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Transient hyperfine field measurements of gyromagnetic ratios in Os and Pt nuclei

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Abstract:

Precessions were measured of the 2_1^+ states in ^{192}Os and ^{198}Pt in the enhanced transient field in thin cobalt foils and comparison made with similar recent studies of ^{188}Os and ^{194}Pt ions in Fe foils. It is concluded that (i) the transient field acting on Pt in Fe is singularly anomalous, and (ii) recent contention that the g-factors of even Pt 2_1^+ states may be substantially lower than reported earlier cannot be sustained.

The mechanisms responsible for the enhanced transient hyperfine magnetic field manifest at nuclei of ions swiftly recoiling through polarized ferromagnetic materials have not, as yet, been exposed to the extent that the transient field strength may be calculated as a function of ion velocity, v, and atomic number, Z. Nevertheless, the Rutgers group[1] has incorporated a body of available experimental data for ions spanning the range from O to Sm in a "universal" field parameterization

$$B(v,Z) = \underline{a}\,(v/v_0)^p\,Z^q\,\mu_B N_p\,, \qquad (1)$$

where $v_0 = e^2/\hbar$ (Bohr velocity), μ_B is the Bohr magneton, and N_p the volume density of polarized electrons in the host ferromagnetic; best-fit parameter values were $\underline{a} = 96.7 \pm 1.6$, $p = 0.45 \pm 0.18$, and $q = 1.1 \pm 0.2$.

However, attempts to employ this parameterization to describe the observed transient field acting on Pt ions traversing polarized Fe have failed. Evidence[2,3] for Pt ion velocities $v/v_0 \lesssim 5$ in polarized Fe is in accord with a linear velocity dependence for the field, but inconsistent with $p = 0.45 \pm 0.18$. Moreover, based on the weighted average of previously measured g-factors of the 2_1^+ states in the even Pt isotopes[4], the strength of the Pt-in-Fe transient field was also found[2,3] to be considerably lower than that predicted by eq. (1). Yet the transient fields exhibited at the nuclei of neighbouring ^{186,188}Os and ^{186}W ions recoiling through magnetized Fe foils within this velocity regime were found by the Rutgers[5] and Melbourne[6] groups, respectively, to be in good accord with eq. (1).

Recently, Levy *et al.*[7] reported simultaneous measurements of the precessions of the 2_1^+ levels in ^{188}Os and ^{194}Pt as these ions recoiled through a saturated 2 μm Fe foil. Their findings were: $\Delta\theta(^{194}\mathrm{Pt})/\Delta\theta(^{188}\mathrm{Os}) = 0.74(7)$, and that $\Delta\theta(^{186}\mathrm{Os})$ and $\Delta\theta(^{188}\mathrm{Os})$ (measured separately and independently) were both consistent with that predicted for Os in Fe by eq.(1) together with the previously measured[4] $g(2_1^+)$ values of these Os nuclides.

These authors pointed out that their results could be due to either (i) an anomalously low transient field for Pt in Fe, or (ii) $g(2_1^+;{}^{194}\mathrm{Pt})$ being considerably smaller than reported earlier. The anticipation[8] that, for ions with $Z \geq 10$, the transient field would increase smoothly with Z (the more complex electronic structures of heavier ions being expected to smear out any sharp field discontinuities, such as were observed[9] for lighter ions), led Levy *et al.*[7] to attribute their findings to cause (ii), above. Consequently, stressing the reliability of most previous measurements[4] of $g(2_1^+;{}^{188}\mathrm{Os})$, they concluded that $g(2_1^+;{}^{194}\mathrm{Pt}) = 0.222 \pm 0.026$ and $g(2_1^+;{}^{196}\mathrm{Pt}) = 0.213 \pm 0.021$; values considerably smaller than and inconsistent with all prior reported measurements[4] [weighted averages of which are

$g(2_1^+;{}^{194}\mathrm{Pt}) = 0.320 \pm 0.003$ and $g(2_1^+;{}^{196}\mathrm{Pt}) = 0.326 \pm 0.014$].

Conversely, we examine the alternative that previously reported $g(2_1^+)$ values for both the even Os and Pt nuclei are indeed correct, but that the fields acting on the nuclei of these two ion species in Fe are disparate, and report our results of simultaneous measurements of the precessions of the 2_1^+ states in ${}^{198}\mathrm{Pt}$ and ${}^{192}\mathrm{Os}$ as these ions recoiled swiftly through polarized Co foils.

Beams of 80-MeV ${}^{32}\mathrm{S}$ and 220-MeV ${}^{58}\mathrm{Ni}$ ions from the Australian National University 14 UD Pelletron tandem accelerator were used to Coulomb excite the states of interest in ${}^{192}\mathrm{Os}$ and ${}^{198}\mathrm{Pt}$. Experimental particulars were virtually identical to those employed earlier[3,10,11] in similar transient field g-factor studies. Two four-layered targets were used: Target I consisted of a lead-backed 4.2 μm Co foil on the upstream side of which was an electroplated layer of ${}^{192}\mathrm{Os}$ [(938 ± 66) μg cm^{-2} enriched to 99.06%] on which a (361 ± 25) μg cm^{-2} thick layer of ${}^{198}\mathrm{Pt}$ (95.83% enriched) was electrodeposited; Target II was similar, but had a Co foil 0.9 μm thick with contiguous ${}^{198}\mathrm{Pt}$ and ${}^{192}\mathrm{Os}$ layers (296 ± 21) and (498 ± 35) μg cm^{-2} thick, respectively.

Target I was bombarded by ^{58}Ni; Target II by ^{32}S ions. A frequently reversed polarizing field of 850 Oe was applied to both targets; effective magnetic shielding rendered beam-bending negligible. For each separate target, the measured and calculated[10,11] angular distributions of all γ-ray transitions observed in both nuclides were in accord.

Data analysis followed that detailed in earlier publications[10,11] and took into account precessions of populated higher states that feed the 2_1^+ states. The pertinent experimental particulars and results of the present work are given in Table I, as are those of Levy _et al._[7] with which they are compared.

As ion transit times through the Co foils were short compared to the mean lives of the excited states populated in both nuclides, the precession angle, $\Delta\theta$, experienced by a level with gyromagnetic ratio g in the transient field, B, may be expressed as $\Delta\theta = g\phi$, in which

$$\phi = \frac{-M\mu_N}{\hbar} \int_{v_i}^{v_e} \frac{B(v,Z)dv}{S(E)} ,$$

where S(E) is the energy-dependent stopping power for the ion of mass M in the ferromagnetic medium, and v_i and v_e are, respectively, the velocities with which the ions are incident upon and emerge from the ferromagnetic foil, and μ_N is the nuclear magneton. The ratio of the simultaneously measured precessions in each target used in the present work is

$$\frac{\Delta\theta(^{198}\mathrm{Pt})}{\Delta\theta(^{192}\mathrm{Os})} = \frac{g(2_1^+;{}^{198}\mathrm{Pt})\ \phi(^{198}\mathrm{Pt})}{g(2_1^+;{}^{192}\mathrm{Os})\ \phi(^{192}\mathrm{Os})} . \tag{2}$$

Since for a given target (i) the ratio [eq.(2)] is independent of the degree of polarization of the ferromagnetic foil, and (ii) the velocities with which the Pt and Os ions traversed that foil were close to the same, the ratio $\phi(^{198}\mathrm{Pt})/\phi(^{192}\mathrm{Os})$ effectively represents the ratio of the Pt-to-Os transient field strengths for that target. The same pertains to the similar simultaneous precession measurements[7] of ^{194}Pt and ^{188}Os in polarized Fe.

The experimental precession ratios [eq.(2)] for each of the two targets used in the present work, and that measured by Levy _et al._[7] in their study, are presented in Table II. As the value of $g(2_1^+;{}^{198}\mathrm{Pt}) = 0.324 \pm 0.026$ reported in the literature was measured[10] relative to $g(2_1^+;{}^{196}\mathrm{Pt})$, and it, in turn, was measured[4] relative to $g(2_1^+;{}^{194}\mathrm{Pt})$, the lower value proposed[7] for the latter [0.222 ± 0.026] would instead imply $g(2_1^+;{}^{198}\mathrm{Pt}) = 0.225 \pm 0.032$. To broaden the scope of assessment of the results of the experimental studies presented in Table II, two different sets of g-factor ratios are listed: one set takes all $g(2_1^+)$ values to be the weighted averages of their prior determinations[4,10]; the other uses the inferred[7] lower values of $g(2_1^+;{}^{194,198}\mathrm{Pt})$, while retaining those of $g(2_1^+;{}^{188,192}\mathrm{Os})$ as in the first set.

It is clear that the results of Levy et al.[7] are consistent with the same field acting on Pt *and* Os in Fe if, *and only if,* the inordinately low value, 0.222 ± 0.026, suggested by them for $g(2_1^+;{}^{194}\mathrm{Pt})$ pertains. If *not* [i.e., if $g(2_1^+;{}^{194}\mathrm{Pt}) = 0.320$], these fields are *different*. In contradistinction, the comparisons in Table II show that the present results are consistent with the same fields at Pt *and* Os in Co if, *and only if,* the higher literature value for $g(2_1^+;{}^{198}\mathrm{Pt})$ [and, consequently, for $g(2_1^+;{}^{194}\mathrm{Pt})$] is adopted.

In light of these combined results, the supposition that the transient fields at both Pt and Os ions in both Fe and Co are the same cannot be sustained. As both Levy et al.[7] and we relied on the previously measured[4] $g(2_1^+)$ values in ^{188}Os and ^{192}Os, respectively - each determined by a variety of methods (the same methods were employed by some authors for both ^{188}Os and ^{192}Os) - it is clear that if the fields for Pt and Os in Co are the same, the transient fields acting on Pt and Os in Fe cannot be, and vice-versa. As such, the ratio of the integrated transient fields for Pt and Os in Co inferred from the present results (Table II) is incompatible with the reliance Levy et al.[7] placed on the equivalence of the transient fields acting on Pt and Os traversing Fe.

This dichotomy is examined in Table III where the ratios of the integrated transient field at Pt to that at Os in the same ferromagnetic medium are calculated (a) taking the field acting on Pt and Os in both Co and Fe as per the Rugers parameterization[1] [eq.(1)], (b) taking the field at Os in both Co and Fe to also be so represented, but that that acting on Pt in Co and Fe to have the specific linear velocity dependence experimentally obtained[2,3] for Pt in Fe over the same velocity domain, and (c) taking the fields at Os in both Co and Fe and that at Pt in Co to have the near-square-root velocity dependence of eq.(1), but that the field at Pt in Fe alone to be linearly velocity-dependent[2,3]. These calculated ratios are compared in Table III with those inferred from the present measurements and those of Levy *et al.*[7]

The comparisons made in Table III, lead to the following self-consistent set of conclusions based on the values of $g(2_1^+;{}^{188}Os)$ and $g(2_1^+;{}^{192}Os)$ both being consistent with the weighted average of all prior measurements[4]:

(i) the values of $g(2_1^+;{}^{194}Pt)$, $g(2_1^+;{}^{196}Pt)$, and $g(2_1^+;{}^{198}Pt)$ are consistent with the weighted average of all prior measurements[4,10] of each, and

(ii) the transient fields acting on the nuclei of both Pt and Os ions recoiling through polarized Co are effectively identical over the same velocity regime, and

(iii) the transient field acting on the nuclei of Pt ions recoiling through Fe is <u>different</u> from that manifest at Os ions recoiling through Fe with the same velocity; that these fields in Fe are, respectively, compatible with a linear velocity dependence and smaller strength[2,3] for Pt and a velocity dependence (and strength) for Os ions that is in accord with the Rutgers parameterization[1] [eq. (1), above].

It appears clear that the transient field acting on Pt ions traversing Fe is quenched relative to that of Os (ref. 7) and ${}^{186}W$ (ref. 6) ions in this ferromagnetic. It has been suggested[12] that due to a virtual concurrence of the 4s and 2p electron energy levels in Pt and Fe, respectively, the observed transient field discontinuity may arise from electron vacancy sharing between the two levels - a similar energy level match does not appear to apply to either Pt or Os ions in Co or to Os in Fe. This possibility and its concomitant consequences are explored in a more complete exposition of the present experimental study now in preparation.

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Table I. Present experimental particulars and results for ^{192}Os and ^{198}Pt recoiling through thin cobalt foils.

Table I. Present experimental particulars and results for ^{192}Os and ^{198}Pt recoiling through thin cobalt foils.

Target; beam	^{192}Os				^{198}Pt				L^c (μm)	T_{Co}(fs)^d		$\varepsilon(65^\circ)(\times10^3)^e$		$\Delta\theta$(mrad)^f	
	E_i^b (MeV)	E_e^b (MeV)	$(v/v_o)_i^b$	$(v/v_o)_e^b$	E_i^b (MeV)	E_e^b (MeV)	$(v/v_o)_i^b$	$(v/v_o)_e^b$		^{192}Os	^{198}Pt	^{192}Os	^{198}Pt	^{192}Os	^{198}Pt
I;220-MeV,^{58}Ni	136	28	5.3	2.4	126	25	5.1	2.2	4.2	522	560	42.6(14)	49.5(31)	-25.6(12)^g	-24.0(17)
II;80-MeV,^{32}S	32	20	2.6	2.0	34	21	2.6	2.1	0.9	179	176	17.7(9)	18.0(28)	-7.4(5)^g	-7.2(11)

[a] Both targets contained contiguous electrodeposited layers of enriched ^{192}Os and ^{198}Pt, as specified in text.

[b] Energies $E_i(E_e)$ and velocities $(v/v_o)_i$ $[(v/v_o)_e]$ of ion incident upon (emergent from) Co foils; $v_o = c/137$.

[c] Measured thickness of Co foil.

[d] Mean transit time of ion through Co foil.

[e] The experimentally measured ratio $\varepsilon = (1-\rho)/(1+\rho)$ multiplied by 10^3, where $\rho = \{[N\uparrow(+)N\downarrow(-)]/[N\downarrow(+)N\uparrow(-)]\}^{\frac{1}{2}}$ measured with detectors positioned at (±) the specified angle to the beam direction, and $N\uparrow(N\downarrow)$ are the normalized counting rates for polarizing field up(down).

[f] Inferred from measured $\varepsilon(65^\circ)$ using logarithmic derivative at 65°, $S(65^\circ)$, of the measured angular distribution of the $2_1^+ \rightarrow 0_1^+$ transition in each nuclide. Target I: $S(^{192}\mathrm{Os}) = -1.62(5)$, $S(^{198}\mathrm{Pt}) = -2.06(6)$; Target II: $S(^{192}\mathrm{Os}) = -2.22(6)$, $S(^{198}\mathrm{Pt}) = -2.50(8)$.

[g] Corrected for small precession of ^{192}Os 2_1^+ state (τ = 420 psec) in external polarizing field.

Table II. Pertinent ratios of experimental precessions, g-factors, and integrated transient fields.

	Experimental ratio $\Delta\theta(\mathrm{Pt})/\Delta\theta(\mathrm{Os})$	Ferromagnetic foil	$g(2_1^+;\mathrm{Pt})/g(2_1^+;\mathrm{Os})$	Inferred[a] $\phi(\mathrm{Pt})/\phi(\mathrm{Os})$
Target I (^{198}Pt + ^{192}Os)	0.94 ± 0.08	Co	0.885 ± 0.075[b] 0.615 ± 0.089[c]	1.06 ± 0.13 1.53 ± 0.26
Target II (^{198}Pt + ^{192}Os)	0.97 ± 0.16	Co	0.885 ± 0.075[b] 0.615 ± 0.089[c]	1.10 ± 0.20 1.58 ± 0.35
Levy *et al.*[d] (^{194}Pt + ^{188}Os)	0.74 ± 0.07	Fe	1.088 ± 0.031[b] 0.76 ± 0.09[c]	0.68 ± 0.07 0.98 ± 0.15

[a] Using eq. (2), text.

[b] Obtained using weighted averages of prior measurements (refs. 4,10) of g-factors: $g(2_1^+;{}^{198}\mathrm{Pt}) = 0.324 \pm 0.026$, $g(2_1^+;{}^{192}\mathrm{Os}) = 0.366 \pm 0.010$, $g(2_1^+;{}^{194}\mathrm{Pt}) = 0.320 \pm 0.003$, $g(2_1^+;{}^{188}\mathrm{Os}) = 0.294 \pm 0.008$.

[c] Obtained using weighted average of prior measurements (ref. 4) of $g(2_1^+;{}^{188}\mathrm{Os}) = 0.294 \pm 0.008$, $g(2_1^+;{}^{192}\mathrm{Os}) = 0.366 \pm 0.010$; $g(2_1^+;{}^{194}\mathrm{Pt}) = 0.222 \pm 0.026$ [inferred by Levy *et al.* (ref. 7)], and its consequentially inferred value of $g(2_1^+;{}^{198}\mathrm{Pt}) = 0.225 \pm 0.032$.

[d] Ref. 7.

Table III. Comparison of calculated and experimentally inferred integrated transient field ratios, $\phi(\mathrm{Pt})/\phi(\mathrm{Os})$.

Target	Ferromagnetic	Calculated		Experimentally	Experimentally

Table III. Comparison of calculated and experimentally inferred integrated transient field ratios, $\phi(\mathrm{Pt})/\phi(\mathrm{Os})$.

Target	Ferromagnetic foil	Calculated			Experimentally inferred[d]	Experimentally inferred[e]
		Basis A[a]	Basis B[b]	Basis C[c]		
Target I (present work)	Co	1.06	0.75	1.06	1.53 ± 0.26	1.06 ± 0.13
Target II (present work)	Co	1.02	0.58	1.02	1.58 ± 0.35	1.10 ± 0.20
Levy *et al.*[f]	Fe	1.03	0.61	0.61	0.98 ± 0.15	0.68 ± 0.07

[a] Basis A: transient fields acting on Pt and Os ions in Fe and Co are as given by Rutgers parameterization (ref.1) [eq.(1), present text].

[b] Basis B: transient field for Os in Co and Fe as given by Rutgers parameterization (ref.1), [eq.(1), present text], but that the fields for Pt in both Co and Fe are as were experimentally determined for Pt in Fe (ref. 3) [linear velocity dependence].

[c] Basis C: all transient fields given by the Rutgers parameterization (ref.1) [eq.(1), present text], except that for Pt in Fe which is taken to have a linear velocity dependence (ref.3).

[d] Obtained taking $g(2_1^+;{}^{188}\mathrm{Os}) = 0.294 \pm 0.008$, $g(2_1^+;{}^{192}\mathrm{Os}) = 0.366 \pm 0.010$ [the weighted averages of prior measurements (ref.4) of each], and $g(2_1^+;{}^{194}\mathrm{Pt}) = 0.222 \pm 0.026$ [inferred by Levy *et al.* (ref.7)] and its consequentially inferred value of $g(2_1^+;{}^{198}\mathrm{Pt}) = 0.225 \pm 0.032$.

[e] Obtained using the weighted averages of prior measurements (refs.4 and 10) of g-factors: $g(2_1^+;{}^{188}\mathrm{Os}) = 0.294 \pm 0.008$, $g(2_1^+;{}^{192}\mathrm{Os}) = 0.366 \pm 0.010$, $g(2_1^+;{}^{194}\mathrm{Pt}) = 0.320 \pm 0.003$, $g(2_1^+;{}^{198}\mathrm{Pt}) = 0.324 \pm 0.026$.

[f] Ref. 7.