Nuclear Moments: Recent Tabulations, Techniques, and Physics of Magnetic Dipole and Electric Quadrupole Moments.

N.J.Stone, Oxford and Tennessee

Codata Meeting, Eltville

February 2015

Outline

Motivation for the study of nuclear moments
- magnetic dipole moments
- electric quadrupole moments

Important aspects of available techniques
- lifetime range
- sensitivity
- resolution

Analysis
- applicable corrections and when they are attempted

Physics
- a few selected interests in the field of magnetic moments

Motivation: Electric quadrupole moments

Why do we need to seek the best possible determinations of nuclear quadrupole moments?

For themselves:

the electric quadrupole moment Q is an important measureable input for nuclear modelling. Oblate Prolate

As a component of the electric quadrupole interaction in atoms, molecules, solids and liquids for analysis of electronic properties:

measurement of electric field gradient and its symmetry has wide application in physics, chemistry and biology.

Concerns relatively few isotopes, but it is important that their moments be determined accurately in order to obtain well measured electronic properties – these cannot be determined to accuracy greater than that of the nuclear quadrupole moment concerned.

Table was published by the Nuclear data Section , IAEA Vienna, December 2013.

IAEA

International Atomic Energy Agency

INDC(NDS)-0650
Distr. EN,ED

INDC International Nuclear Data Committee

TABLE OF NUCLEAR ELECTRIC QUADRUPOLE MOMENTS

Some statistics:

The table contains **1055** measured quadrupole moments of nuclei of **95** elements between hydrogen and einsteinium (Z = 99)

Of these **642** are either **stable or radioactive ground states** or **long-lived isomers**

413 are **short lived excited states**

No measurements for: He and the trans lead elements Cm, Bk and Cf.

Latest entries: **mid 2013**

There are **adopted standard efgs** for **83** elements

Those **without adopted standards** are; **Si, P, Ar, Ag, Cd, Te, Ce, Tm, W, Pt, Po, At**.

New Table of Recommended Values of Electric Quadrupole Moments

What is measured? Nuclear quadrupole moment coupled with electric field gradient [efg] Unlike magnetic moment studies where an applied magnetic field can supplement an internal field, adequate laboratory produced efg's are not available.

Efgs are (almost always) calculated not measured (exceptions Coulomb excitation, electron scattering ..)

For many elements, since the first measurements, **differing estimates of the efg in the same system** and/or efg estimates in different systems have been used to extract nuclear moments from the electric quadrupole interaction strength

Advances in computational ability in making high precision calculations in multi-electron systems, atoms, ions and compounds, yield ever more reliable values of electric field gradients acting at nuclei.

The work of Pekka Pyykko needed to be applied to all quadrupole moment determinations to ensure consistency in extracted moments.

Ref. Pyykko, Molecular Physics **99** 1617 (2001) and **106** 1965 (2008).

The adopted ‘primary’ standards. These usually involve measurements on either stable or long-lived isotopes. Many other measurements can be directly related to the adopted values.

Table relies heavily on **Pyykko** listings (expert in efg calculations)

P. Pyykko Molec Phys 106 1965 (2008) Stable Q Moments

Philosophy: **adopt result having best efg calculation**

Systems for adopted efg measurements:

Atomic/ionic hfi analysis	**36 elements**
Molecular hfi analysis	**17**
Muonic/Pionic atomic hfi	**24**
Non-cubic metals NQR	**2**

Several, although adopted, are not well determined - later

The secondary standards

Required to extract moments from measurements of quadrupole interactions which **cannot be directly linked** to primary standards

Mainly **excited state measurements**

Examples of systems providing secondary standards

metal crystals	**8**
different atomic/ionic states	**9**
molecular compounds	**5**
measured transition B(E2)	**3**
nuclear theory Q estimates	**8**
liquid state relaxation	**1**

Estimates of error

Often not limited by experiment

Being **based on computational methods**, estimation of uncertainty is not straightforward. Authors often offer estimates of uncertainty.

One check is the degree of agreement between independent calculations

but remember the old saying ………….

Examples of good agreement and of discrepancies : -

Agreements and divergences

Variation in best ground state Q moment values from different types of measurement and analysis. Where two isotopes are indicated the entry is their moment ratio.

Isotope	atomic	molecular	solid state	mesonic	variation (%)
^{23}Na	0.104(1)	0.104(1)			**0.0(10)**
^{35}Cl	-0.0817(8)		0.0850(11)		**4.0(16)**
^{69}Ga	0.174(3)	0.171(2)			**1.8(22)**
^{79}Br	0.302(5)	0.313(3)			**3.6(19)**
^{85,87}Rb	0.48050(16)	0.48383(2)			**0.69(3)**
^{115}In	0.772(5)	0.770(8)			**0.3(6)**
^{127}I	-0.680(10)		0.722(21)		**6.2(30)**
^{175}Lu		3.415(34)		+3.49(2)	**2.2(11)**
^{197}Au	0.521(7)	0.510(15)	0.560(30)		**9.8(54)**

Atomic - molecular **agree** Na, Ga, In **differ** Br, Rb, Au

Atomic - solid state **differ** Cl, I, (Au)

Atomic - mesonic **differ** Lu

Conclusion: quadrupole moments accurate to ~ 1% at best.

Changes and problem elements

All Table entries have been **adjusted to the adopted standards** wherever necessary. Often these changes are very minor, but in some cases they are not:

1. Values

2. Uncertainties

3. Problems

1. Values.

Elements for which **new efgs have produced considerable change** in the extracted quadrupole moments as **compared to most recent previous listing [N.J.S. IAEA 2011]**

.

Element	Change from 2011 listing (%)
F	-22
Ca	-26.1
Ge	+15.3
Se	-30.9
Sr	-7.6
In	-5.1
Sn	+25.7
Sb	+52
Cs	-6.0
Ba	+9.6
Gd	-5.0

2. Uncertainties

Elements for which **recent improved efg calculations** have reduced uncertainties by a substantial factor.

Element	Error reduction factor	Element	Error reduction factor
C	**0.10** (i.e x 10)	Sr	**0.10**
F	**0.25**	In	**0.4**
Ge	**0.03**	Sn	**0.7**
Se	**0.14**		

Exception to minimum uncertainty

The quadrupole moment of the deuteron has been recently recalculated using new methods to estimate the efg in HD and D_2 molecules, the result

Q (2H) = +0.0028578(3) compared to the previous best **+0.00286(2)**

claims accuracy of **0.01%** and uncertainty reduced by a factor of **50.**

Ref M. Pavanello et al., Phys Rev A **81** 042526 (2010) .

3. Elements for which adopted efg inaccuracy causes large (>9%) quadruple moment uncertainty.

Element	Error (%) in best efg value	Element	Error (%) in best efg value
V	**20**	Sm	**10**
Cr	**33**	Rn	**10**
Zn	**10**	Ac	**12**
Nd	**10**	Th	**21**
Pm	**27**	Es	**12**

Recall also

Elements **without adopted standards** are;

Si, P, Ar, Ag, Cd, Te, Ce, Tm, W, Pt, Po, At.

All of which have some problems or conflicts and would benefit from detailed theoretical effort.

Conclusions

Determination of nuclear electric quadrupole moments is a changing scene in which recent developments in multi-electron computation capability is producing major improvements in the quality of our knowledge.

The new table aims to be a timely gathering of all published moment values brought up-to-date with the best computational efg results available, thus enabling:

Nuclear theory

to access accurately what we know about nuclear quadrupole moments.

Other sciences using nuclear quadrupole interactions

to make the best use of measurements of quadrupole interactions in an ever widening range of applications.

Magnetic dipole moments

Motivation

Nuclear structure	sensitive tests of **single particle** composition of nuclear state wave-functions Schmidt limits, nuclear medium effects, meson exchange currents, configuration mixing **Collective** contributions to magnetism collective rotational g-factor
Applications	NMR widely used – proton resonance, few stable nuclei
Theory	Fundamental questions re e.g. QED require well measured nuclear dipole moments to enable true tests of predicted vacuum polarisation and radiative corrections.

Uses of nuclear dipole moments

Although certain nuclear dipole moments have great significance and require extremely precise measurement to deliver their optimal **theoretical** usefulness, the great majority have more humble application.

In **QCD tests** heavy nuclei, ions with single electron – high E and B fields mean self energy and radiative corrections to HFS attain 1% levels

For **nuclear physics** modelling measurement of the dipole moment of a state gives detailed information concerning the make-up of the wave-function. It is thus a very informative data element which complements energy, spin and parity

The magnetic moment determines:

The primary **single particle** component of the wave-function and
The degree of **admixture** of other significant configurations which can involve other single particle states of states coupled to **'collective'** excitations.

Applications: **NMR** in many technologies including
non-invasive imaging,
microscopy

Magnetic field measurement etc etc

Methodology of Measurement.

Moment values obtained by ratio with 'known' moment' which is used to establish an applied magnetic field

Proton moment: Penning trap Mooser et al. Nature 509 13388 (2014) measured ratio of cyclotron resonance frequency to Larmor frequency in the same field to obtain g(p)/2.

For the 98 elements having at least one measured moment, the best measurement for the element gave reference to:

the proton moment	12
the deuteron moment	31
11B	1
14N	2
17O	1
19F	1
23Na	6
35,37Cl	2
39K	1
45Sc	1
129Xe	1
137Ba	1

All reference isotopes have moment errors < 1 in 10^6

Most precise is the proton: 3 in 10^9

(Others not recorded)

Magnetic dipole moments – some basic statistics

Recent tabulation [Stone, IAEA Nuclear Data Section Report (2014)] contains results on ~**2200 magnetic moments** of nuclear states.

~ **1000 are moments of stable or longer-lived** (> 0.1 s ground states or isomeric states)
~ **1200 concern short-lived excited states**.

If we **limit ourselves to methods** which involve resonance or frequency modulation signal detection and have estimated **errors to +/- 10%** many of the excited state results, which concern '**collective' rotation and vibration excitations** are thereby **eliminated** through **lack of fully reliable calibration or larger experimental errors**.

The more accurate (< few %) methods:

longer lived : Laser Resonant spectroscopy (547)
NMR on polarised samples (at mK temperatures or by reactions) (162)
Atomic beam resonance (126)
Conventional NMR (stable isotopes) (110)
Mossbauer Effect (54).

shorter lived: Time dependent angular correlation (TDPAC) and time dependent angular distribution (TDPAD) (386)

Comments on Errors

Nuclear theory has limited ability to make precise calculations, only rarely is a calculation considered reliable beyond 3 significant figures (i.e.1.25 μ_N).

It follows that a moment measured to better than 1 % is usually more than adequate to establish the wave-function properties as well as, or better than, theory can estimate them.

Excessive resolution

Experimentally a method can be ‘too precise’ in a way which is not useful.

This arises, for example, the **narrow linewidth** of a signal may render the task of searching for an unknown resonance daunting and time consuming, **unrealistic in terms of accelerator time and data rates**.

This is in direct contrast to values of interest to Codata where the value required is already very well established and there is very little by way of a ‘search’ problem.

Example of complementary methods having low and high resolution

Cu laser spectroscopy at Isolde.

Corrections to raw experimental data

Methods fall into **two groups**,

1. Those in which the magnetic field is essentially an **applied, external field**.

   Here the field can be accurately controlled and measured. The first correction is for **diamagnetism,** which can be complex .
   Calculations by Feioch and Johnson give estimates for atoms.
   Correction depends upon details of chemical environment.
   Not generally available to high precision (< 0.01%).
   This correction **is usually applied** to beta-NMR results which have narrow absorption lines and resolution of order 1 in 10^5 or better.

2. Those which utilise **internal fields generated by electrons in the** sample.

   For these the **origin of the field** is important. The presence of a significant **s- electron, Fermi contact**, contribution means that the interaction is subject to both **hyperfine anomaly** (which depends upon the distribution of spin and orbital contributions to the nuclear moment) and also a **nuclear charge radius correction** which determines the variation of the electron wavefunction over the nucleus.
   Both can reach magnitudes of **1 – 2 % in high Z nuclei, occasionally larger**, and are **not amenable to precision calculation. Usually ingnored.**

Methods, errors and corrections

	group	typical error	largest uncer.	poss corr	applied usually	size
NMR	1	< 10^-5	dia	dia	**yes**	0.1 – 2 %
B-NMR	1	< 10^-4	dia/resol	dia	**yes**	0.1 – 2 %
Atom beam	2	~ 10^-3	resol A, B terms hf anom	hf anom	**no**	0.1 …. %
Laser Methods	2	~ 10^-3	resol A,B terms hf anom	hf anom	**no**	0.1 …. %
NMR/ON	2	~ 10^-2	Bhf, Q int	hf anom Q unres.	**no**	0.1 … %

Comment: **Corrections are attempted when they are required, but not in great detail. Driven by difficulty and by limitation of nuclear theory interpretation.**

Acknowledgement of assistance with table preparation

Pekka Pyykko	**for advice and consultation re Q's.**
Joann Totans **Boris Pritychenko** **Jagdish Tuli**	**NNDC, Brookhaven for help in location of many older and obscure papers.**
Daniel Abriola	**IAEA Vienna, Nuclear Data Section for financial support.**

Recent topics in nuclear magnetic moment research

1. At the closed shells.
2. Between closed shells.
3. In deformed nuclei

1. At close shell nuclei

- **more correctly closed shell +/- 1 nucleon**

where the nuclear structure is best under control

Nuclear magnetic moments.

Nuclear moment μ has contributions from all angular motion with unit the nuclear magneton.

g-factor is ratio **moment**(in nuclear magnetons)/**angular momentum** (in units of hbar)

Orbital angular momentum:

Single particle - proton (charge 1) $g_l = 1$, neutron (charge 0) $g_l = 0$

Collective - whole nucleus (?) average charge Z/A $g_l = Z/A$

Spin angular momentum

Free particle - proton $s_{1/2}$ moment $\mu_P = +2.79$ n.m $g_s = 5.587$

neutron $s_{1/2}$ moment $\mu_N = -1.91$ n.m. $g_s = -3.826$

Single particle shell model – only odd nucleon(s) contribute, others all to paired to zero

MAGNETIC MOMENT OPERATOR $\boldsymbol{\mu} = g_s\mathbf{S} + g_l\mathbf{L}$ with free particle g-values

Odd proton	$\mu = (j-1/2) + \mu_P$	$j = l + 1/2$	Schmidt Limits
	$\mu = [j/(j+1)][(j+3/2) - \mu_P$	$j = l - 1/2$	
Odd neutron	$\mu = \mu_N$	$j = l + 1/2$	
	$\mu = -[j/(j+1)]\mu_N$	$j = l - 1/2$	

In real nuclei there are two types of departure from the extreme single particle model:

1. The **wavefunction** is more complex

2. The magnetic moment **operator** has to take account of the presence of other nucleons in the nucleus

Wavefunction admixtures: **Configuration mixing caused by residual interaction. For magnetic moments important terms are spin orbit partners. These are usually in adjacent shell – effect known as core polarisation. This becomes rapidly very complex when more than one valence nucleon is involved.**

Magnetic moment **operator** adjustment: **involves meson exchange currents between nucleons not present for free nucleons and an additional term involving a one-body operator $[Y_2,S]$ which arises from coupling of a spherical harmonic of multipolarity 2 coupled to the spin operator to form a spherical tensor of rank 1.**

These complications lead to a **revised operator**

$$\mu_{eff} = g_{L,eff}\mathbf{L} + g_{S,eff}\mathbf{S} + g_{P,eff}[\mathbf{Y_2,S}]$$

where the factors g_{eff} are written as

$$g_{eff} = g_{free} + \delta g$$

For an excellent account see Modern Theories of Nuclear Moments by Castel and Towner

Experimental explorations (1)

Magnetic moment operator – this can only be done when the nuclear structure is under good control, which effectively means single nucleon outside double magic nuclei.

Oxford NO group concentrated on such nuclei at On-line Nuclear Orientation facilities at Studsvik, Sweden and Isolde, CERN.

Main theory effort is by Towner and Arima.

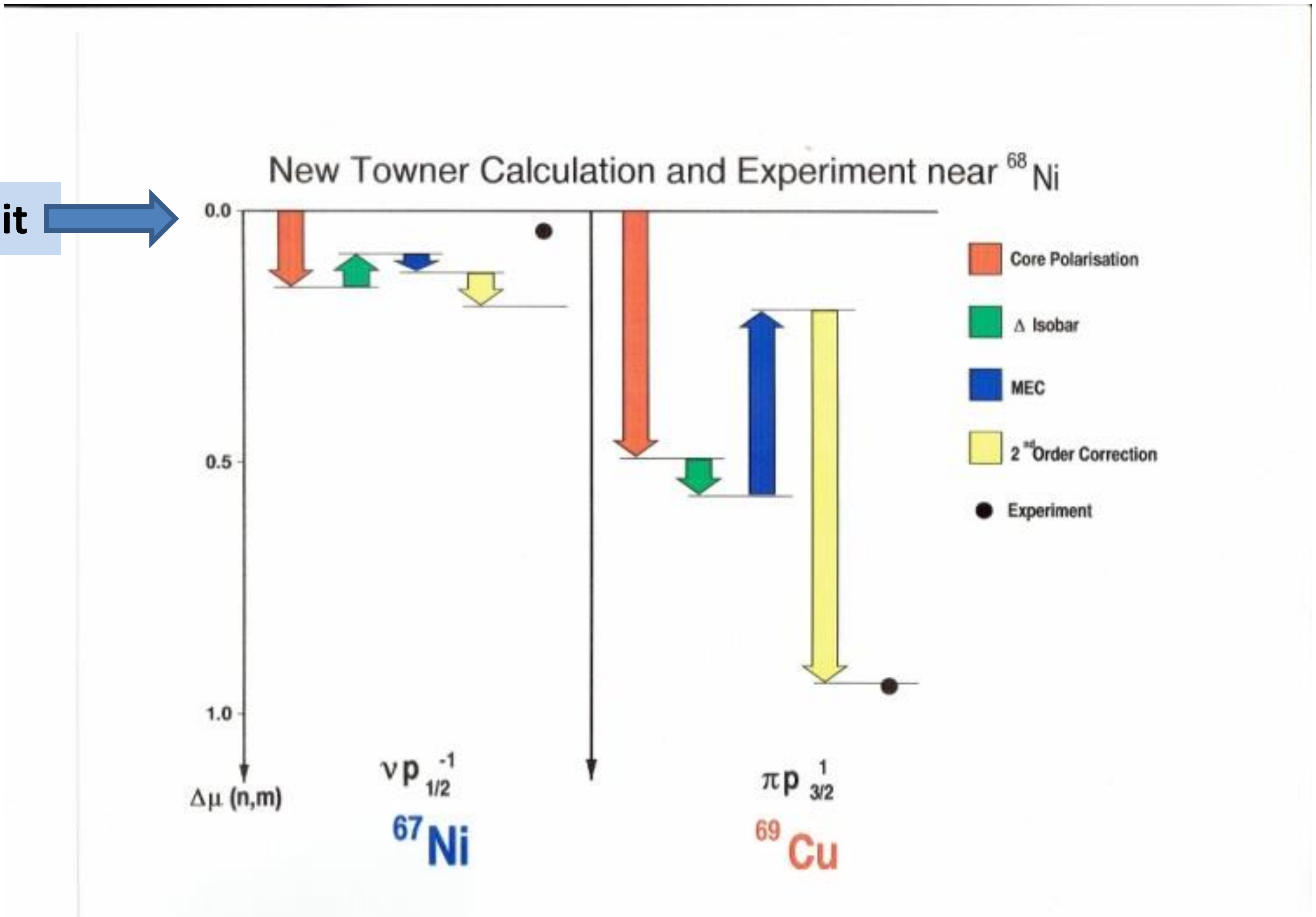
Terms in calculation are:

Core polarisation – first and second order
Meson exchange currents
Relativistic effects
Δ isobar term

All contribution to δg_L, δg_S and δg_P

Isolde – Nicole - results on ^{67}Ni and ^{69}Cu – related to ^{68}Ni.

Schmidt limit



Isotope	Configuration	Schmidt Limit	Experiment	Calculation (Towner)	Reference
^{49}Sc	$^{48}Ca + \pi f_{7/2}$	+5.794	+5.62(3)	+5.583	T. Ohtsubo et al. PRL 109 032504 (2012)
^{67}Ni	$^{68}Ni - \nu p_{1/2}$	+0.637	+0.601(5)	+0.45	J. Rikovska et al. PRL 85 1392 (2000)
^{69}Cu	$^{68}Ni + \pi p_{3/2}$	+3.793	+2.84(1)	+2.85	J. Rikovska et al . PRL 85 1392 (2000)
^{133}Sb	$^{132}Sn + \pi g_{7/2}$	+1.716	+3.00(1)	+2.93	N.J. Stone et al. PRL 78 820 (1997)

These results, with those for lighter nuclei A ~ 41 and in the Pb region, (Castel and Towner Table 4.4) show that the **deviations from the Schmidt limits can be reasonably explained by existing theory.**

More specifically, the meson exchange terms, which can ONLY be examined in these relatively simple configuration isotopes, are seen to be adequately treated.

2. Across major shells and subshells

Complete sequences from one shell closure to another are rare.

Basic ideas

Examples

(Very) Basic Nuclear Theory

- **Nucleons move in an average potential produced by interaction with the other nucleons.**
- **This leads to a sequence of single particle levels with quantum numbers associated with their orbital and spin angular momenta and parity.**
- **The strongest term in their interaction after this is the spin-orbit which produces splitting between levels of $\underline{j} = \underline{l} + \underline{s}$ and gives quantum labels e.g $1f_{5/2}$, $1f_{7/2}$ with the higher j lying lower.**
- **The larger energy gaps between states of higher l produce the magic numbers and the idea of closed shell nuclei.**
- **The next strongest term is the pairing interaction which acts between like nucleons and leads to pairs in the same j state coupling to zero angular momentum in their ground states.**
- **What remains after these terms is called the 'residual interaction' and acts between both like and unlike nucleons. Evidence for its nature is elusive…..**

The Residual Interaction

We do not have an analytic understanding, or form, for the interaction between nucleons in nuclei.

Simple effective potentials are used to construct a general scheme of energies of nucleon states in terms of their (spherical) quantum numbers, with an additional spin-orbit interation, e.g. $1f_{5/2}$.

Then there is the pairing interaction between like nucleons

All other parts of the interaction are called 'residual' and described by a multipole expansion with monopole, [no dipole - C of M], quadrupole etc terms, connected to the shape of the nucleus.

This is merely a DESCRIPTION, not an UNDERSTANDING of the origin or magnitude of the terms in the residual interaction. It is a language to describe what is observed.

In the absence of the residual interaction

Energies of single nucleons are independent of the occupation numbers of the same or other nucleon states, with the clear exception of the phenomenon of Pairing, whereby two nucleons with the same (spherical) potential quantum numbers combine to form a state of total angular momentum zero.

As early as the 1960's examples were known where this situation did not apply:

Example: Proton ground states in Sb isotopes

As the neutron $h_{11/2}$ shell fills the single proton ground state changes from $d_{5/2}$ [in lighter] to $g_{7/2}$ [in heavier] Sb's.

Since these nuclei are not deformed, i.e. their potentials have little or no quadrupole or higher terms, the effect which was seen as responsible for the dependence of the occupancy of the neutron $h_{11/2}$ orbital was called the 'monopole' shift term in the residual interaction.

Kisslinger and Sorensen, Pairing + Quadrupole Model [RMP 35 853 1963]

Knowledge of local behaviour of the residual interaction is needed to give nuclear models predictive power.

Experimental exploration

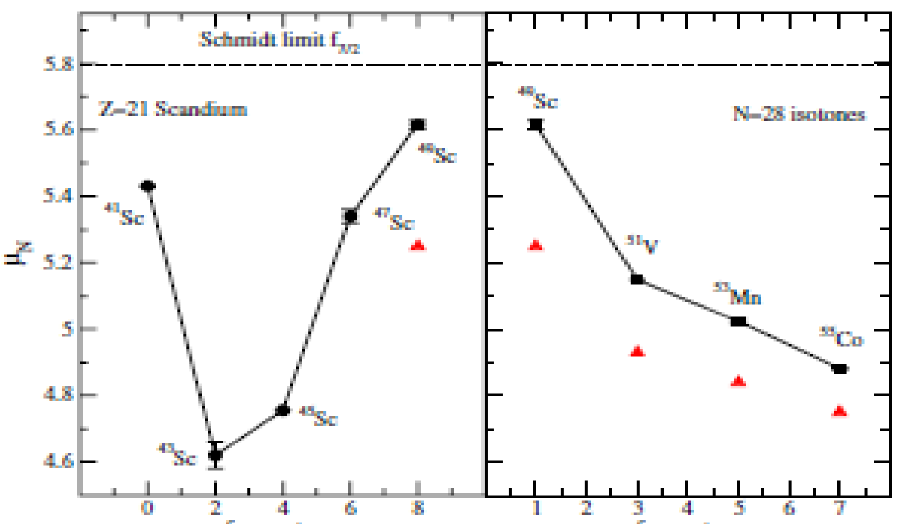
Wave-function development across a shell from single particle to single hole

Complete sequences are surprisingly rare even today

First figure shows complete sequence of single $f_{7/2}$ proton configurations from zero $f_{7/2}$ neutrons (^{41}Sc) to the full 8 f7/2 neutrons (^{49}Sc)

Demonstrating variation of configuration mixing across neutron subshell filling. Initial work by Arima and Horie

Second shows complete sequence of odd numbers of $f_{7/2}$ protons all with full $f_{7/2}$ neutron subshell from ^{49}Sc to ^{55}Co.

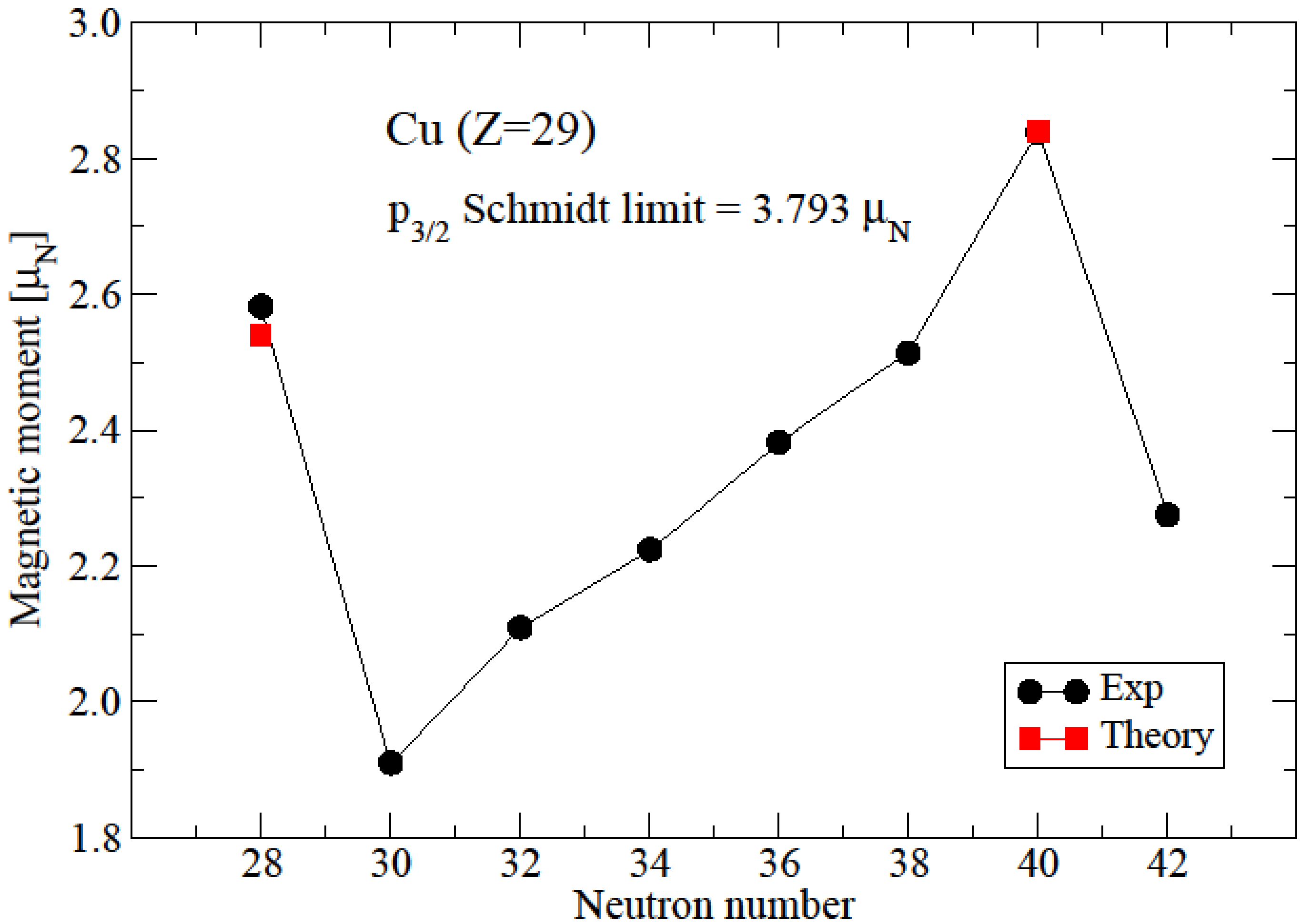


$(f_{7/2})^n$ neutrons
n even, single proton

$(f_{7/2})^n$ protons
n odd, full neutron shell

Red triangles show latest theory : Towner at ^{49}Sc and Honma et al . for Sc – Co sequence.

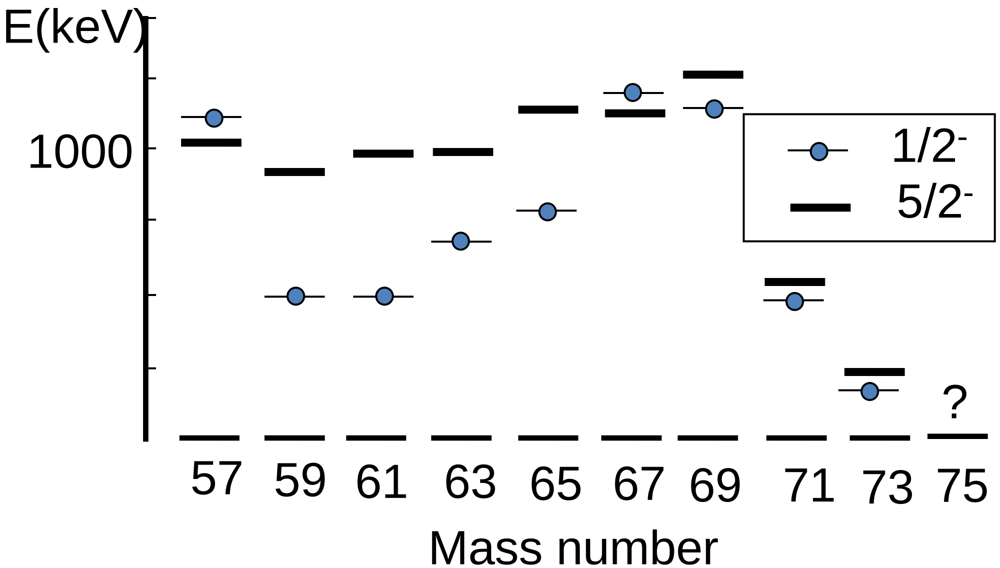
Odd-A copper isotopes ^{57}Cu to ^{69}Cu – **all single $p_{3/2}$ proton**



Note lack of symmetry of ^{67}Cu and ^{71}Cu about ^{69}Cu (full neutron shell)

Systematic migration of nuclear states in copper isotopes

•5/2- level associated with the π(*f*5/2) orbital



I = 5/2⁻ level:

- **Remains static between $^{57-69}$Cu at ~1MeV**
- **Systematically drops in energy as the ν(g9/2) shell begins to fill**
-
- **Predictions on the inversion of the ground state lie between ^{73}Cu and ^{79}Cu.**
- **Experimental evidence for the inversion to occur at ^{75}Cu.**

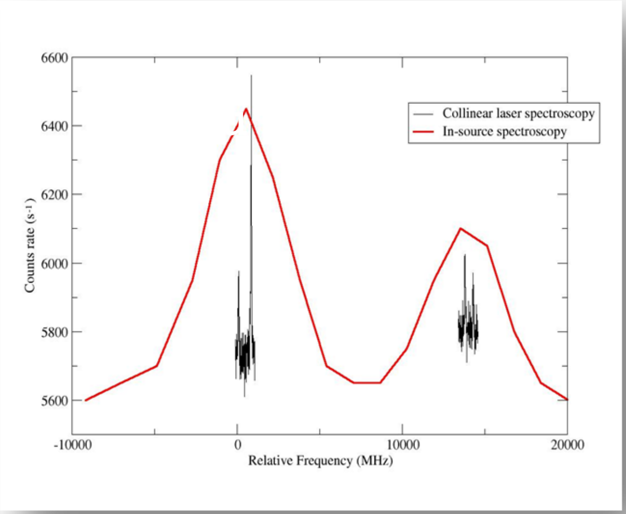
S. Franchoo et al. Phys. Rev. C 64 054308
I. Stefanescu Phys. Rev. Lett 100 (2008)
A.F. Lisetskiy et al. Eur. Phys. J. A, 25:95, 2005
N.A. Smirnova et al. Phys. Rev. C, 69:044306, 2004

From Kieren Flanagan

On-Line Laser spectroscopy

Collinear and In-Source **Methods**

High resolution vs high sensitivity



In Source, Doppler width resolution ~ 250 MHz

Collinear Concept - add constant energy to ions

$$\Delta E = const = \delta(^1/_2 mv^2) \approx mv\delta v$$

Resolution ~ MHz, resulting from the velocity compression of the line shape through energy increase.

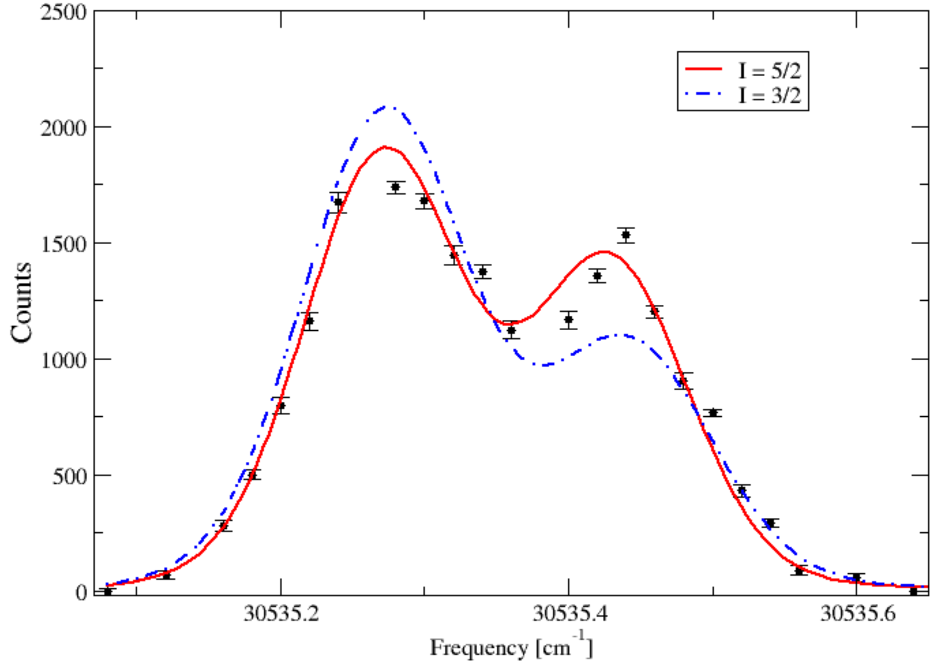
In Cu+ ion, electron states involved are $s_{1/2}$ and $p_{1/2}$.

With nuclear spin I these each form a doublet with F (= I + J) = I +1/2 and I - 1/2.

Transitions between these doublets give four lines in two pairs with related splittings.

- can be fitted with poor resolution only for the A (magnetic dipole) splitting and in good resolution, for both A and B (electric quadrupole splitting)

In source laser data, ^{75}Cu, fits for I = 3/2,5/2



Peaks barely resolved, but clear preference for spin 5/2

Moment of ^{75}Cu(I = 5/2) μ = 0.99(4) n.m. [Aug 2008]

Confirmed during collinear run, later Aug 08, which used the in-source moment to set line search frequencies.

Conclusions

1. Best shell model calculations have yielded odd-A Cu magnetic moments at N = 28, 40 very close to experiment and adequately described the variation between these shell closures.

2. Now that the shift of the $f_{5/2}$ state has been identified, magnetic moments of $^{71-78}$Cu can be calculated reasonably well. The residual interaction monopole shift of this level has been established by spectroscopy and direct moment and spin measurements.

3. Models which give these results successfully may be expected to give useful predictions concerning the A = 78 shell closure and related r-process properties.
Models which fail to reproduce them may not be trusted in other predictions.

Magnetic moments provide an aid to development, and a stringent test of the reliability, of nuclear model calculations.

Collective aspects of nuclear motion

Investigation of the 'collective' magnetism associated with rotation of deformed nuclei in the Yb – W region

K - isomers

g-factors for deformed nuclei g_K, g_R

combination of measurements of band head magnetic moment and in band spectroscopy
=> *g_K (relates to quasi-particle motion) and g_R (relates to collective motion).*

Magnetic dipole moment
= $g_K[K/(K+1)] + g_R[1/(K+1)]$
Note small effect of g_R vis g_K.

Band branching ratios and E2/M1 mixing ratios
depend upon $[g_K - g_R]/Q_0$

single-particle properties

collective properties

$$K g_K = \sum (\Lambda g_\Lambda + \Sigma g_\Sigma)$$

$g_R = I_p/[I_p + I_n] = Z/A$ in simple terms

=> configurations and admixtures

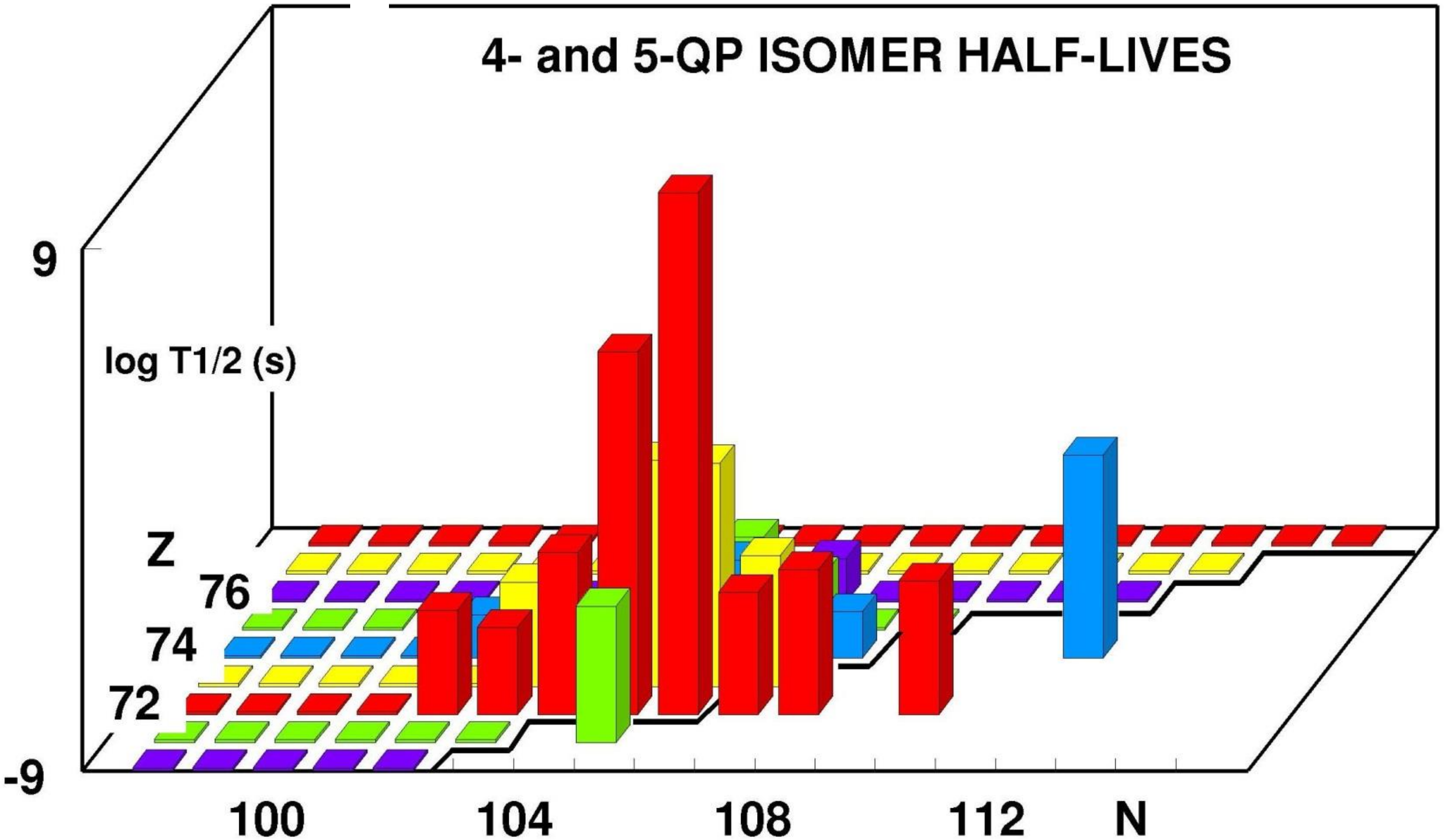
$$\mathcal{J}_{p,n} = \mathcal{J}_{\rm rig}\left(1 - \frac{\ln[x_{p,n} + (1 + x_{p,n}^2)^{1/2}]}{x_{p,n}(1 + x_{p,n}^2)^{1/2}}\right)$$

$$x_{p,n} = \frac{(\delta\hbar\omega_0)_{p,n}}{2\Delta_{p,n}}$$

=> neutron and proton pair quenching

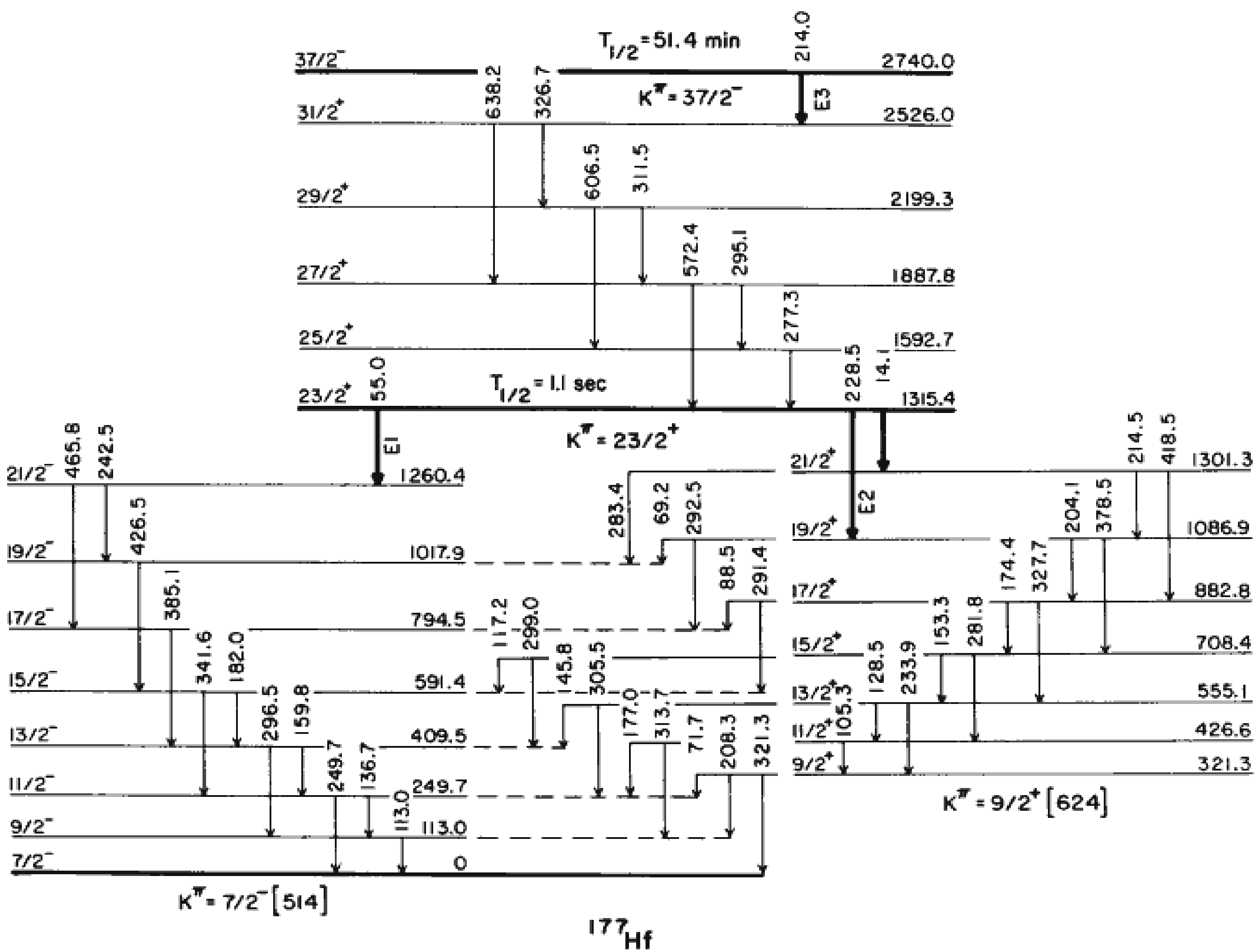
see, for example:
Purry et al., NPA632 (1998) 229
El-Masri et al., PRC72 (2005) 054306

Hf isotopes (Z = 72) at the centre of the multi-quasi-particle K-isomer region – neighbours Lu, Ta, W and Re.



[Walker and Dracoulis, Hyp. Int. 135 (2001) 83]

Decay scheme of ^{177}Hf 51.4 minute 37/2- isomer



Results of NICOLE, ISOLDE experiment on ^{177}Hf

dipole moment of 37/2- isomer = 7.33(9) nuclear magnetons

g_R of band above this isomer = 0.21(4)

g_R of band above the 23/2+ isomer = 0.30(3)

g_R of band built on 9/2+[624] state = 0.209(23)

g_R of band built on 7/2-[514] state = 0.247(8)

Also g_R of band built on ^{178}Hf 0+ ground state = 0. 280(7)
and g_R of band on 6+ two proton isomer in ^{178}Hf = 0.43(6)

Reference: S. Muto et al. Phys Rev C 89 044309 (2014)

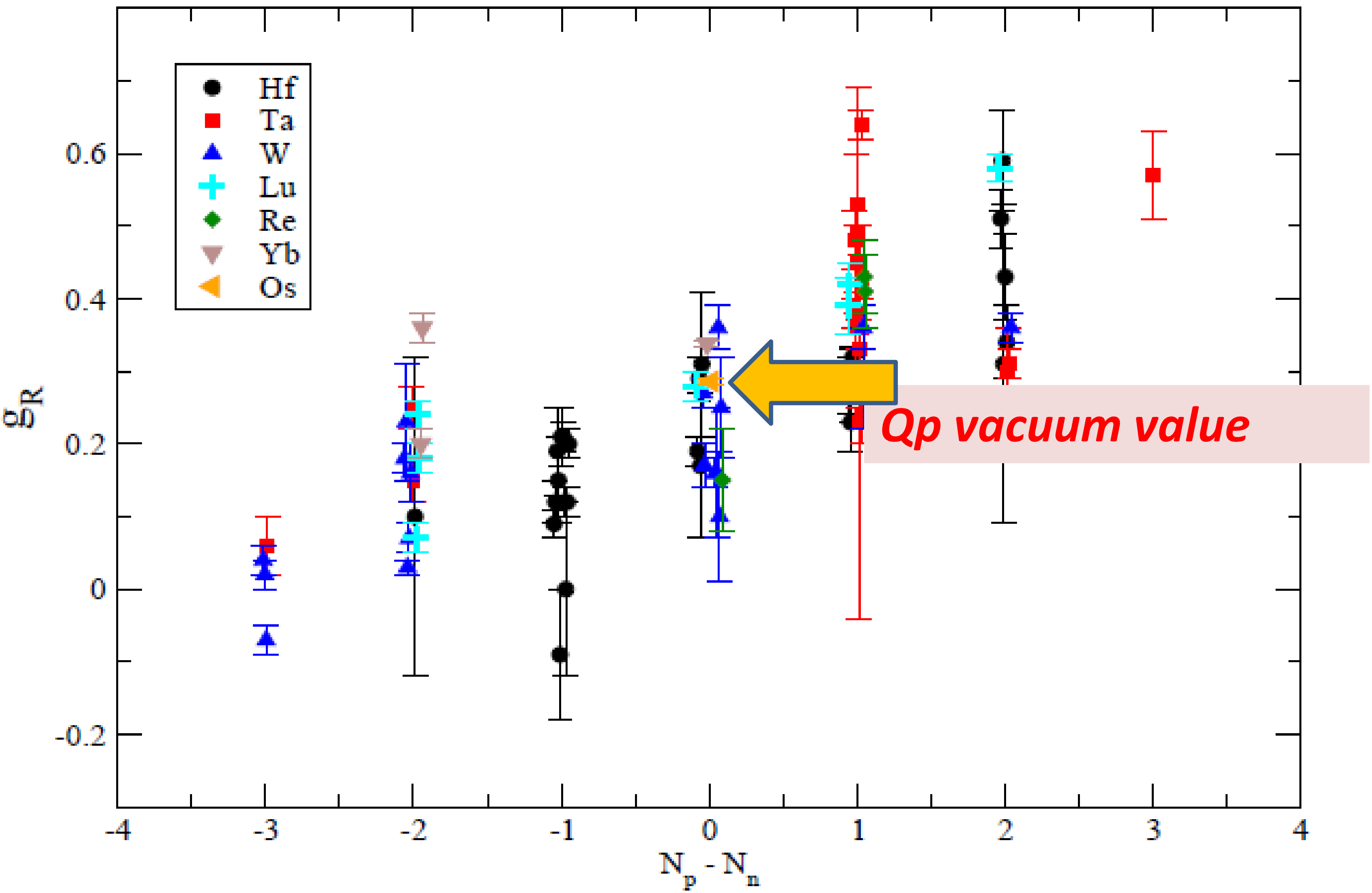
It helps to arrange these results

Spin	configuration	gR factor
6+	two protons in ^{178}Hf	0.43(6)
23/2+	two protons, one neutron in ^{177}Hf	0.30(3)
0+	**quasi-particle vacuum**	0.280(7)
9/2+	single neutron [624]	0.209(23)
7/2-	single neutron [514]	0.247(8)
37/2-	two protons, three neutrons in ^{177}Hf	0.21(4)

This finding led to **a systematic investigation** of the **g_R parameter** in all high-K isomers of Yb, Hf, Ta, and W (which have almost constant deformation).

Finally – the plot of g_R vs the (net) number of quasi-particles, $N_p - N_n$

Ref. N.J.Stone et al. Phys Lett B 726 675 (2013)



On **a fundamental level** the nucleus exhibits a unique type of **superfluidity.** **Pairs** form the superfluid and **do not contribute** to the moment of inertia or g-factor.

Breaking pairs reduces to superfluidity of those nucleons and increases their contribution

The combination of

Moment of Inertia $[I = I_p + I_n]$

and g_R $[= I_p/(I_p + I_n]$

allows **separation** of the proton and neutron contributions.

Also the changes produced in g_R and in Moment of Inertia by **breaking pairs with specific angular momentum properties** offers a unique opportunity to study the effects of removing individual pairs from the superfluid.

Nuclear electric quadrupole moments
and magnetic dipole moments
form an active field
of research, having multiple
aspects and applications
in nuclear physics and
beyond.

Thank you!

Colleagues in Experiment and Theory

France	C. Gaulard, L. Risagari, S. Roccia
ISOLDE	K. Flanagan, U. Koester
Japan	S. Muto, H. Nishimura, T. Ohtsubo, S. Ohya
Serbia	J. Novakova, M. Veskovic
U.K.	G. Simpson, J. R. Stone, P. M. Walker
USA/Canada	C. Bingham, I. Towner, W. B. Walters