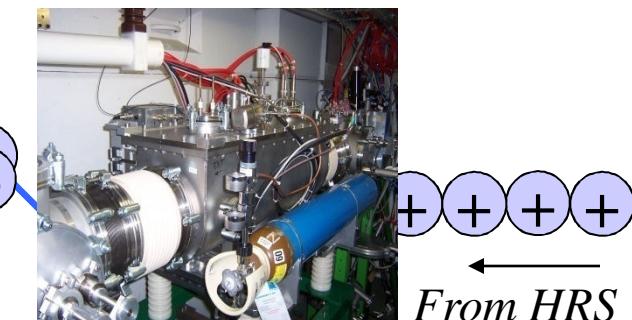
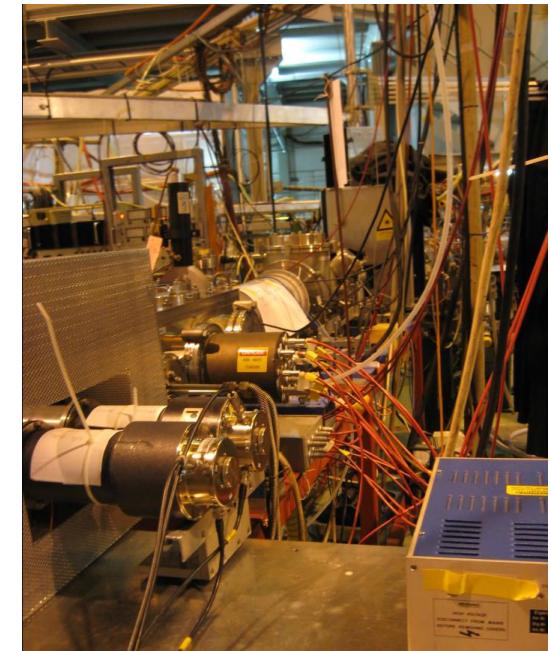


Dye laser

Wavelength 648nm,  
Doubled to 324nm



Photomultiplier tubes



RFQ beam cooler/buncher

$$\nu_{laser} = \nu_{transition} \frac{1 \pm \beta}{\sqrt{1 - \beta^2}}$$

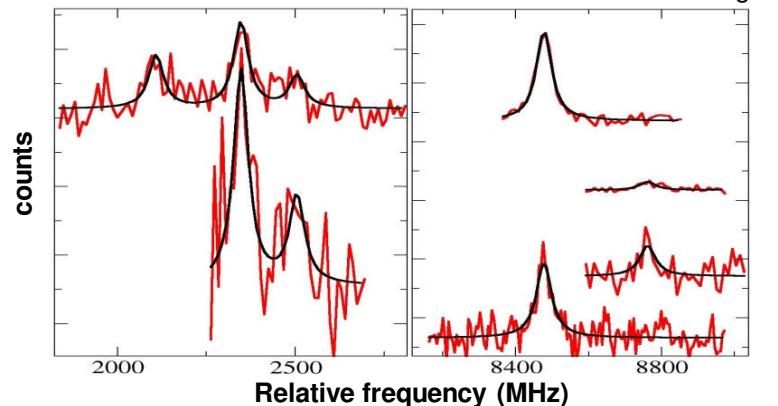
$$\beta = \sqrt{1 - \frac{M_0^2 c^4}{(Uq + M_0 c^2)^2}}$$

Varying post-acceleration voltage to scan frequency:

# $^{72}\text{Cu}$ : spin confirmation of 2, a challenge for nuclear shell model

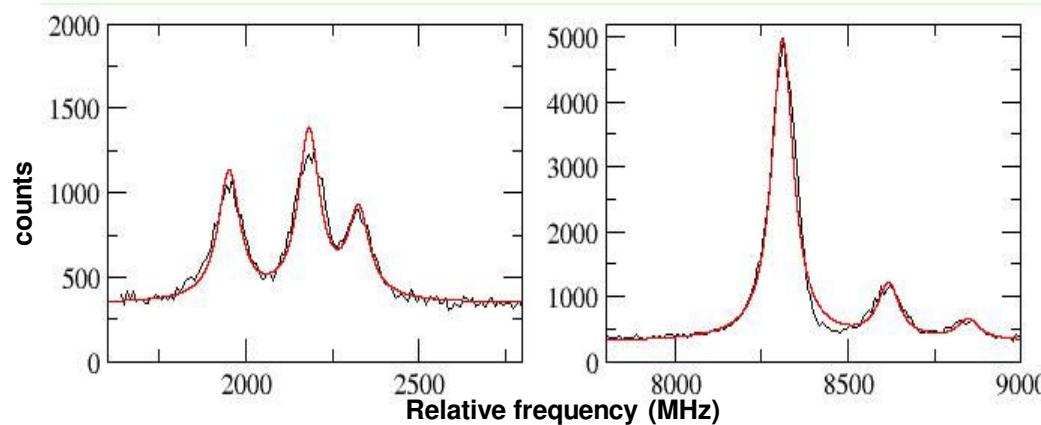
2007, without ISCOOL buncher

K. Flanagan



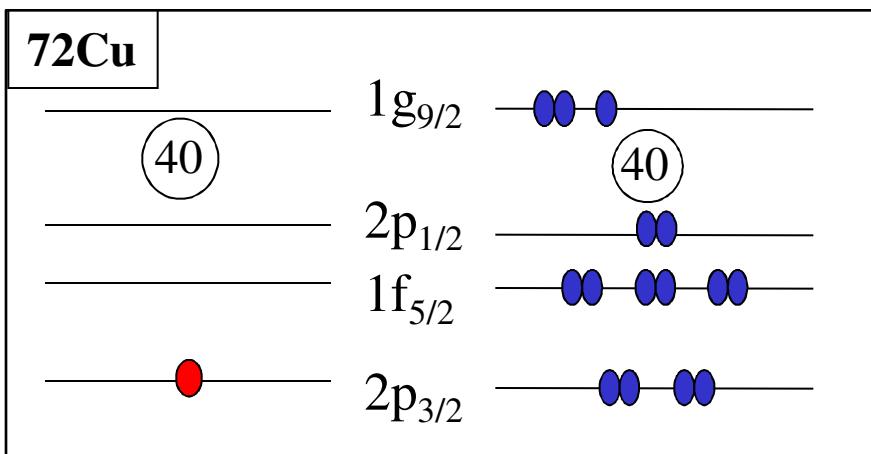
>40 hours measured, 5 out of 6 peaks resolved

2008, with ISCOOL buncher

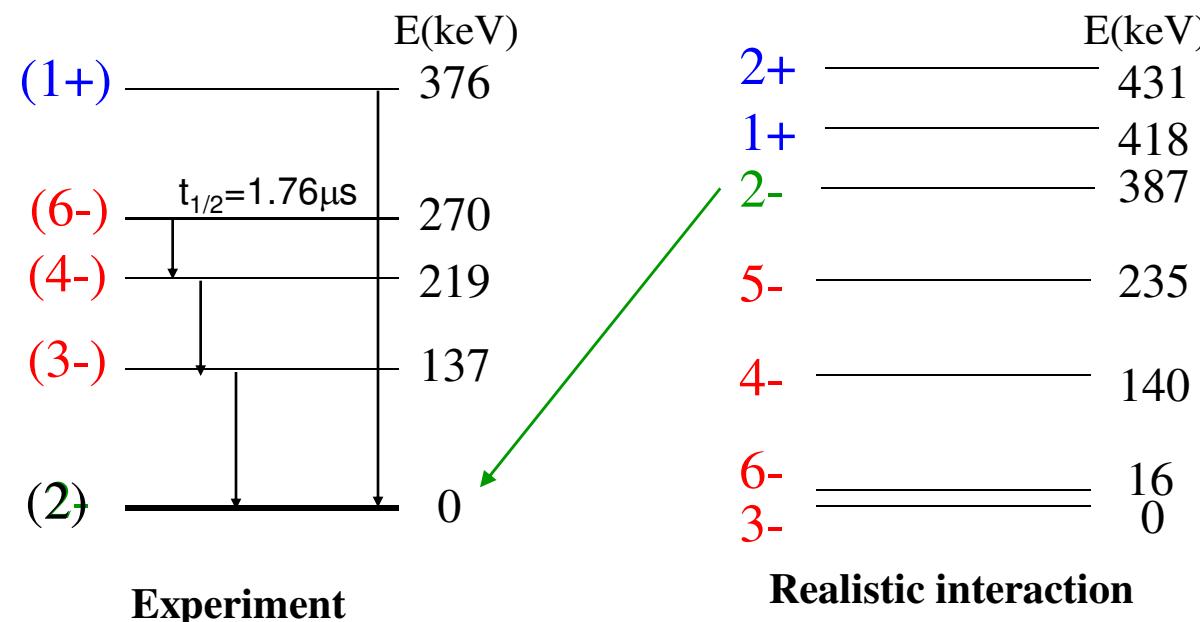


2.5 hours measured, 6 out of 6 peaks resolved

# $^{72}\text{Cu}$ : spin confirmation of 2, a challenge for nuclear shell model



$(\pi p_{3/2} \nu g_{9/2}^3) \rightarrow (3,4,5,6)^-$   
 $(\pi f_{5/2} \nu g_{9/2}^3) \rightarrow (2,\dots,7)^-$   
 $(\pi p_{3/2} \nu p_{1/2}^{-1} g_{9/2}^4) \rightarrow (1,2)^+$



What would we expect?  
empirical magnetic moments

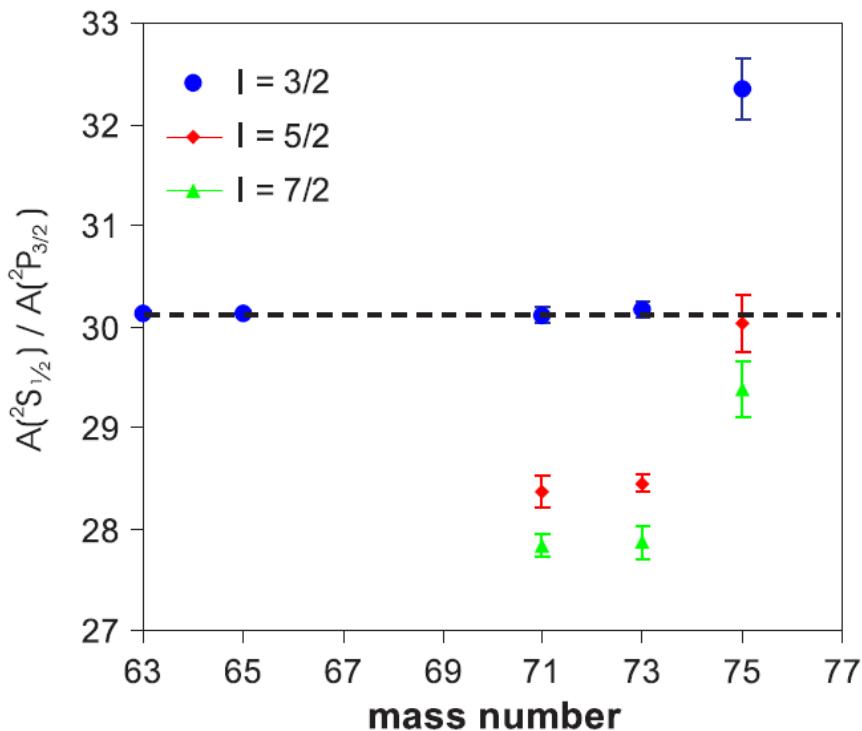
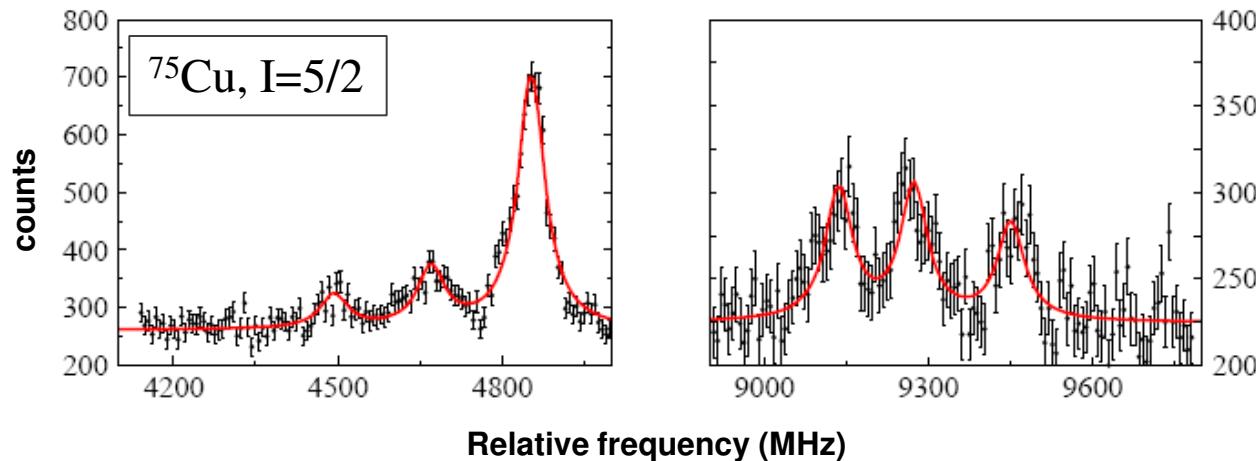
$\mu(\pi f_{5/2} \nu g_{9/2}^3; 2^-)$ :  
 $\mu_{\text{emp}}(2^-) = -1.94 \mu_N$

$\mu(\pi p_{3/2} \nu p_{1/2}^{-1} g_{9/2}^4; 2^+)$ :  
 $\mu_{\text{emp}}(2^+) = +1.44 \mu_N$

$\mu_{\text{exp}}(72\text{Cu}) = -1.3460(5) \mu_N$

# $^{75}\text{Cu}$ : Spin assignment

Flanagan et al., PRL103, 142501 (2009)



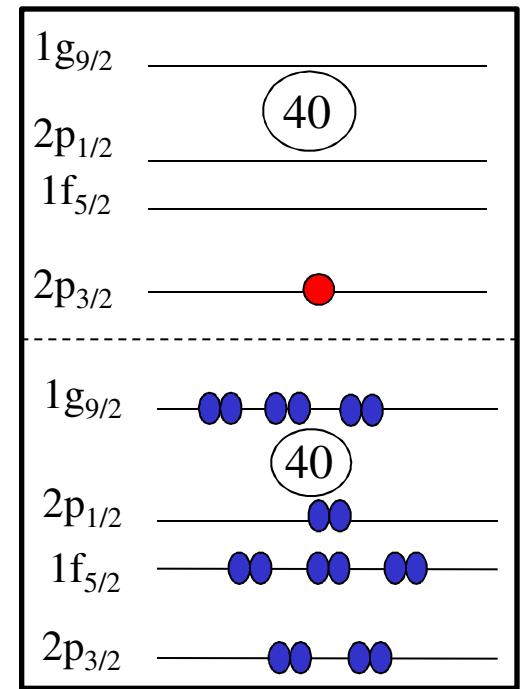
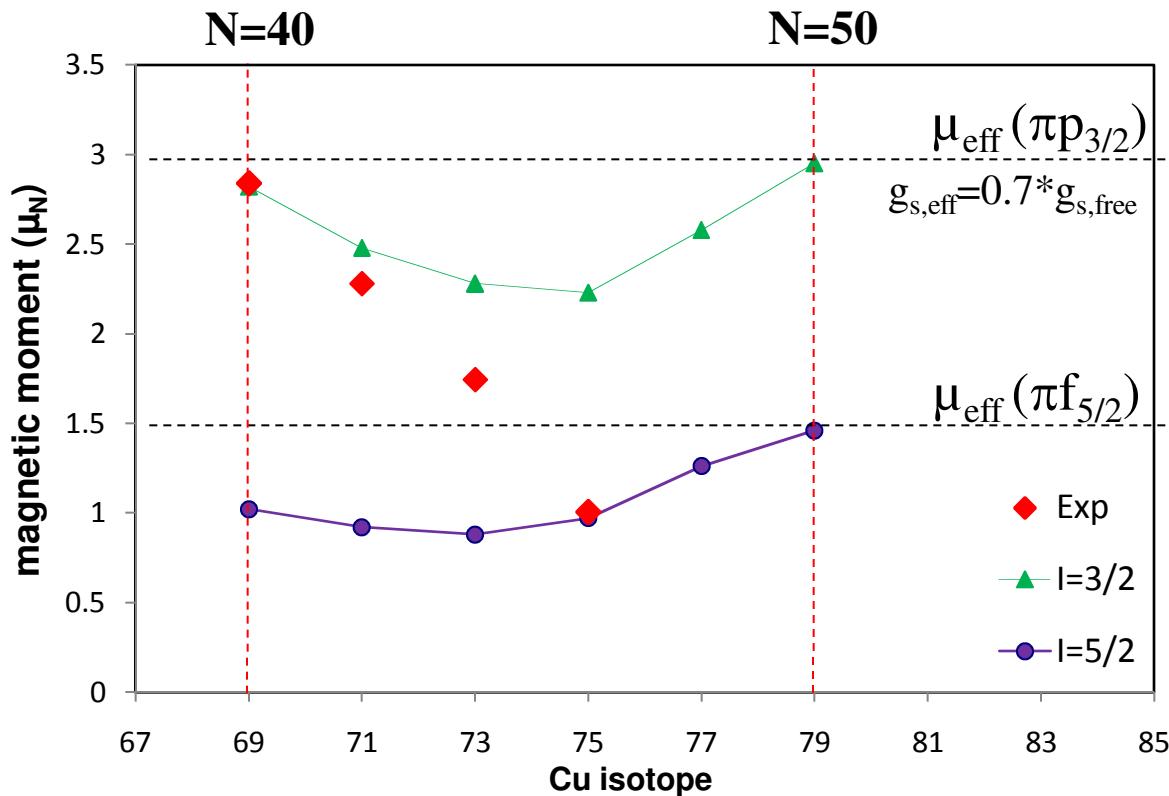
- Yield  $\sim 5 \cdot 10^4$  ions/ $\mu\text{C}$
- Accumulation time 100ms
- Background reduction of  $10^3$

$$A(^2\text{S}_{1/2}) = +1592(1) \text{ MHz}$$
$$B(^2\text{P}_{3/2}) = -34(2) \text{ MHz}$$

**SPIN OF  $^{75}\text{Cu}$  IS  $5/2$**

# Comparison odd magnetic moments with theory

Flanagan *et al.*, PRL103, 142501 (2009)

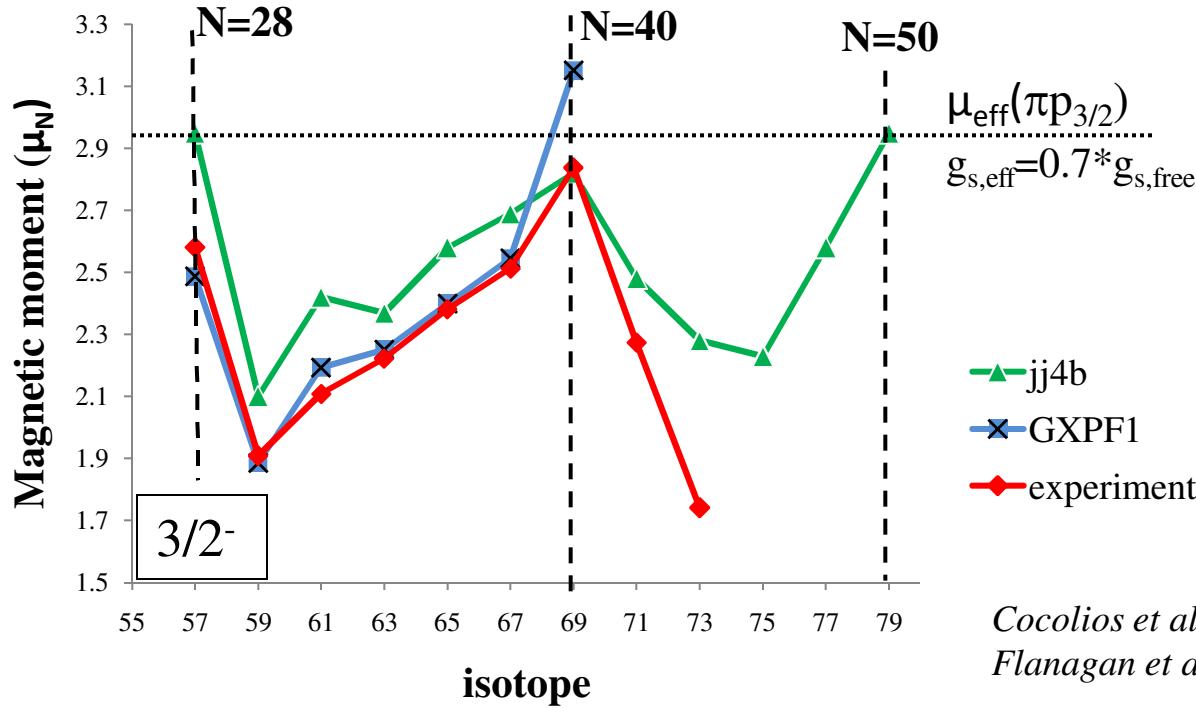


**Model space:**  $1f_{5/2}, 2p_{3/2}, 2p_{1/2}, 1g_{9/2}$  for both proton and neutron orbits,  $^{56}\text{Ni}$  core

**Interaction:** jj4b, by Brown and Lisetskiy(private communication),  
 $g_{s,\text{eff}} = 0.7 * g_{s,\text{free}}$

# Comparison with theoretical calculations

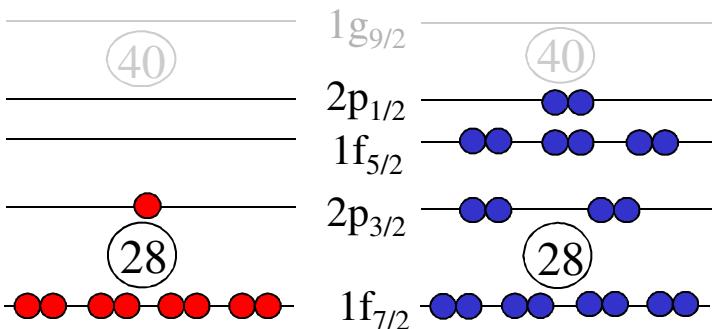
## odd-Cu magnetic moments



GXPF1

$g_{s,\text{eff}} = 0.9 * g_{s,\text{free}}$

**$^{69}\text{Cu}$**

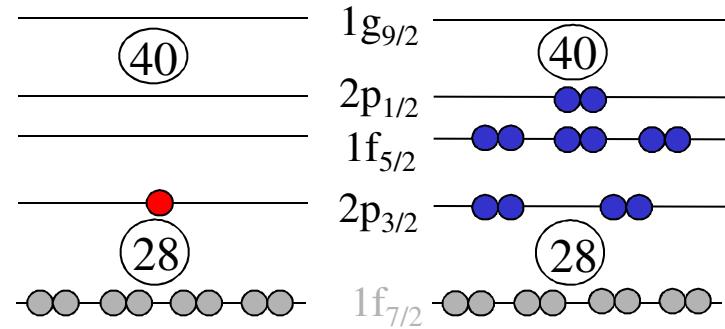


Honma et al., private comm.

jj4b

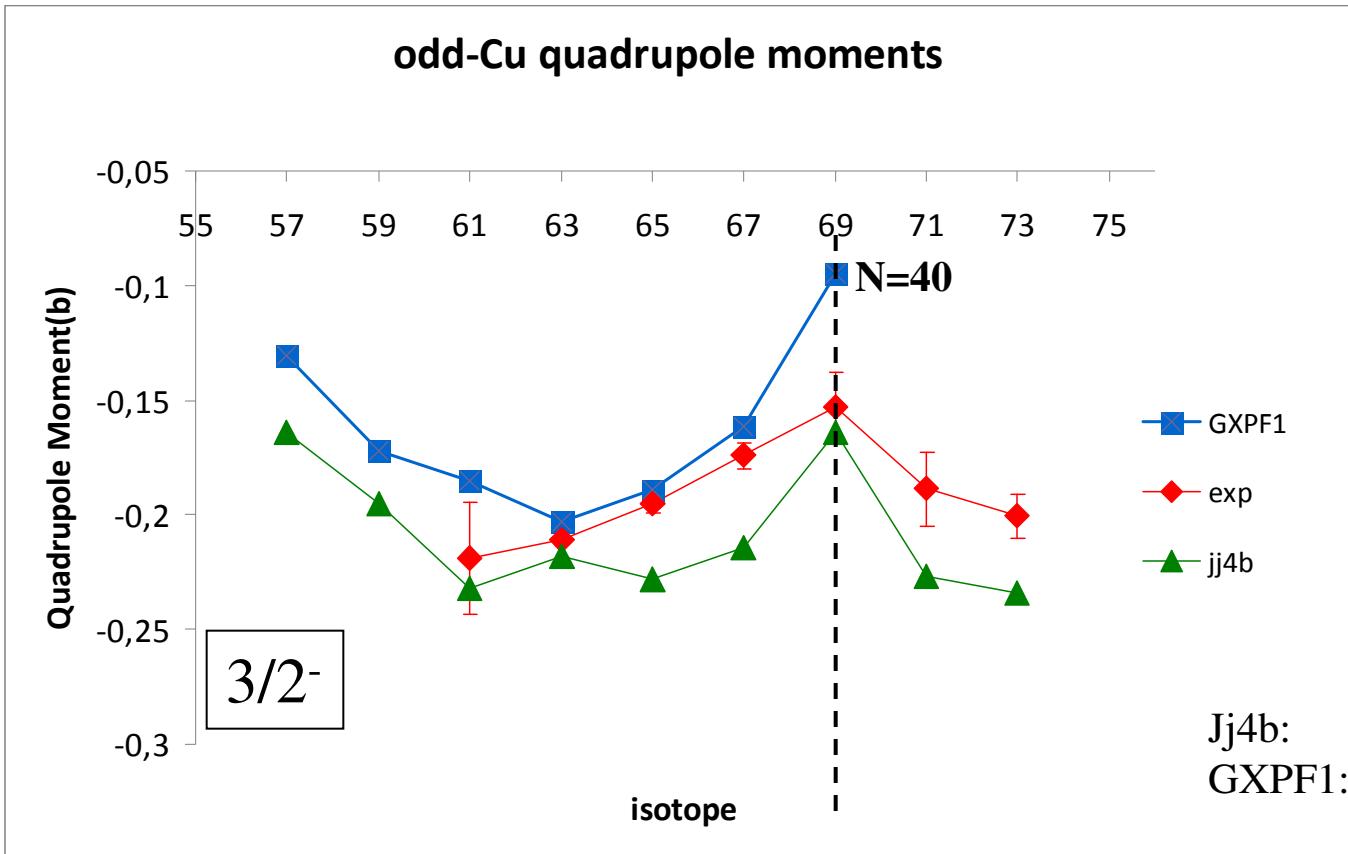
$g_{s,\text{eff}} = 0.7 * g_{s,\text{free}}$

**$^{69}\text{Cu}$**



A. Brown, A. Listetskiy, private comm.

# Comparison with theoretical calculations



- Jj4b is doing a fair job in reproducing the trend
- Again N=40 behaves more or less like a magic shell closure
- No sign of increased deformation after N=40

# Conclusions and Outlook

## Conclusions

- The copper isotopes  $^{61}\text{Cu}$  -  $^{75}\text{Cu}$  have been measured at COLLAPS, ISOLDE. During the 2008 experiment 11 different isotopes were measured.
- **Background reduction of  $10^3$  and more** due to the RFQ beam cooler/buncher allows measurements on more exotic isotopes.
- The spin of  $^{72}\text{Cu}$  presents a challenge for shell model calculations
- N=40 exhibits magic properties for the magnetic and quadrupole moments thanks to parity considerations
- Quadrupole moments reveal no sign of increased deformation after N=40

## Outlook

- 9 shifts of beamtime on neutron-deficient Cu isotopes

# The Collaboration

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M.Kowalska<sup>9</sup>, J. Krämer<sup>4</sup>, A.Krieger<sup>4</sup>, E.Mane<sup>3</sup>, R. Neugart<sup>4</sup>, G. Neyens<sup>1</sup>, W.Nörtershäuser<sup>10</sup>,  
G.Ory<sup>1</sup>, A. Smolkowska<sup>1</sup>, G.Tungate<sup>6</sup>, M. Schug<sup>4</sup>, H. Stroke<sup>11</sup>, D.Yordanov<sup>4</sup>

THANK YOU !

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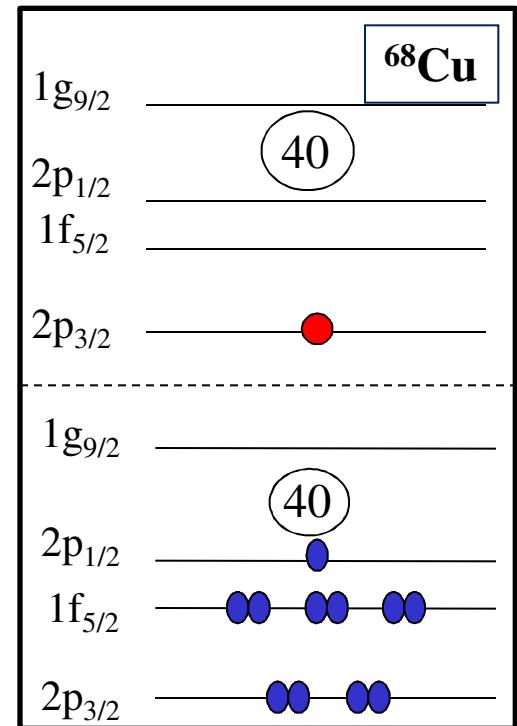
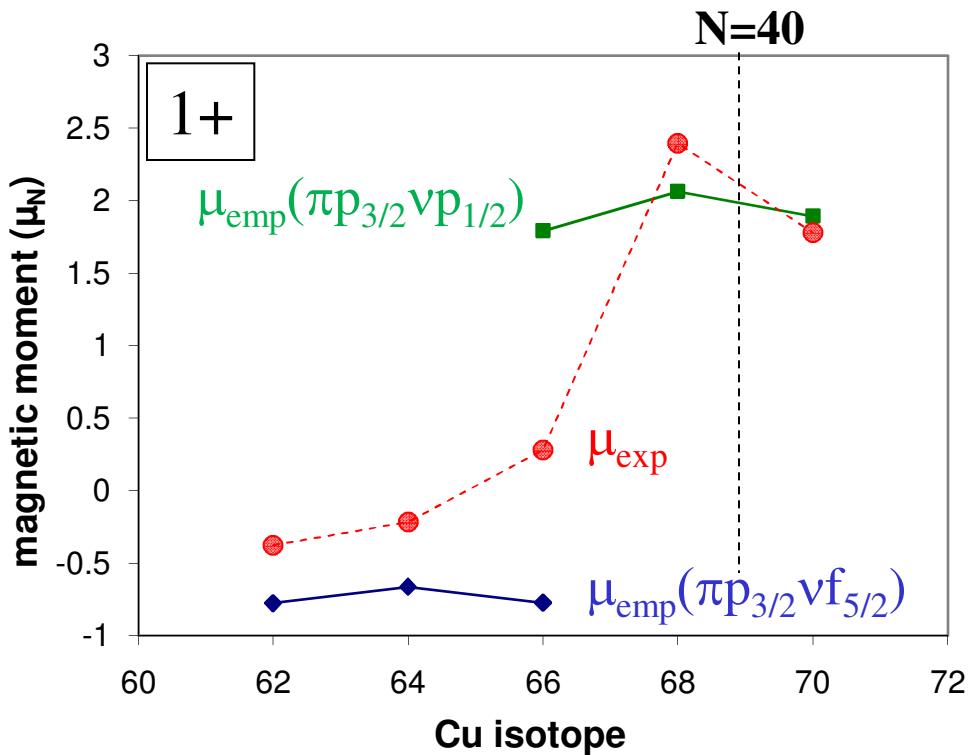
<sup>8</sup>*VSM, K.U. Leuven, Belgium*

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<sup>10</sup>*Institut für Kernchemie, Universität Mainz, Germany*

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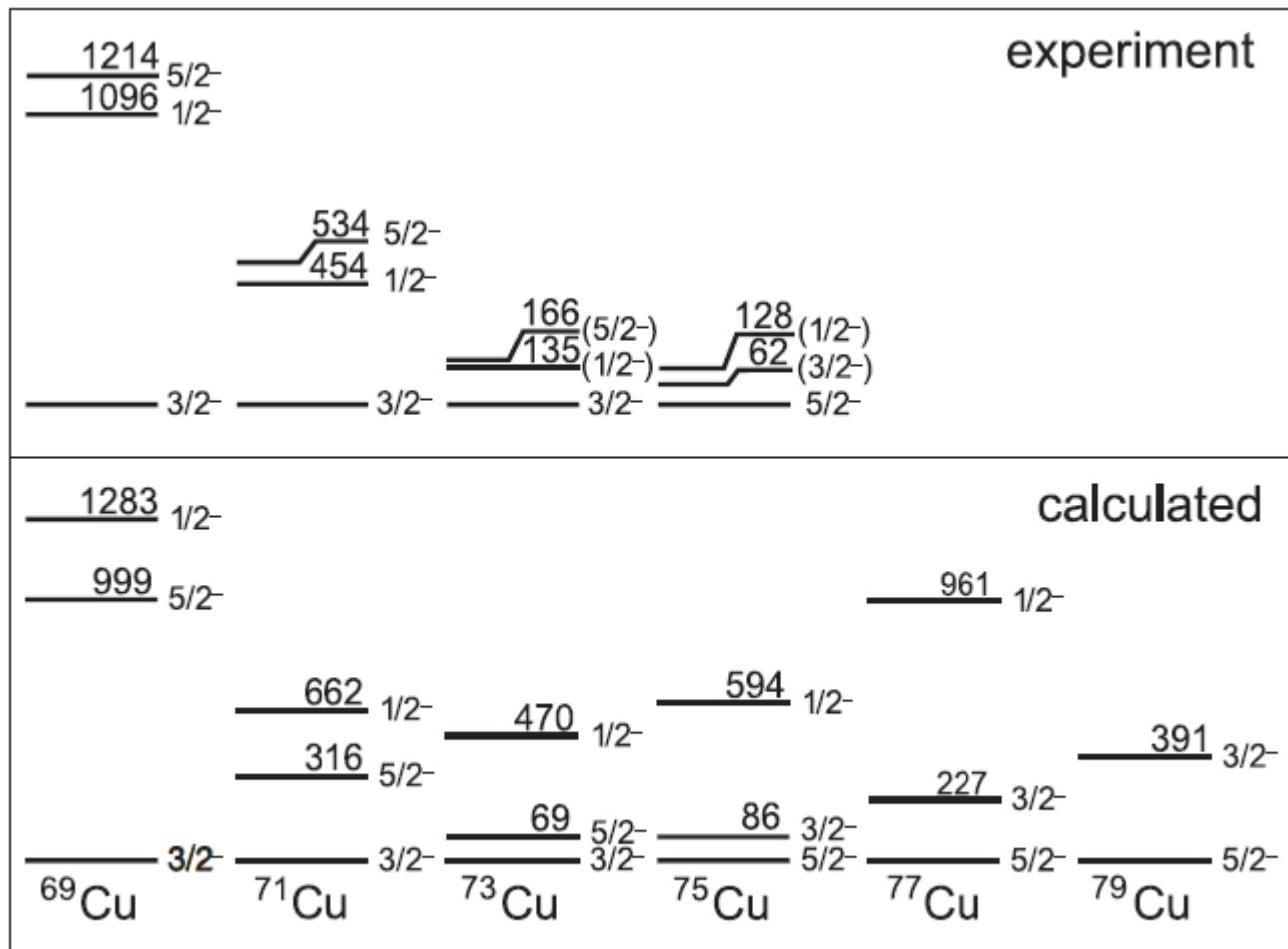
# Evolution of the 1+ magnetic moments



For  $^{68}\text{Cu}$ :  $\mu_p = \mu(^{69}\text{Cu})$   
 $\mu_n = \mu(^{67}\text{Ni})$

Assume weak proton-neutron coupling:

$$\mu(I) = \frac{I}{2} \left[ \frac{\mu_p}{j_p} + \frac{\mu_n}{j_n} + \left( \frac{\mu_p}{j_p} - \frac{\mu_n}{j_n} \right) \frac{j_p(j_p+1) - j_n(j_n+1)}{I(I+1)} \right]$$



- S. Franchoo et al., Phys.Rev. C 64,054308 (2001)  
 I. Stefanescu et al., Phys.Rev.Lett. 100, 112502 (2008)  
 I. Stefanescu et al., Phys.Rev. C 79, 044325 (2009)  
 B.A. Brown and A.F. Lisetskiy, private comm.

$\mu(\pi f_{5/2} \nu g_{9/2}^3; 2^-) \rightarrow$  write as a function of  $\mu(\pi f_{5/2})$  and  $\mu(\nu g_{9/2}^3; 9/2^+)$  using additivity

$$\mu(I) = I \left[ \frac{1}{2} \left( \frac{\mu_1}{j_1} + \frac{\mu_2}{j_2} \right) + \frac{1}{2} \left( \frac{\mu_1}{j_1} - \frac{\mu_2}{j_2} \right) \frac{j_1(j_1+1) - j_2(j_2+1)}{I(I+1)} \right]$$

	Schmidt value	exp. value (ADNDT, Stone)
$\mu(\pi f_{5/2}) = \mu_1$	+0.86	+1.58(16) $^{69}\text{As}$ , Z=33, 5/2 $^-$
$\mu(\nu g_{9/2}^3; 9/2^+) = \mu_2$	-1.91	+1.674(2) $^{71}\text{As}$
		+1.63(10) $^{73}\text{As}$
		(-) 1.097(9) $^{67}\text{Zn}$ , N=37, 9/2 $^+$
		(-) 1.157(2) $^{69}\text{Zn}$ , N=39
		(-) 1.052(6) $^{71}\text{Zn}$ , N=41

$$\begin{aligned}\mu_{\text{free}}(2^-) &= 2 [ 0.5 (0.86/2.5 - 1.91/4.5) + 0.5 (0.86/2.5 + 1.91/4.5)(35/4 - 99/4)/6 ] \\ &= 2 [ 0.5 (-0.08) + 0.5 (0.77)(-16)/6 ] \\ &= 2 [ -0.04 - 1.027 ]\end{aligned}$$

$$\mu_{\text{free}}(2^-) = -2.13 \mu_N$$

$$\begin{aligned}\mu_{\text{emp}}(2^-) &= 2 [ 0.5 (1.63/2.5 - 1.05/4.5) + 0.5 (1.63/2.5 + 1.05/4.5)(35/4 - 99/4)/6 ] \\ &= 2 [ 0.5 (+0.42) + 0.5 (0.885)(-16)/6 ] \\ &= 2 [ 0.21 - 1.18 ]\end{aligned}$$

$$\mu_{\text{emp}}(2^-) = -1.94 \mu_N$$

$\mu(\pi p_{3/2} v p_{1/2}^{-1} g_{9/2}^4; 2^+) \rightarrow$  write as function of  $\mu(\pi p_{3/2})$  and  $\mu(v p_{1/2}^{-1})$

	Schmidt value	exp. value (ADNDT, Stone)
$\mu(\pi p_{3/2}) = \mu_1$	3.79	+2.5135(8) $^{67}\text{Cu}$ , Z=29, 3/2-
		+2.8372(9) $^{69}\text{Cu}$
		+2.28(3) $^{71}\text{Cu}$
$\mu(v p_{1/2}^{-1}) = \mu_2$	0.64	0.601(5) $^{67}\text{Ni}$ , N=39, 1/2-

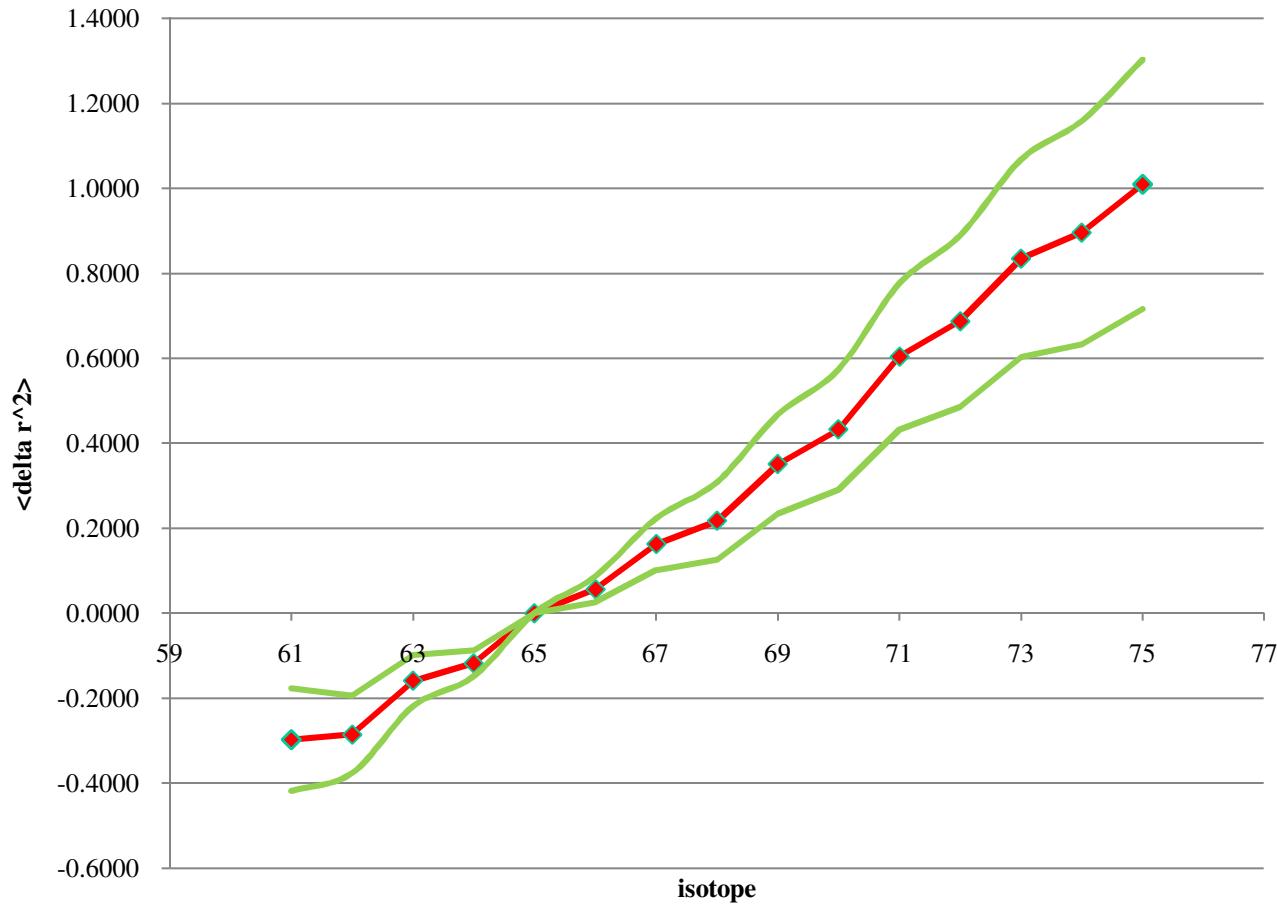
$$\begin{aligned}\mu_{\text{free}}(2^+) &= 2 [ 0.5 (3.79/1.5 + 0.64/0.5) + 0.5 (3.79/1.5 - 0.64/0.5) (15/4-3/4)/6 ] \\ &= 2 [ 0.5 (3.81) + 0.5 (1.25) 3/6 ] \\ &= 2 [ 1.91 + 0.31 ]\end{aligned}$$

$$\mu_{\text{free}}(2^+) = +4.44 \mu_N$$

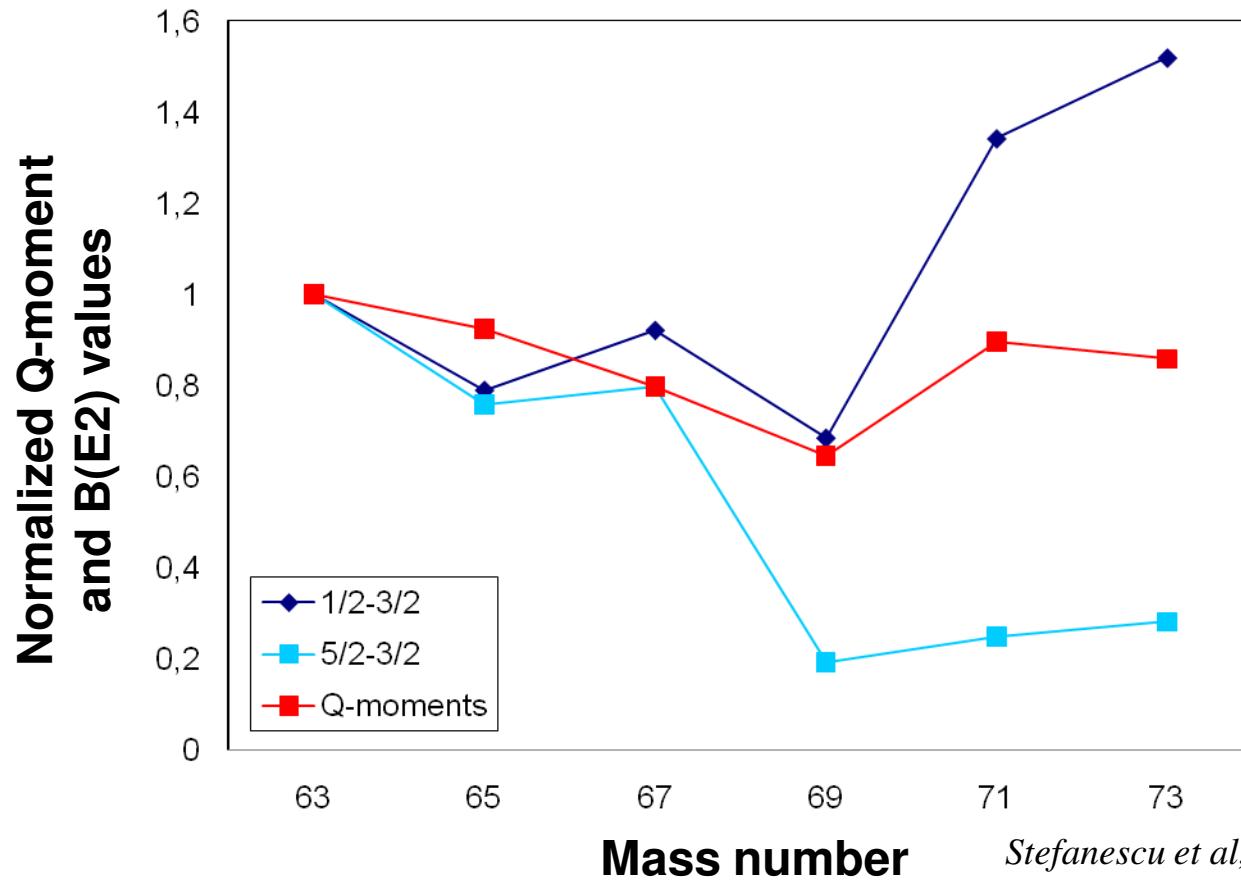
$$\begin{aligned}\mu_{\text{emp}}(2^+) &= 2 [ 0.5 (2.28/1.5 + 0.6/0.5) + 0.5 (2.28/1.5 - 0.6/0.5) (15/4-3/4)/6 ] \\ &= 2 [ 0.5 (2.72) + 0.5 (0.32) 3/6 ] \\ &= 2 [ 1.36+0.08 ]\end{aligned}$$

$$\mu_{\text{emp}}(2^+) = +1.44 \mu_N$$

## charge radii Cu



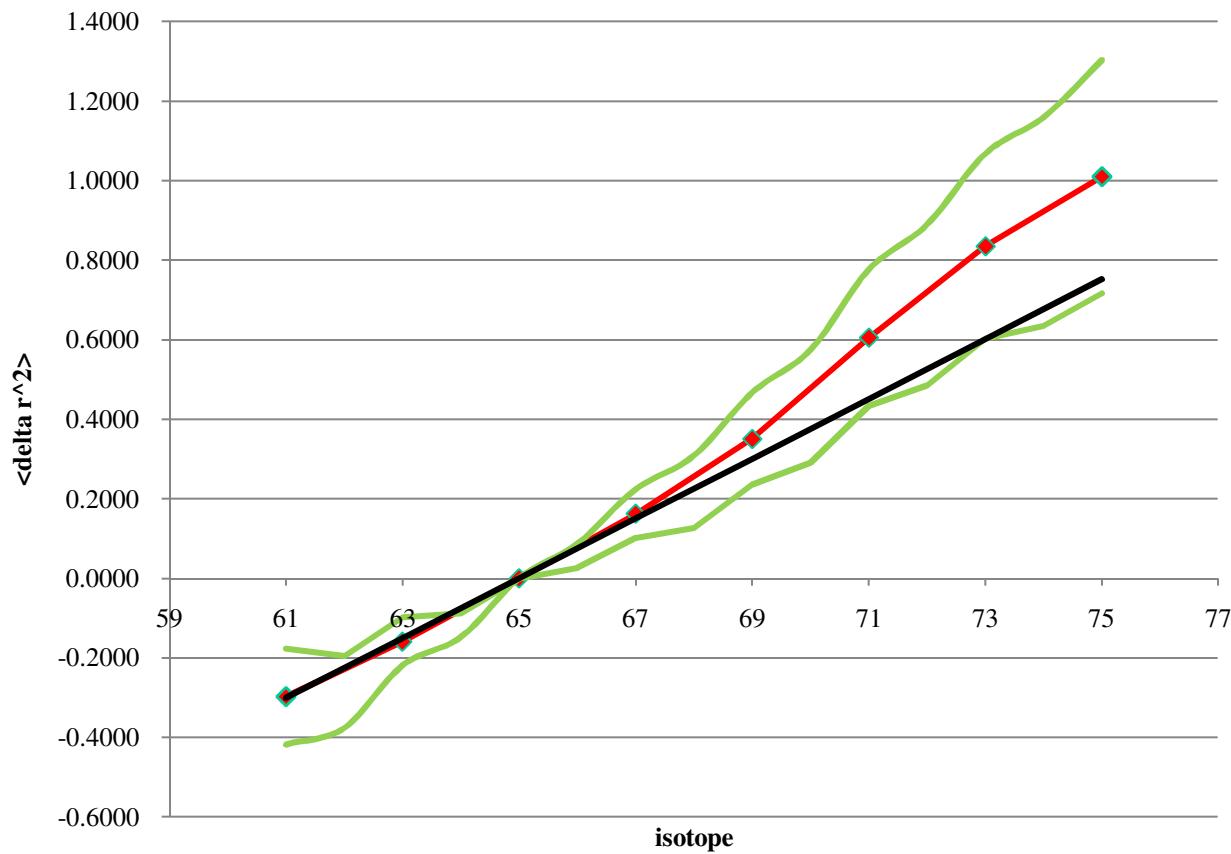
# Quadrupole moments vs B(E2) values



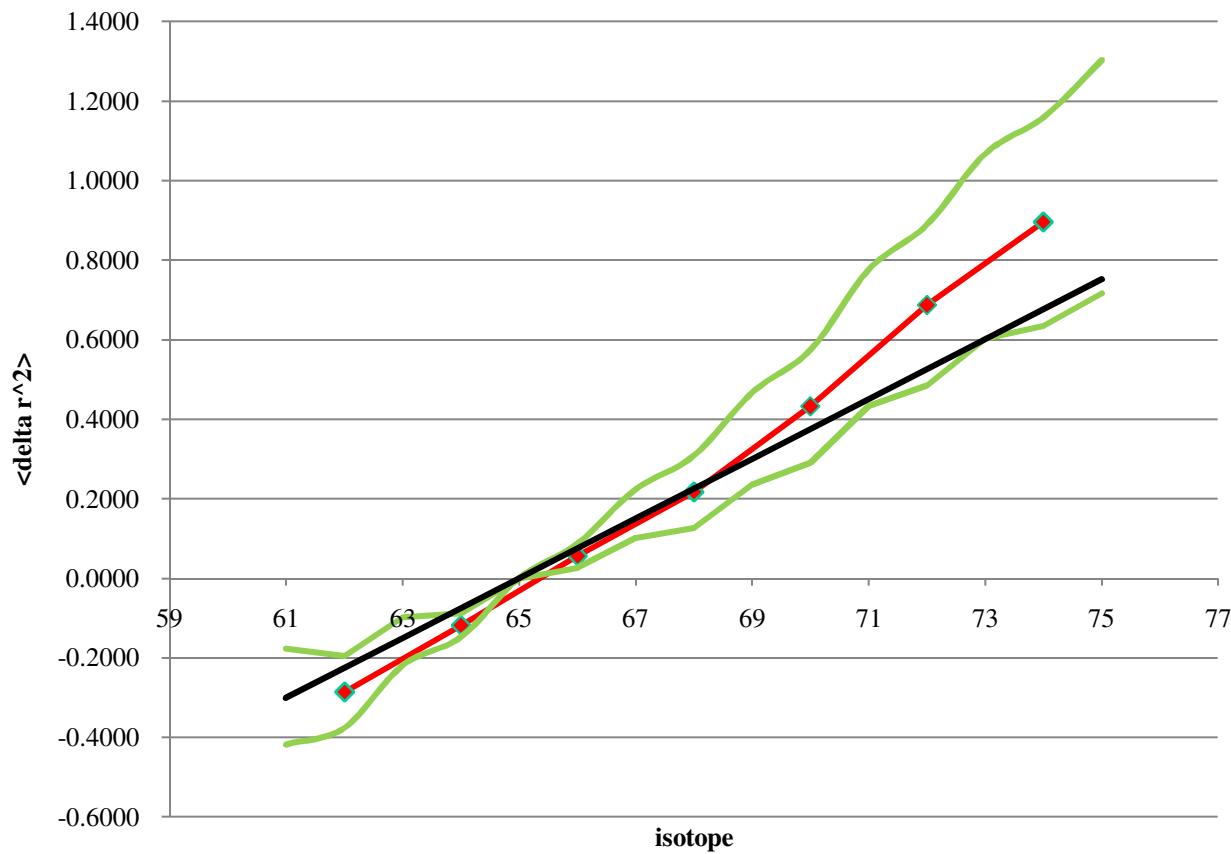
*Stefanescu et al, Phys.Rev.Lett. 2008*



## odd charge radii Cu



## even charge radii Cu



## Even Cu magnetic moments

