The Table of Nuclear Moments

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- 1. Status of Table
  - Sensitive corrections to most precise measurements

- 2. New methods of magnetic moment measurement

  - TDPAC in Gammasphere

  - RIV with RIBs at HRIBF

Status of Table of Magnetic Dipole and Electric Quadrupole Static Nuclear Moments

- **Table maintained on Brookhaven National Laboratory National Nuclear Data Centre Web Site [BNL.gov]**

- **Contains all reported nuclear magnetic dipole moments and electric quadrupole moments of ground and excited states.**

- **Currently on website to end 2001.**

- **available from n.stone@physics.ox.ac.uk to mid 2004.**

- **Table also prepared for publication in Atomic Data and Nuclear Data Sheets [2005].**

Current activity: recommended values

- What's involved ?

- Magnetic dipole moments:
  - Basic NMR ratios
  - The diamagnetic correction
  - Hyperfine anomalies
  - The Knight shift

- Electric quadrupole moments:
  - Basic NMR ratios
  - The Sternheimer correction

Nuclear magnetic moment measurements can be divided into two categories:

1. Measurements involving an external applied magnetic field [uniform].

NMR in liquids, gases. Atomic beam experiments [includes lasers]
Optical pumping in atoms.

In these methods, to extract the true nuclear dipole moment the measured energy splitting has to be corrected for:

a) the diamagnetic correction caused by the action of the applied field on the electrons. Calculated for neutral atoms in various approximations. Increases with Z reaching ~ 2% for Bi [Johnson et al ADNDT 28 333 (83)]

b) any chemical shift caused by action of the applied field on the surrounding molecules. Hard to calculate, estimated uncertainty 1 in 10^3. [Gustavsson and Martensson-Pendrill PRA 58 3611 (98)]

These provide the basic standards for nuclear magnetic moments

2. Measurements involving internal fields [Hyperfine fields e.g in Fe.]

NMR in magnetic materials, including ferromagnetic metals, where field at nucleus is dominated by local electrons.

These measurements are liable to corrections for:

Variation in local field over the nuclear volume [Bohr-Weisskopf Effect or Hyperfine Anomaly]. Field varies with isotope.

This involves the distribution of nuclear magnetism within the nucleus and variation of the field over the nuclear volume. The correction can be as large as 10% but is more usually 0.l - 1%.

In metals, the Knight shift which describes polarisation of the conduction electrons and the field they produce at the nucleus. Modifies applied field but not hyperfine field.

Such measurements are NOT the basic standards of nuclear moment determination.

Only for the most precise measurements is there a real problem in setting 'recommended values' for magnetic moments.

For many the experimental error is larger than such considerations as diamagnetic corrections and hyperfine anomalies.

Why are these small corrections important?

1. For some light nuclei theory can make accurate prediction - but this is rare!

2. Increased precision gives access to more sensitive phenomena.

   e.g. for hydrogen like systems hyperfine interactions can probe QED effects which reach 0.5% for heavier elements. To provide a critical test of QED requires the corrected moment to be known to [far] higher precision.

The Standards

The basic standards of nuclear magnetism are:

The proton and the deuteron [values from Fundamental Physical Constants see e.g. PR D66 010001 (02)]

Principle secondary standards are:

^{23}Na, ^{203,205}Tl
^{165}Ho, ^{207}Pb
^{185,187}Re, ^{209}Bi
^{199}Hg,

From these other standards are derived by ratio to give a complete reference structure throughout the periodic table.

Gustavsson and Martensson-Pendrill have reviewed the status of knowledge of these secondary standards

[PR A58 3611]

TABLE I. Diamagnetic shielding factors σ_a for atomic systems. The values are obtained by three different procedures based on nonrelativistic Hartree and Hartree-Fock calculations (H/HF) for neutral atoms [23], the relativistic Hartree-Fock-Slater (RHFS) electron theory for closed-subshell systems [24,25], and the relativistic random-phase approximation (RPA) for closed-shell systems [26,27], respectively. In addition, values for neutral Na, Ho, and Tl are also given in the RHFS column, these values are obtained from the table of spherical average diamagnetic corrections for neutral atoms, calculated by Lin, Johnson, and Feiock, and quoted in the compilation by Fuller [10].

System	H/HF[a]	RHFS	RPA
Na	0.000 629	0.000 6491[b]	
Na^+		0.000 6426[c]	0.000 6322[d]
Ho	0.007 56	0.010 65[b]	
Re^{7+}		0.013 56[c]	0.013 31[e]
Hg	0.009 65	0.015 87[c]	0.015 77[e]
Tl	0.009 82	0.016 36[b]	
Tl^+		0.016 36[c]	0.016 24[e]
Pb	0.009 98	0.020 55[c]	
Pb^{2+}		0.016 86[c]	0.016 74[e]
Bi^{3+}		0.017 39[c]	0.017 27[e,f]

[a] Dickinson [23].

[b] Lin, Johnson, and Feiock, quoted by Fuller [10].

[c] Feiock and Johnson [25].

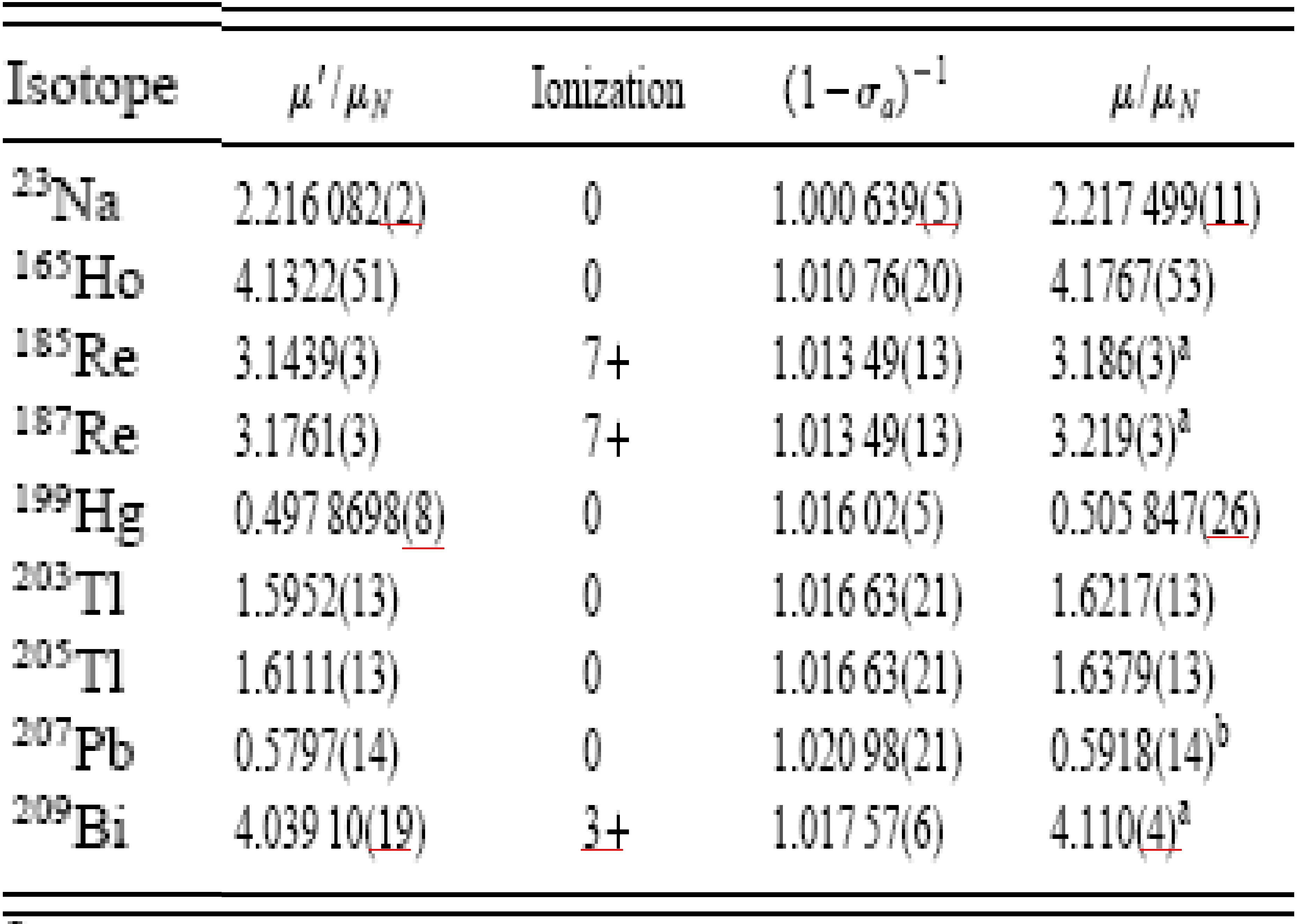
[d] Johnson, Kolb, and Huang [27].

[e] Johnson [31].

[f] Baştuğ *et al.* [46].

moment before correction

moment after correction



Isotope	μ'/μ_N	Ionization	$(1-\sigma_a)^{-1}$	μ/μ_N
^{23}Na	2.216 082(2)	0	1.000 639(5)	2.217 499(11)
^{165}Ho	4.1322(51)	0	1.010 76(20)	4.1767(53)
^{185}Re	3.1439(3)	7+	1.013 49(13)	3.186(3)[a]
^{187}Re	3.1761(3)	7+	1.013 49(13)	3.219(3)[a]
^{199}Hg	0.497 8698(8)	0	1.016 02(5)	0.505 847(26)
^{203}Tl	1.5952(13)	0	1.016 63(21)	1.6217(13)
^{205}Tl	1.6111(13)	0	1.016 63(21)	1.6379(13)
^{207}Pb	0.5797(14)	0	1.020 98(21)	0.5918(14)[b]
^{209}Bi	4.039 10(19)	3+	1.017 57(6)	4.110(4)[a]

Conclusions

- Printed version will appear in ADNDS during 2005.
- Basic Table is up-to-date.
- Recommended Value Table is straightforward for the great majority of entries. Some policy questions.
- Immediate consultation available in all cases from NJS.
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TIPAC with Gammasphere

- Excited states having lifetimes in the 0.1-10 ns range.

- Mass ~ 100 fission fragments produced by fission of ^{252}Cf at the centre of the gammasphere array of 101 Ge detectors [high efficiency].

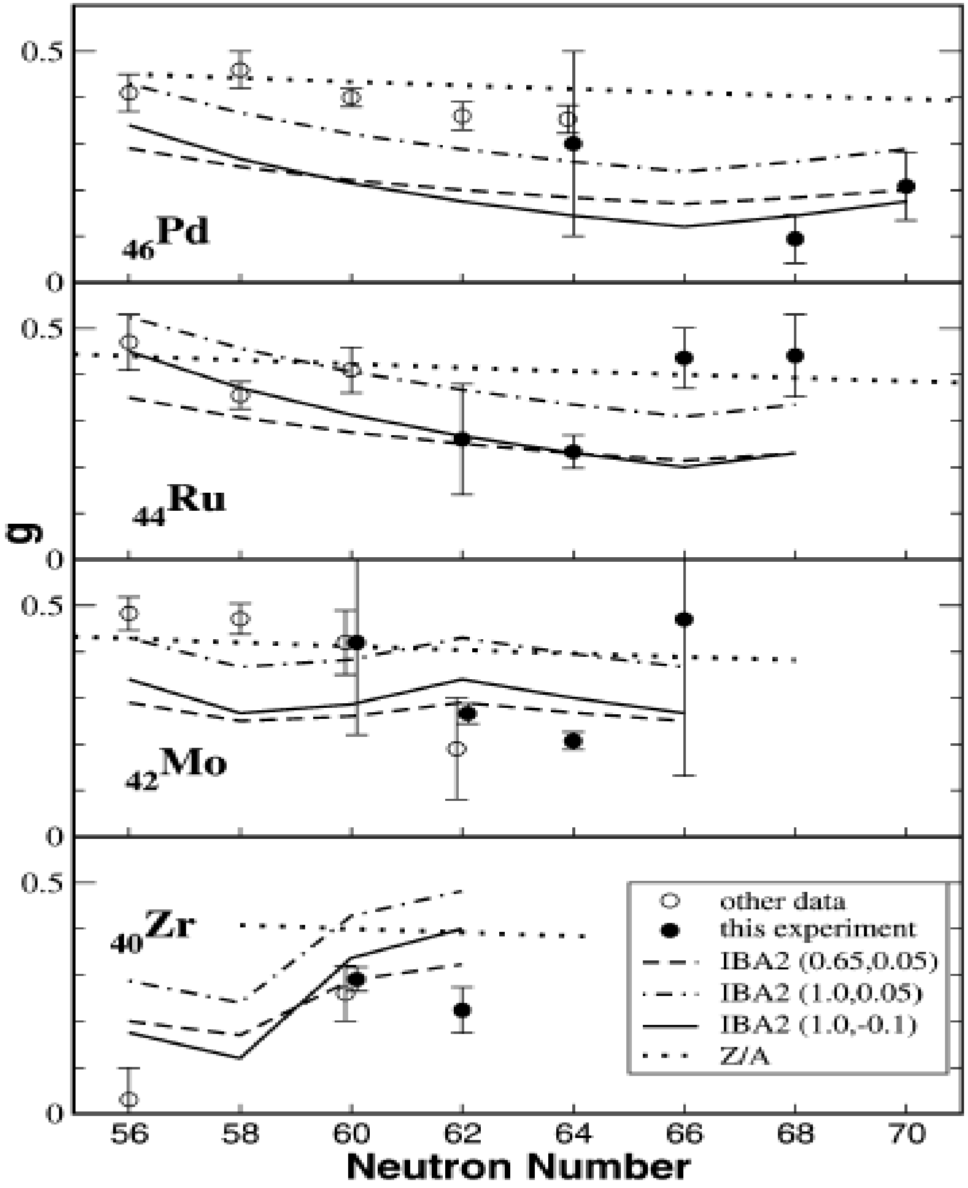
- Fragments implanted by recoil [few ps] into an iron foil. Subject to static hyperfine fields [well determined].

- Gamma-gamma perturbed angular correlations observed. Rotation of correlation gives magnitude and sign of intermediate state g-factor.

- Main feature: utilises high efficiency of gammasphere.
- Ref A.G.Smith et al. Phys Lett B591 55 (04)

Nucleus	2^+ half-life [ns]	g-factor
100 Zr	0.78(3)	+0.30(3)
102 Zr	2.8(4)	+0.22(5)
102 Mo	0.180(6)	+0.4(2)
104 Mo	1.04(6)	+0.27(2)
106 Mo	1.80(4)	+0.21(2)
108 Mo	0.7(4)	+0.5(3)
106 Ru	0.29(3)	+0.3(1)
108 Ru	0.50(4)	+0.23(4)
110 Ru	0.43(3)	+0.44(7)
112 Ru	0.46(4)	+0.44(9)
110 Pd	0.067(2)	+0.3(2)
112 Pd	0.29(9)	+0.09(5)
114 Pd	0.16(4)	+0.2(1)

A.G. Smith et al. / Physics Letters B 591 (2004) 55–60



Excited State g-factors with Radioactive Ion Beams

- Excited state lifetimes in 0.1 - 10 ps range.

- States produced by Coulomb Excitation of radioactive beam. Nuclear spins are aligned giving anisotropic decay. Anisotropy large [factor 7 max/min for 2^+ - 0^+ decay].

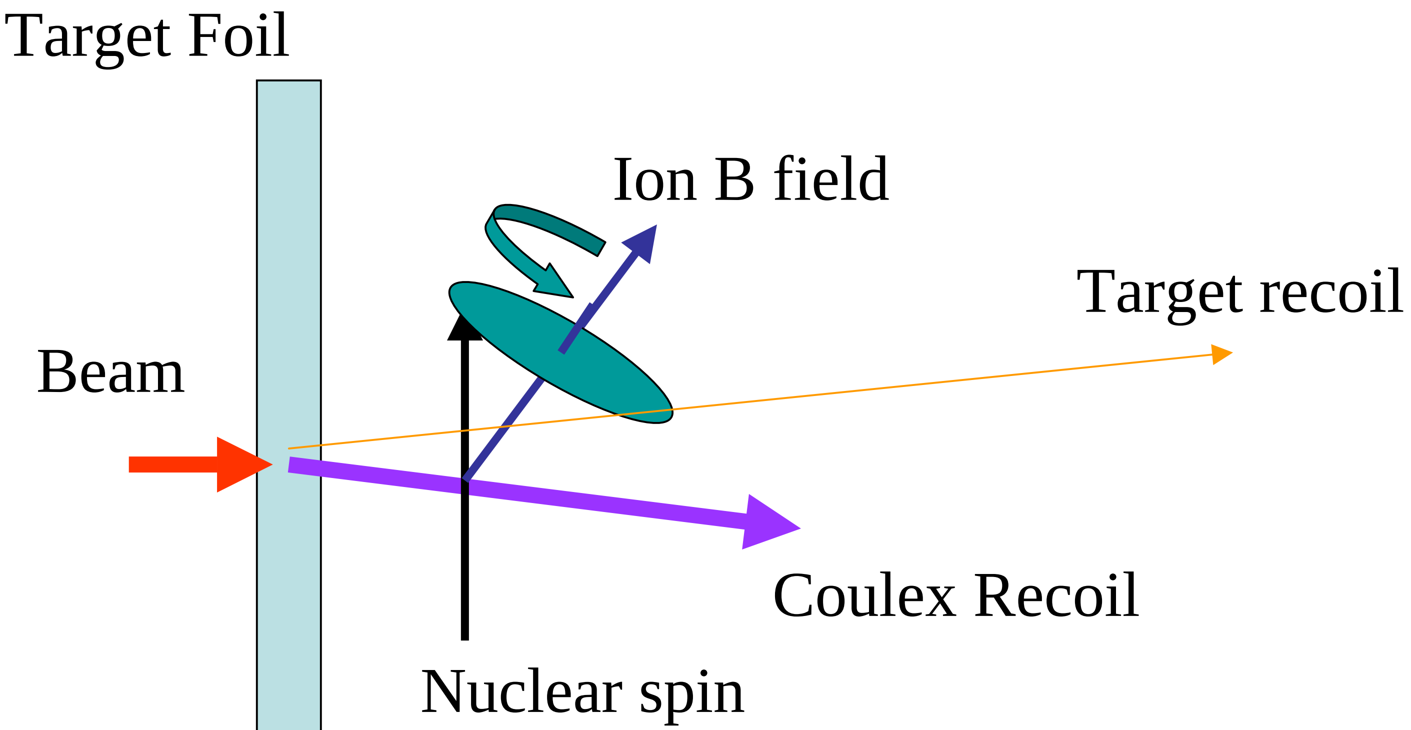
- Nuclei recoil from target into vacuum - alignment is perturbed by electronic state fields [~ 10^5 T] producing attenuation of the anisotropy.

- Attenuation calibrated using stable beams with known excited state g-factors. [Recoil-in-Vacuum method]. Extract lg-factorl.

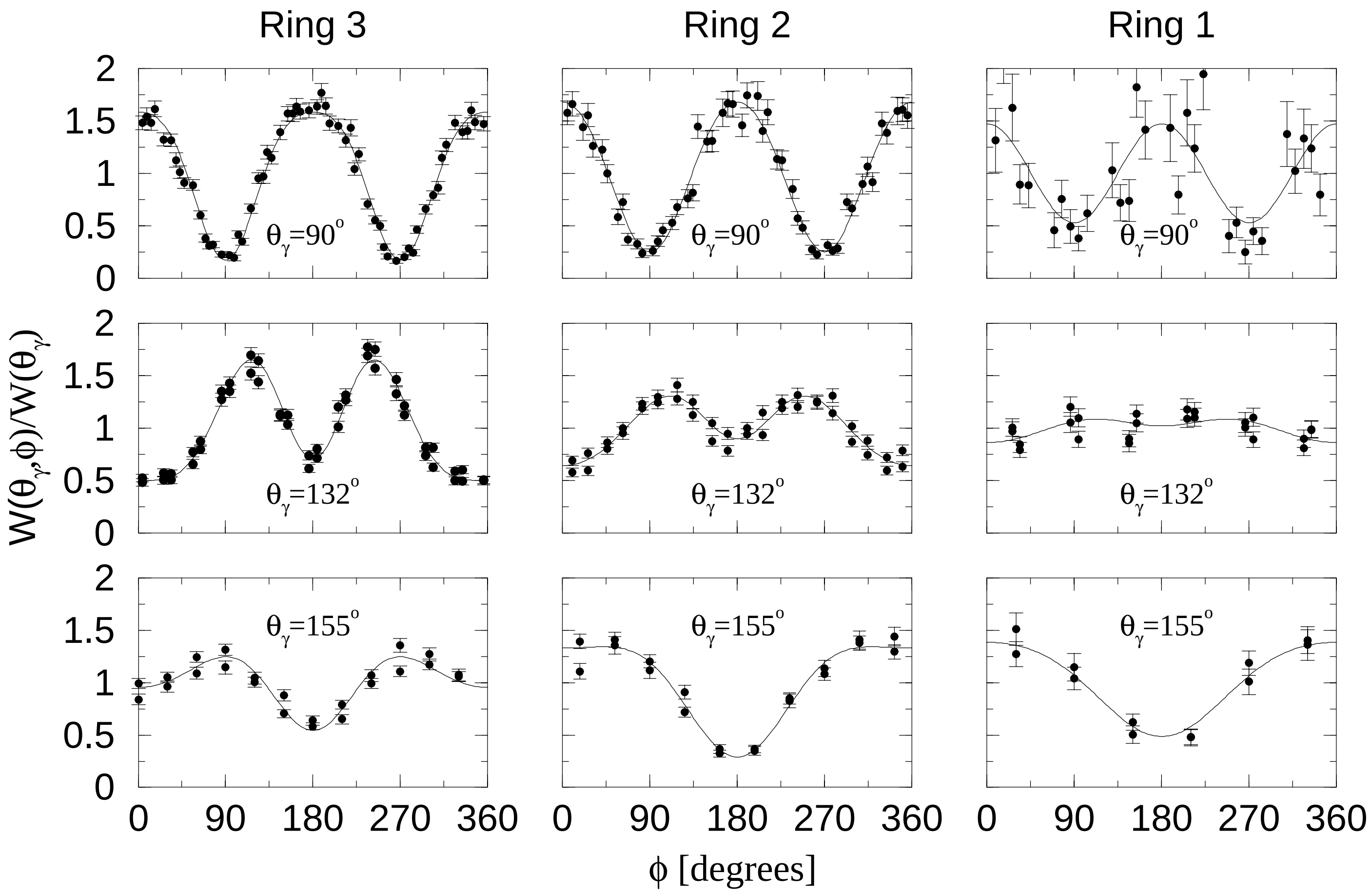
- First result: g-factor 2^+ state in ^{132}Te = 0.35(5) [HRIBF to be published]

- Novelty: applicable to RIBS and weak beams [~10^6 s^{-1}]

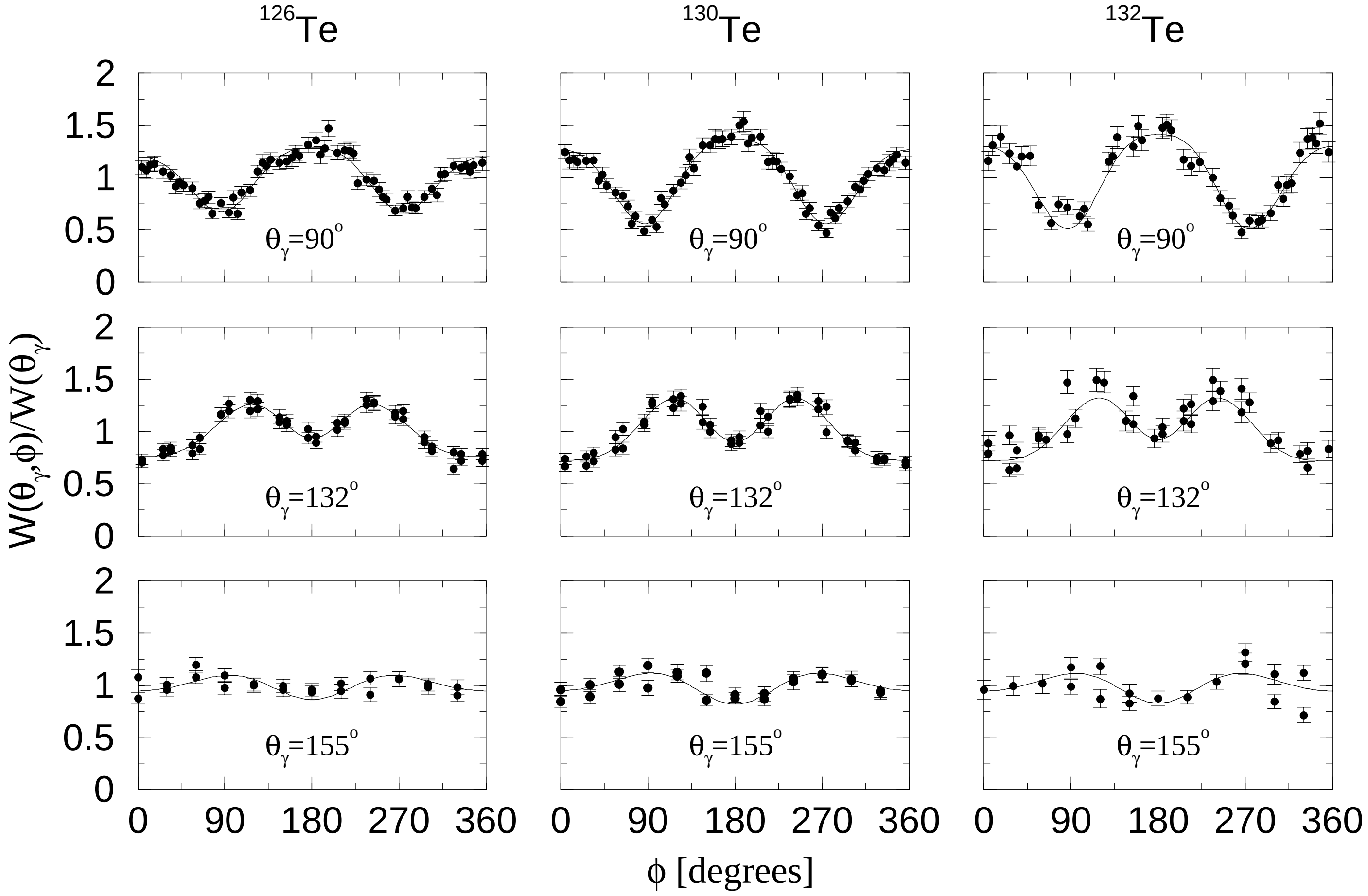
Recoil in Vacuum



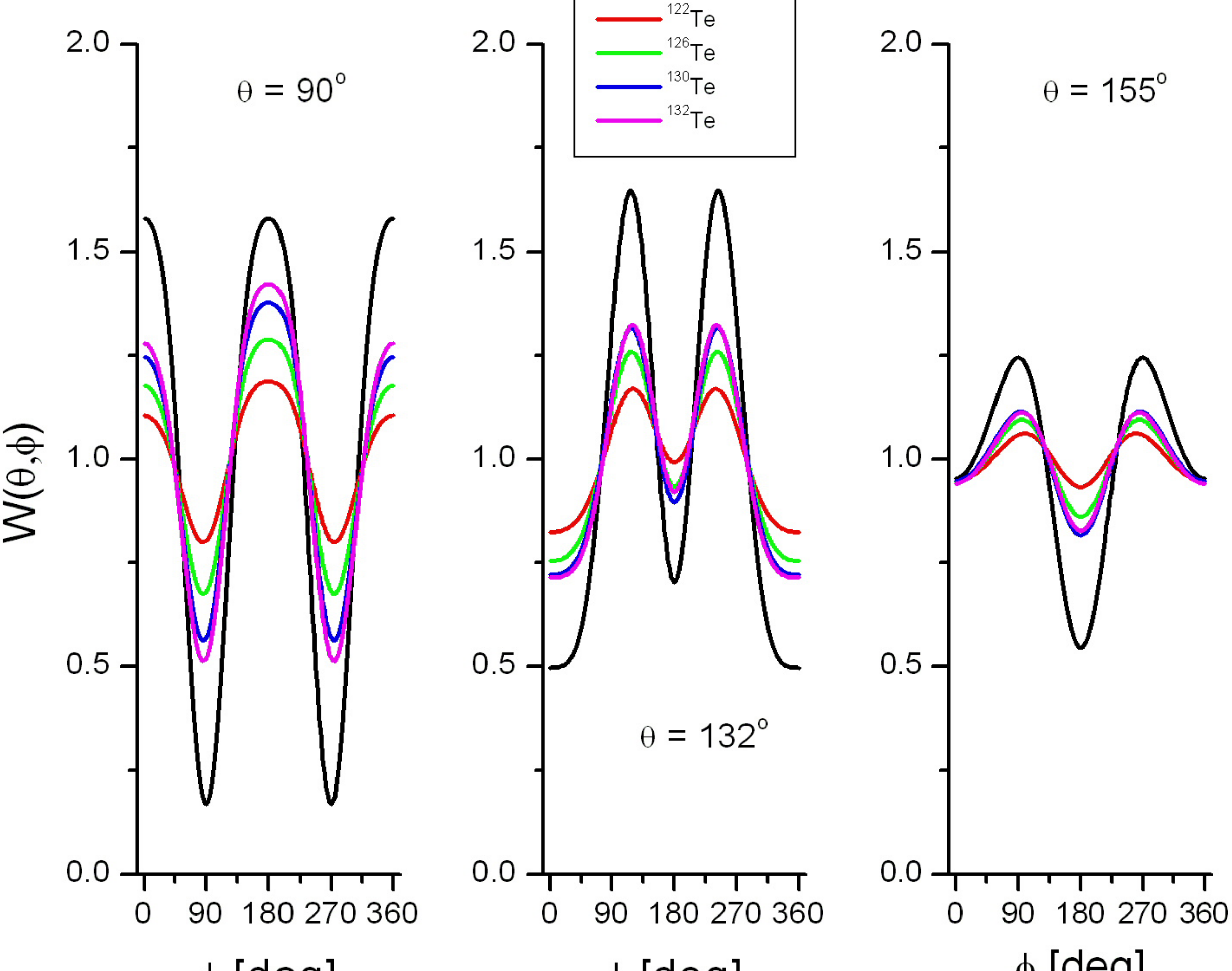
In vacuum, B field direction is random. Recoiling Coulex nuclear spins, initially aligned in plane of target, precess about B fields so angular distribution of decay gamma emission becomes attenuated.



Angular Distribution for ^{126}Te stopped in Cu backed target, fitted with calculated unattenuated theory.



Angular Distribution for $^{126, 130,132}$Te recoiled into vacuum from C target, fitted with attenuated theoretical distribution. N.B. Similarity of ^{130,132}Te



W(θ,φ)
2.0
1.5
1.0
0.5
0.0
θ = 90°
θ = 132°
θ = 155°
^{122}Te
^{126}Te
^{130}Te
^{132}Te
0
90
180
270
360
φ [deg]