Magnetic moment measurements in osmium and platinum nuclei

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(Received 17 August 1981)

The magnetic moments of the 2_1^+ states in ^{186,188}Os and ^{194,196}Pt isotopes have been measured by the transient field technique at ion recoil velocities $1.6 \lesssim v/v_0 \lesssim 2.8$. The transient field was assumed to follow the parametrization proposed by Shu *et al.* for ions in the range $8 < Z < 62$. The g factors obtained for osmium isotopes $g(^{186}\text{Os}) = 0.262(15)$ and $g(^{188}\text{Os}) = 0.300(15)$ are in excellent agreement with independent Mössbauer and external field measurements, indicating that the adopted parametrization is valid up to $Z = 76$. However, the same analysis yields g factors for the platinum isotopes which are smaller than previously reported: $g(^{194}\text{Pt}) = 0.203(6)$ and $g(^{196}\text{Pt}) = 0.213(21)$.

[NUCLEAR REACTIONS ^{186,188}Os(^{32}S,^{32}S′)^{186,188}Os(2_1^+), ^{194,196}Pt(^{32}S,^{32}S′)^{194,196}Pt(2_1^+); $E_S \sim 80$ MeV; enriched targets; measured $W(\theta, B, \infty)$ through polarized iron; deduced $g(2_1^+)$.]

I. INTRODUCTION

The complexity of the mechanisms involved in the production of the intense field experienced by fast ions slowing down in a polarized ferromagnetic medium is responsible for the failure of all models proposed to describe the transient field to reproduce the vast amount of data accumulated since its discovery in 1966 by Borchers *et al.*[1] Different phenomenological descriptions of the field, all expressed in terms of a few basic parameters, such as the atomic number Z of the recoil ion, its velocity v, and the magnetization M of the ferromagnet, have been suggested by different groups and applied with various degrees of success. The parametrization of the field $B(v,Z)$ adopted in the present work was derived from the overall fit[2] of transient field precession data for ions with $8 \leq Z \leq 62$, moving in the intermediate velocity region ($v_0 < v < Zv_0$) in iron and gadolinium foils. The field is expressed as

$$B(v,Z) = a \left[\frac{v}{v_0} \right]^{p_v} Z^{p_z} \mu_B N_p \ , \qquad (1)$$

where $v_0 = e^2/\hbar$ is the Bohr velocity, μ_B is the Bohr magneton, N_p is the volume density of polarized electrons, and $\mu_B N_p = M = 0.1752$ T for a saturated iron foil. The values of the parameters a, p_v, and p_z obtained for the best fit ($\chi^2 = 1.2$) to the data[2] are $a = 96.7 \pm 1.6$, $p_v = 0.45 \pm 0.18$, and $p_z = 1.1 \pm 0.2$.

The 2^+ first excited states in ^{186}Os and ^{188}Os are the most suitable candidates for calibrating the transient field at heavy nuclei. The g factors of these states have been accurately measured by Mössbauer spectroscopy[3] and in external fields,[4,5] and provide a check on the validity of the above parametrization up to $Z = 76$. The hyperfine interactions in Pt ions traversing ferromagnets were determined in earlier studies.[2,6] If the g factors adopted in the literature are correct, the transient field at Pt ions traversing iron foils is much lower than predicted by either Eberhardt *et al.*[7] on the basis of a linear velocity dependence or by expression (1). On the other hand, if the proposed parametrization of the transient field is correct, the precession data suggest g factors for the platinum isotopes smaller than those measured in earlier experiments. The present investigation aims at resolving this ambiguity by calibrating the transient field at the nearest isotopes (osmium) for which the magnetic moments have been determined by independent and direct methods.[3–5]

II. EXPERIMENT

The details of the technique have been described in previous publications from this laboratory.[8] Targets of enriched ^{186,188}Os and ^{194,196}Pt isotopes (400–500 μg/cm^2) were prepared by electroplating the isotope on thin annealed iron foils (1.4–1.6 mg/cm^2) backed by a thick copper foil (12–15

mg/cm^2). The copper backing stops both the beam and the recoils and provides a perturbation-free environment for the decaying nucleus.

An incident 80 MeV beam of $^{32}S^{+9}$ ions from the Rutgers-Bell tandem accelerator was used to Coulomb excite the 2^+ first excited states; ^{186}Os: $E_\gamma=137$ keV, $\tau=1197$ psec; ^{188}Os: $E_\gamma=155$ keV, $\tau=1024$ psec; ^{194}Pt: $E_\gamma=328$ keV, $\tau=60$ psec; and ^{196}Pt: $E_\gamma=356$ keV, $\tau=47\pm5$ psec. The γ decay was observed in four 12.7×12.7 cm NaI(Tl) detectors set at $\pm67.5°$ and $\pm112.5°$ to the beam axis, in coincidence with the backscattered beam particles detected in a Si(Li) ring counter subtending a solid angle of $165°-175°$. An external field of 0.03 T was applied perpendicular to the beam-detector plane at the site of the target in order to saturate the iron foil. The field was reversed every 3–5 min, while the data were correspondingly routed to two different areas of the computer memory. The beam-bending effects were reduced to negligible proportions by effective shielding of the beam trajectory with a soft iron cone.

The iron foils were first annealed at 700 °C for 1 h in a H_2 atmosphere. The foil magnetization was measured in an ac magnetometer[9] after target preparation and before and after each run. The unperturbed particle-gamma angular distribution was measured for each target and the value of the normalized slope $S=(1/W)(dW/d\theta)$ was evaluated at the angles $\theta_\gamma=\pm67.5°$ and $\pm112.5°$, where it is maximum. Data and fits to Legendre polynomials are shown in Fig. 1.

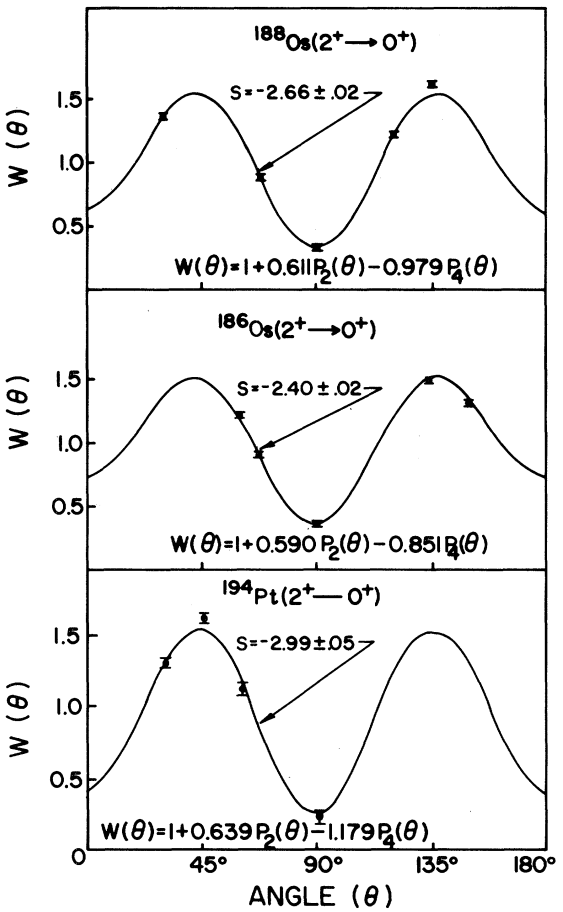

FIG. 1. Unperturbed particle-gamma angular distributions for the $2^+\rightarrow0^+$ transitions in ^{186}Os, ^{188}Os, and ^{194}Pt isotopes in backscattered geometry. The normalized slope $S=(1/W)(dW/d\theta)$ is given in each case at the angle at which the precession was measured.

III. RESULTS

The general procedure followed to extract g factors from the measured angular precessions $\Delta\theta_{\text{exp}}$ involves the calculation of the expression

$$g=-\frac{\Delta\theta_{\text{exp}}}{(\mu_N/\hbar)\int_0^T B[v(t)]e^{-t/\tau}dt}, \tag{2}$$

where T is the transit time of the recoil ion through the ferromagnetic foil, and $B[v(t)]$ is given by expression (1). The effect of decays in flight is taken into account by the factor $e^{-t/\tau}$ multiplying the integrand in (2). By introducing the stopping power $S(E)=dE/dx$ of the host, the time integral is transformed into an energy integral:

$$g=-\frac{\Delta\theta_{\text{exp}}}{(\mu_N/\hbar)\int_{E_i}^{E_f} e^{-t/\tau}[B(E)dE/S(E)]}, \tag{3}$$

where E_i and E_f are the initial and final recoil velocities at the entrance and exit of the iron foil. The stopping powers $S(E)$ needed in Eq. (3) were obtained at each integration point by interpolation of the Northcliffe and Schilling tables[10] and included an estimate of the nuclear stopping powers[2] in the range of velocities considered. An uncertainty of 3% in the determination of the iron foil thickness was added in quadrature to the statistical error in g.

A. Osmium

The characteristics of the different targets used in this experiment are summarized in Table I, together with the results of the precession measurements. Because of the relatively long lifetimes of

TABLE I. Summary of results for ^{186}Os and ^{188}Os isotopes recoiling through thin iron foils.

Isotope	Target	L (iron) (mg/cm^2)	$\left[\frac{v}{v_0}\right]_{in}$	$\left[\frac{v}{v_0}\right]_{out}$	T (psec)	$\Delta\theta$ (mrad)	g factor	Ref.
^{188}Os $\tau=1024$ psec	I	1.424	2.81	1.77	0.371	−15.90(60)	0.300(15)	This work
							0.305(15)	3
							0.270(18)	4
^{186}Os $\tau=1197$ psec	II	1.523	2.84	1.72	0.398	−14.80(70)	0.262(15)	This work
							0.281(8)	3
							0.274(19)	5
^{188}Os[a]	III	1.580	2.76	1.61	0.434	−16.60(150)	0.275(26)	This work

[a]Mixed ^{188}Os+^{194}Pt target.

the 2^+ states in both isotopes (^{186}Os and ^{188}Os), the data were corrected in each case for the small precession of the nuclear moment in the external field ($\Delta\theta_c \approx 0.5$ mrad). For target I, prepared from highly enriched ^{188}Os isotope (90% ^{188}Os, $<0.5\%$ ^{186}Os), a g factor for the 2_1^+ state $g(^{188}\text{Os}) = 0.300(12)$ was obtained, in excellent agreement with the Mössbauer[3] and external field[4,5] measurements. For target II, for which the ^{186}Os enrichment was only 60%, a second correction was applied to take into account the precession of the unresolved 155 keV γ ray from the 2_1^+ state of the contaminant ^{188}Os isotope. The γ spectrum was observed with a large Ge(Li) detector to determine accurately the relative yields of the 137 keV (^{186}Os: $2_1^+ \rightarrow 0^+$) and 155 keV (^{188}Os: $2_1^+ \rightarrow 0^+$) transitions. A value $r =$ Yield(^{188}Os)/Yield(^{186}Os) $= 0.16 \pm 0.01$ was obtained. The data were corrected by assuming

$$\Delta\theta_{\text{meas}} = \frac{\Delta\theta_1(^{186}\text{Os}) + r\Delta\theta_2(^{188}\text{Os})}{1+r}, \tag{4}$$

where $\Delta\theta_2(^{188}\text{Os})$ was obtained from the measurements performed at similar recoil velocities on target I. The g factor $g(^{186}\text{Os}) = 0.262(13)$ was thus obtained, again in good agreement with the Mössbauer and external field measurements. (See Fig. 2.)

Target III consisted of a layer of ^{188}Os (90% enrichment) evaporated over a ^{194}Pt film. The measurements on this target were performed for the purpose of investigating possible systematic errors in the Pt measurements described below. The energy loss of the Os ions recoiling through the Pt layer before entering the iron foil was taken into account. The value obtained for the ^{188}Os g factor, $g = 0.275(26)$, agrees within the error with the above results. The larger error obtained in this case arises from the subtraction of a relatively high background on the low energy part of the γ-coincidence spectrum due to the Compton edge of the Pt γ ray (see Fig. 3).

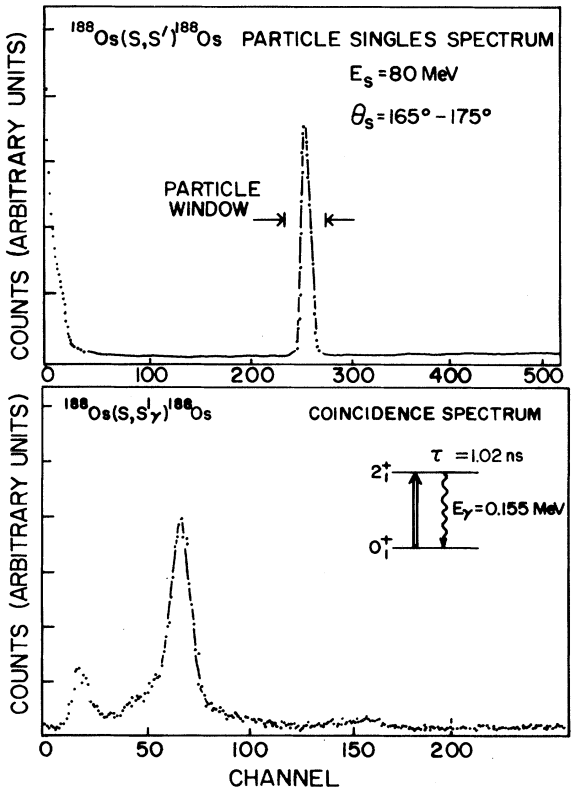

FIG. 2. Particle and gamma coincidence spectra for the ^{188}Os$(S,S'\gamma)^{188}$Os reaction.

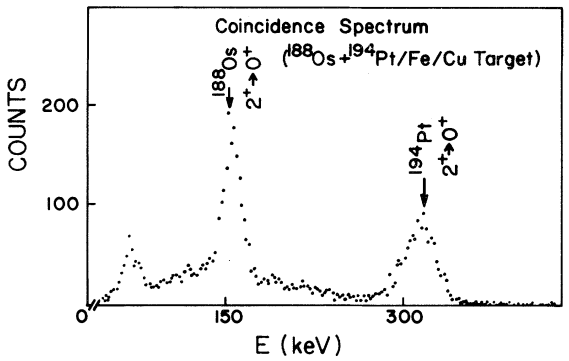

FIG. 3. Coincidence spectrum obtained for the mixed ^{188}Os+^{194}Pt target.

The excellent agreement between the g factors of the 2_1^+ states of ^{186}Os and ^{188}Os measured here and those determined by Mössbauer spectroscopy and external field measurements implies that the parametrization of the transient field derived from data for ions in the range $8 \leq Z \leq 62$ is indeed valid up to $Z=76$.

B. Platinum

The composition of the ^{194,196}Pt targets, the velocity range of the recoiling ions, and the results of the measurements are summarized in Table II together with the precession measurements of the Chalk River[11] and Melbourne[12] groups performed under similar conditions. The transient field at the Pt ions was calculated from Eq. (1). The g factors $g(^{194}\text{Pt})=0.203(6)$ and $g(^{196}\text{Pt})=0.213(21)$ were obtained.

Table III summarizes the most recent measurements of the g factors of the 2_1^+ states in ^{194,196}Pt by ion implantation perturbed angular correlation (IMPAC)[14,15] radioactivity,[16,17] and transient field methods.[11,12] The present results are considerably lower than all previously reported values. For the present data to yield moments in agreement with those obtained by other techniques, the hyperfine field acting on the Pt ions would have to be much smaller than that measured at the Os ions.

In the following discussion, the different methods used to determine hyperfine interactions and g factors of Pt isotopes are examined and possible explanations of the observed discrepancies are presented. First, consider the transient field measurements. The measured precessions on ^{194}Pt ions determined by the Rutgers and Chalk River[11] groups are in excellent agreement with each other. The quoted g factors differ because different formulations of the transient field were used by the two groups, with the Chalk River group proposing a much smaller transient hyperfine field than predicted from the systematics and Eq. (1). In addition, both the Melbourne group[12] and deRaedt *et al.*[13] have obtained velocity dependent data on platinum ions which are consistent with a linear parametrization of the hyperfine field. However, the calibration of the transient field provided by the measurement on the neighboring Os isotopes provides in effect an unambiguous determination of the magnetic hyperfine interaction at Pt ions, if one assumes that atomic structure effects do not play an important role as the atomic number of the ion is changed from $Z=76$ to $Z=78$. Sharp discontinuities in hyperfine fields have been ob-

TABLE II. Summary of precession data from transient field experiments on Pt isotopes at intermediate velocities.

Isotope	L (iron) (mg/cm^2)	$\left[\frac{v}{v_0}\right]_{in}$	$\left[\frac{v}{v_0}\right]_{out}$	T (psec)	$\Delta\theta$ (mrad)	g factor	Ref.
^{194}Pt	1.44	2.717	1.683	0.390	−10.94(95)	0.195(17)[a]	6
^{194}Pt	1.503	2.725	1.646	0.410	−12.60(60)	0.215(12)	This work
^{194}Pt[b]	1.580	2.739	1.607	0.433	−12.30(30)	0.199(8)	This work
					average	0.203(6)	This work
^{194}Pt	1.95	3.48	1.86	0.45	−12.40(80)		11
^{196}Pt	1.250	2.701	1.814	0.327	−10.20(10)	0.213(21)	This work
^{196}Pt	0.888	2.52	1.81	0.241	−6.7(0.7)		12
^{196}Pt	0.888	3.15	2.46	0.186	−7.0(1.0)		12

[a]The data of Ref. 6 were reanalyzed with improved background, resulting in a somewhat larger g factor than quoted in Ref. 6 [$g=0.164(14)$].
[b]Mixed ^{188}Os+^{194}Pt target.

TABLE III. Experimental g-factor values of the 2_1^+ state in Pt isotopes with various methods. The value of the lifetime used in the derivation of the g factor is specified in each case.

Isotope	τ (psec)	g factor	Method	Ref.
^{194}Pt	50 ±5	0.351±0.041	IMPAC	14
	51 ±4	0.32 ±0.04	IMPAC	15
	51 ±4	0.354±0.031	Radioactivity	16
	60 ±4	0.274±0.025[a]	Radioactivity	11,17
	60 ±4	0.203±0.006	TF	This work
^{196}Pt	43.6±3.0	0.328±0.045	IMPAC	14
	47.6±5.0	0.27 ±0.04	IMPAC	15
	47.0±5.0	0.292±0.036	Radioactivity	17
	47.0±5.0	0.213±0.021	TF	This work

[a]This value, adopted by the Chalk River group to calibrate their data, corresponds to the measurement of Beraud *et al.* (Ref. 17) $g=0.326$ corrected for the more up-to-date value of the lifetime $\tau=60$ psec (Ref. 18).

served as a function of Z for light ions[19] ($6<Z<20$), and have been attributed to shell structure effects. Such effects are, however, not expected to occur in heavy ions where the large number of atomic shells and complex excitation processes will tend to smear out any such discontinuity. Therefore, if one assumes a smooth variation ($\sim Z^{1.1}$) of the transient field between osmium and platinum, one is inclined to conclude that the g factors in ^{194}Pt and ^{196}Pt are indeed smaller than the previously reported values.

The IMPAC measurements, on the other hand, are subject to a number of systematic errors, since both the nuclear lifetime and the static hyperfine field have to be known accurately in order to interpret the data. The latter is not a well known quantity for a large number of ion species. In addition, during implantation experiments where the ion stops in the target material, radiation damage effects can significantly change the value of the field at the implantation site. Most of the IMPAC data must also be corrected for the transient field effects, which in some cases[14] add a major contribution ($\sim 50\%$) to the net precession.

The γ-γ radioactivity coincidence measurements by Katayama *et al.*[16] are, therefore, likely to be the most reliable, as they do not suffer from radiation damage or transient field effects. However, their results also disagree strongly with our results. A possible explanation for the discrepancy with this particular experiment could arise from a large underestimate of the *static field* at Pt impurities implanted in an iron matrix. Several investigators have measured the static field at Pt ions using nuclear magnetic resonance (NMR),[20] Mössbauer,[21,22] and heat capacity[23] methods. The Mössbauer and heat capacity measurements were performed on high concentration (~ 3 at. %) Pt-Fe alloys. NMR measurements carried out for various concentrations by Kontani and Itoh[20] yielded a value for the static field H(Pt-*Fe*)=0.128 T which was "universally" adopted. These authors did, however, observe in the specific case of very dilute Pt alloys (0.5 at. %) an additional high frequency line. They, nevertheless, only consider the low frequency line of the spectrum when they calculate the magnitude of the static field and ignore the possible implications of the high frequency transition. These results suggest that the value of the static hyperfine field at extremely low concentration Pt ions implanted in iron may well be higher than the value adopted for the analysis of all IMPAC and radioactivity data. If, indeed, the static field at *dilute* impurities is higher than was suspected, both IMPAC and radioactivity measurements would yield g factors in agreement with the present transient field data.

It must be emphasized that, although the parametrization of the field written in Eq. (1) was used to derive the $^{194-196}$Pt g factors, the same results are obtained independently of any parametrization by using as calibration the value of the field at the neighboring Os isotopes. All measurements on Pt and Os were done at very similar recoil velocities and on iron foils of identical thickness. Furthermore, the measurements performed on the

TABLE IV. Theoretical estimates for the g factor of the 2_1^+ state in ^{194}Pt and ^{196}Pt isotopes.

Nucleus	Kumar-Baranger (Ref. 25)	Greiner (Ref. 26) Deformed	Greiner (Ref. 26) Spherical	Weeks-Tamura (Ref. 24)	Experiment
^{194}Pt	0.29	0.295	0.320	0.368	0.203(6)
^{196}Pt	0.30	0.29	0.316	0.387	0.213(21)

mixed Pt and Os target provide by themselves a reliable calibration point for the Pt data totally consistent with the results obtained for the separate targets and confirming the validity of the adopted parametrization up to $Z=76$. From the ratio $g(^{194}\text{Pt})/g(^{188}\text{Os})=\Delta\theta(\text{Pt})/\Delta\theta(\text{Os})=0.74(7)$, the value $g(^{194}\text{Pt})=0.222(26)$ is obtained, in good agreement with that obtained if the transient field obeys Eq. (1).

IV. DISCUSSION

The Os-Pt region seems to be as interesting for nuclear structure investigation as for hyperfine interactions studies. Nuclei in this region have been found to be subject to a large scale competition between prolate and oblate shapes, which causes a change in the sign of the quadrupole moment $Q(2_1^+)$ between Os and Pt.[24] Os isotopes have also been found, in general, to be more deformed than the Pt isotopes, which could explain their relatively higher g factors.

The theoretical estimates based on collective excitation of the g factors of the 2_1^+ states in Pt isotopes[24–26] are given in Table IV. As none of these values approach the experimental values obtained here, a simple calculation based on single particle wave functions was attempted. Although it is doubtful whether the shell model applies to Pt, such a calculation could yield an indication of the importance of single particle states in the description of the 2_1^+ state.

Since $N=116$, $Z=78$, two neutrons occupy the $p_{3/2}$ shell, and two protons occupy the $d_{3/2}$ shell, a possible configuration for the 2^+ state is given by

$$\psi=\frac{1}{\sqrt{2}}[(\pi d_{3/2}{}^2)^{L_p=2}(\nu p_{3/2}{}^2)^{L_n=0} + (\pi d_{3/2}{}^2)^{L_p=0}(\nu p_{3/2}{}^2)^{L_n=2}] ,$$

which together with the Schmidt values of g_p and g_n yields

$$g(2_1^+)=-0.60 .$$

Though naive, this calculation is encouraging. The shell model predicts a large negative moment, while collective modes will tend to make it positive ($Z/A\sim 0.4$). If instead of the Schmidt values, g_p and g_n, the experimental values of moments of odd nuclei[27] are used in the calculation, a value $g(^{194}\text{Pt};2_1^+)=-0.15$ is obtained, showing in this case that some of the collectivity has been taken into account. On the basis of these estimates it is reasonable to assume that the competition between the shell and the collective structure tends to decrease the magnetic moments from those obtained from purely collective predictions and low g values are quite plausible for the Pt isotopes.[28]

This work was supported in part by the National Science Foundation.

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