g factors of the lowest $\frac{5}{2}^+$ and $\frac{7}{2}^+$ states in ^{197}Au and calibration of the transient magnetic field in Gd

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The angular precessions of the lowest $\frac{5}{2}^+$ and $\frac{7}{2}^+$ states in ^{197}Au have been measured employing the transient field method. The ^{197}Au nuclei, Coulomb-excited by a 180 MeV ^{63}Cu beam, traversed the Gd foil with velocities between $5v_0$ and $2v_0$ ($v_0=c/137$). We have obtained the values $g(\frac{5}{2}^+)=0.21(2)$ and $g(\frac{7}{2}^+)=0.15(2)$, which are consistent with the predictions of the particle-core weak-coupling model. The field has been calibrated with the Chalk River parametrization, which has been checked using the known g factors of the lowest 2^+ states in ^{184}W, ^{186}W, ^{194}Pt, and ^{196}Pt as probes.

I. INTRODUCTION

Over the last few years the transient magnetic field (TF) technique has allowed the body of the g-factor measurements to be considerably enlarged, in particular for states with lifetimes of the order of 1 ps.[1] These measurements were first concerned mainly with the lowest 2^+ states of the stable even-even nuclei. More recently, the range of application has been extended to higher excited levels in even-even nuclei and to even-odd nuclei, especially for stable heavy nuclei, where a transient field strength (B_{TF}) of several kT can occur.

As an example of TF g-factor measurement using gadolinium as ferromagnetic medium, we report here on the g-factor determination of the $\frac{5}{2}^+$ state at 279 keV and the $\frac{7}{2}^+$ state at 548 keV in ^{197}Au, for which no data of reasonable accuracy have been so far reported.[2] The investigated levels have also been recently described in the framework of the weak coupling core excitation model.[3] The aim of the present experiment is to check further whether that kind of approach can be maintained or more refined models are necessary.

The comprehensive experimental work of the Chalk River (CR) group on heavy nuclei[4] has illustrated the advantages of using gadolinium as ferromagnet, i.e., an effect almost three times larger than the one obtained using iron for states with $\tau \geq 1$ ps, a reasonably accurate calibration of the transient field in the velocity range $2v_0 < v < 5v_0$ as given by the formula

$$B_{\mathrm{TF}} = a v/v_0 Z \exp(-\beta v/v_0) ,$$

where $v_0=c/137$, and both Z and v refer to the moving ion.

For recoil into iron the same CR parametrization with proper a and β coefficients has been proposed, which is equivalent to the Rutgers parametrization.[1] However, a 30% reduction of the TF for platinum in iron with respect to the general behavior has been observed in the velocity range $2v_0 < v < 4v_0$.[5] This fact has been attributed to a matching of the $4s$ electron binding energy in the Pt with that of the $2p$ electrons in Fe in the framework of a molecular orbital mechanism.

The use of iron as ferromagnet is then quite troublesome in the mass region around platinum. On the contrary, such an energy matching does not occur in the case of gadolinium and in fact no anomalies have so far been experimentally observed.[4]

However, since the TF calibration remains a quite delicate problem, the reliability of the CR calibration in gadolinium has been further checked for the neighboring Pt and W nuclei.

II. EXPERIMENTAL PROCEDURE

The investigated nuclei were Coulomb excited at the Laboratori Nazionali di Legnaro (LNL) XTU tandem and the usual technique with four gamma detectors in coincidence with backscattered beam ions[1] was employed. The experiment was performed in two runs under slightly different conditions.

In the first run a 180 MeV ^{63}Cu beam of 2–3 particle nA intensity was used to Coulomb excite the nuclei ^{197}Au, ^{194}Pt, and ^{196}Pt. The gold target consisted of a 1.0 mg/cm^2 layer evaporated on a 4.6 mg/cm^2 gadolinium foil, backed with 6.0 mg/cm^2 of copper. The natural platinum target consisted of a 1.0 mg/cm^2 layer evaporated on a 4.9 mg/cm^2 gadolinium foil, backed with 6.0 mg/cm^2 of copper. The particle detector was a square 4 cm$\times$4 cm parallel plate avalanche counter (PPAC) with a gap of 1.5 mm and a 10 mm central dead region with a 4 mm central hole.[6] The solid angle was about 1.0 sr. The entrance window was a 5 μm thick macrofol foil (Bayer), which stopped most of the copper ions backscattered from the gadolinium. In this way a drastic reduction of the

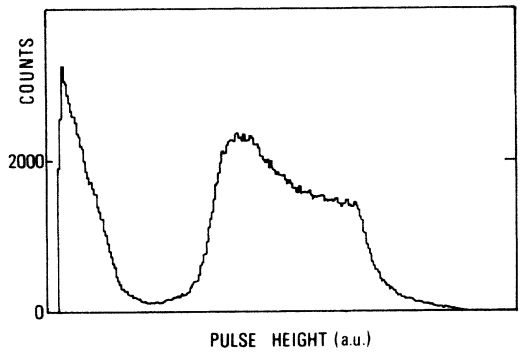

FIG. 1. Single particle spectrum taken with an annular SSB detector at backward angles and at a ^{63}Cu bombarding energy of 180 MeV (a.u. means arbitrary units).

background counting rate and a good rejection of the ions backscattered from gadolinium were obtained.

In the second run a 150 MeV ^{58}Ni beam was used to Coulomb excite ^{194}Pt, ^{196}Pt, ^{184}W, and ^{186}W. The natural Pt target consisted of a 1.0 mg/cm^2 layer evaporated on a 1.70 mg/cm^2 gadolinium foil, which was attached to a 100 μm thick copper foil by means of a 300 μg/cm^2 layer of indium. Analogously, the natural W target consisted of a 1.0 mg/cm^2 layer on a 4.20 mg/cm^2 gadolinium foil. In this run the particle detector was an annular silicon surface barrier detector, which covered the angles between 170 and 156 deg. Also in this case a 5 μm absorber drastically reduced the counting due to the gadolinium. An example of a single particle spectrum is shown in Fig. 1.

The gadolinium foils were obtained by rolling thicker commercial foils (Goodfellow Metals). Their thicknesses were determined both by areal density measurement and with an americium α source with consistent results. The foils were annealed at 600 °C for a few minutes in a 10^{-7} bar vacuum in order to improve their magnetic properties, which were then checked with a double coil induction magnetometer.

A sketch of the experimental chamber has already been reported in Ref. 7. In the present experiment we were concerned with lower energy gammas, therefore the target assembly was slightly modified in order to minimize absorption effects. The target was screwed between the pole tips of an electromagnet and kept at a temperature of about -185 °C by cooling with liquid nitrogen. Furthermore, in order to avoid local heating of the target, the beam was kept defocused in the 3 mm entrance collimator.

The gamma rays were detected in four ~ 60 cm^3 intrinsic germanium detectors positioned at a distance of about 8 cm from the target.

According to the procedure described in Ref. 7, the experiment consisted of two parts: (a) a TF effect measurement performed while inverting the direction of the external magnetic field and (b) an effect measurement for small right-left rotations of the gamma ray detector assembly, which determines the slope of the angular distribution at the gamma detector angles.

During the TF effect measurement the external field was kept at 250 G, which was more than sufficient to saturate the gadolinium. The calculated beam bending effect[8] is, for such field strength, negligible. The external

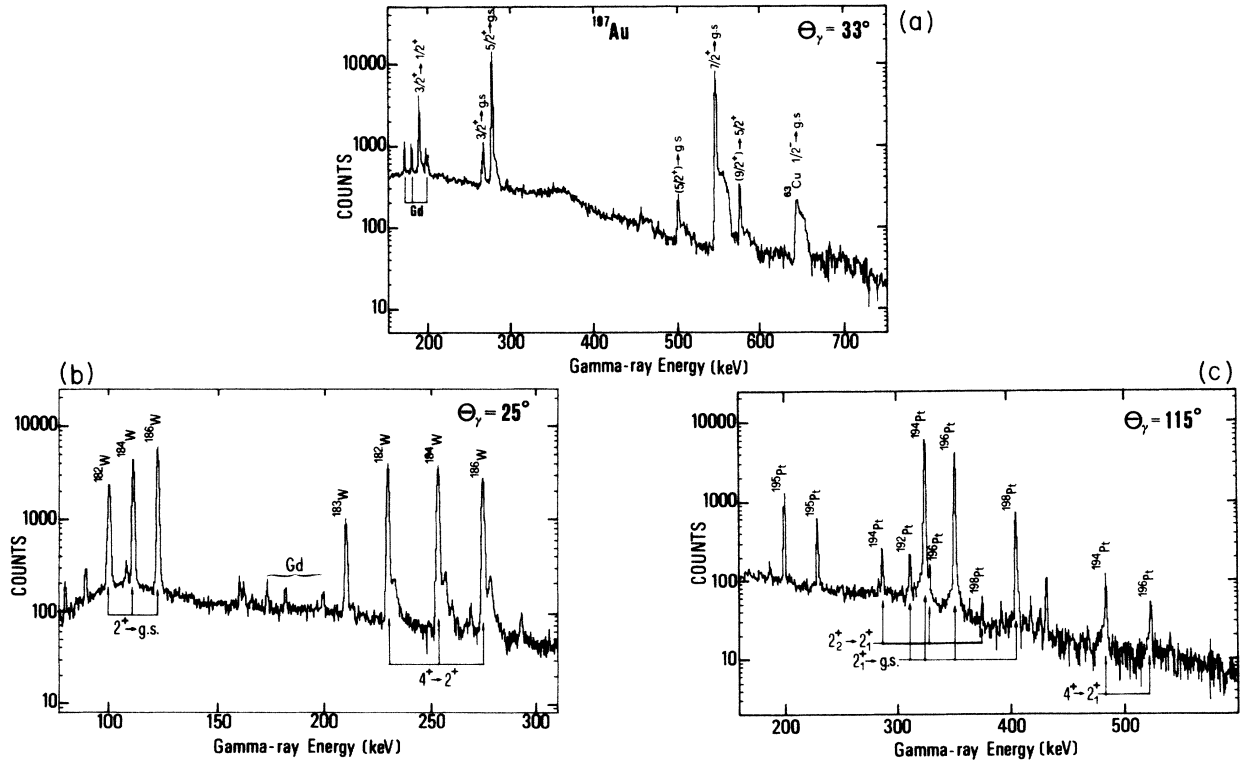

FIG. 2. Typical coincidence gamma spectra with (a) 180 MeV ^{63}Cu beam on gold; (b) 150 MeV ^{58}Ni beam on tungsten; (c) 180 MeV ^{63}Cu beam on platinum.

field direction was reversed at a prefixed beam charge about every 2 min. In the slope measurement, the germanium detectors were rotated by a fixed angle about every 20 min.

In the case of gold two germanium detectors were located at $\pm 33°$ and the other two at $\pm 115°$ in order to get a good sensitivity for the $\frac{5}{2}^+ \rightarrow \frac{3}{2}^+$ and the $\frac{7}{2}^+ \rightarrow \frac{3}{2}^+$ transitions, respectively. The angles were chosen according to the expected angular correlation on the basis of the known mixing ratios.[9] In the case of platinum and tungsten, two detectors were located at $\pm 25°$ and the other two at $\pm 115°$ to get a good sensitivity to the $2^+ \rightarrow 0^+$ transitions.

The electronic setup consisted of four fast-slow coincidence lines. The triparametric coincidence events were recorded on magnetic tapes for the off-line analysis, which was performed separately for each field-up, field-down sequence (or left-right for the slope measurement). Examples of coincidence gamma spectra are shown in Figs. 2(a)—(c).

III. DATA ANALYSIS

The data analysis follows the procedure previously adopted.[7] The effects are defined as

$$\epsilon = \frac{\sqrt{r}-1}{\sqrt{r}+1} \text{ with } r = \frac{N^+ N_-}{N_+ N^-} .$$

For small rotations one may approximate

$$\epsilon = S\Delta\theta \text{ with } S = \frac{1}{W}\frac{dW}{d\theta} .$$

In our setup the slope S of the angular distribution W was deduced by rotating the germanium detector assembly by $\pm 2°$ in the case of platinum and tungsten and by $\pm 2.5°$ in the case of gold, getting precessions of the order of those produced by the transient field. For such angular rotations the linear approximation is valid to better than 1%.

For a directly fed level of lifetime τ the angular precession is related to the transient field through the expression

$$\Delta\theta = g\frac{\mu_N}{\hbar}\int_{t_{in}}^{t_{out}} B_{TF}\exp(-t/\tau)dt . \quad (1)$$

For explicit evaluation of this formula the ion stopping power comes into play through the relation

$$dt = m\frac{dv}{dE/dx} .$$

We have adopted the stopping power dE/dx of Ref. 10, imposing to the electronic part a linear dependence on the velocity for energies below 0.2 MeV/nucleon. This requirement is, at any rate, of little relevance under the present experimental conditions. The stoppings for recoil in gadolinium have been further compared with those used by the Chalk River group[4] which resulted in values 5—10% larger. For the sake of homogeneity we decided to adopt those values.

The stopping power used in this study was directly checked by measuring the Doppler shift of the 548 keV gold line in a run with a target on gadolinium without copper backing.

Owing to the insufficient resolution in the particle detection, the gamma transitions under consideration were partly due to feeding by upper levels. This contribution was of a few percent in the case of gold and platinum, and of about 30% in the case of tungsten.

Concerning the calibration measurements in tungsten and platinum, the indirect feeding corrections to the precessions directly deduced from form (1) was negligible. In fact, the relevant upper levels in ^{194}Pt and ^{196}Pt have g factors similar to that of the 2^+ states[11] in which case form (1) can be easily demonstrated to be still valid. A similar situation is expected to occur for the good rotators ^{184}W and ^{186}W, and has been directly verified for ^{186}W.[12] ^{182}W could not be analyzed owing to the interference with a ^{183}W line.

Finally, referring to the measurement on gold, the indeterminacy caused by the indirect feeding is negligible as compared to the experimentally achieved precision. The derived experimental angular precessions are given in Table I. In the case of W a small precession of about one mrad due to the external field was taken into account.

The adoption of a reference g-factor value on the basis

TABLE I. Summary of target configurations and kinematics for the recoiling isotopes. For all cases the target thickness was 1.0 mg/cm^2. L denotes gadolinium foil thickness. v_{in} and v_{out} are the mean input and exit velocities of the recoiling ion in the gadolinium. T is the mean transit time in the ferromagnet.

Nucleus	E_x (keV)	Beam	L (Gd) (mg/cm^2)	v_{in}/v_0	v_{out}/v_0	T (fs)	$\Delta\theta_{sp}$ (mrad)	$\Delta\theta_{calc}$ (mrad)
^{197}Au	279	^{63}Cu	4.6	4.9	2.5	760	34(4)	162/g
	548	^{63}Cu	4.6	4.9	2.5	760	25(4)	167/g
^{194}Pt	328	^{63}Cu	4.9	4.9	2.4	820	55(3)	55
		^{58}Ni	1.7	4.4	3.4	255	15(3)	18
^{196}Pt	356	^{63}Cu	4.9	4.9	2.4	820	52(3)	56
		^{58}Ni	1.7	4.4	3.4	255	16(3)	19
^{184}W	111	^{58}Ni	4.2	4.5	2.3	721	42(5)	44
^{186}W	122	^{58}Ni	4.2	4.5	2.3	721	53(7)	50

TABLE II. Summary of g factor and mean life measurements.

Nucleus	E_x (keV)	J^π	τ (ps)	g	
^{197}Au	g.s.	$\frac{3}{2}^+$		0.097164(1)	Ref. 2
	77	$\frac{1}{2}^+$	2760(20)	0.840(8)	Ref. 2
	269	$\frac{3}{2}^+$	20(5)		
	279	$\frac{5}{2}^+$	23(4)	0.21(2)	present work
	548	$\frac{7}{2}^+$	6.7(4)	0.15(2)	present work
^{194}Pt	328	2^+	60(4)	0.30(2)	see text
^{196}Pt	356	2^+	46(3)	0.31(2)	see text
^{184}W	111	2^+	1800(30)	0.288(7)	Ref. 2
^{186}W	122	2^+	1460(60)	0.326(15)	Ref. 2
^{198}Hg	412	2^+	32(2)	0.38(5)	Ref. 2

of the reported experimental ones is a very delicate point when calibrating the transient field.

The data useful for the following discussion are summarized in Table II. By the way, we note that for the gold states we adopt the lifetimes of Ref. 9 deduced from Coulomb excitation, since they resulted in better agreement than the recoil distance data obtained with a Doppler shift attenuation method (DSAM) analysis of the line shape of the gamma peaks. The effects of this choice are, however, negligible for the present discussion.

For the platinum isotopes the following considerations were made. The values $\tau(^{194}\text{Pt})=60(4)$ ps (Ref. 13) and $\tau(^{196}\text{Pt})=46(3)$ ps (Ref. 14) were used together with $g(^{196}\text{Pt})/g(^{194}\text{Pt})=1.05(4)$ from Refs. 13, 15, and 16 and the present work. From the reported[2] implantation perturbed angular correlation (IMPAC) data we obtain $g(^{194}\text{Pt})=0.30(2)$ and $g(^{196}\text{Pt})=0.31(2)$. However, $g(^{194}\text{Pt})$ was taken as 0.274(25) in Ref. 13 and as 0.320(16) in Ref. 11.

In the case of W we adopted $g(^{184}\text{W})=0.288(7)$ and $g(^{186}\text{W})=0.326(15)$, relying on the values reported in Ref. 2. It should be noted that in Ref. 12 $g(^{186}\text{W})$ was to be 0.357(13) by averaging a selected sample of measurements.

Inserting the adopted reference g factors into formula (1) and using for B_{TF} the CR parametrization as deduced for Pb,

$$B_{\text{TF}}=28v/v_0 Z \exp(-0.135v/v_0)\ kT\ ,$$

one obtains for Pt and W the angular precessions shown in Table I. The agreement between predicted and measured values confirms the reliability of the field calibration, which was adopted in the case of Au. The obtained g-factor values are $g_{5/2}=0.21(2)$ and $g_{7/2}=0.15(2)$. The quoted error is only statistical.

After completion of the experimental part of the present work we became aware of a measurement made under similar experimental conditions but using a 5.4 μm iron foil as ferromagnet.[7] The reported angular precessions were $\Delta\theta_{5/2}=24.2(30)$ mrad and $\Delta\theta_{7/2}=21.4(20)$ mrad. The authors deduced $g_{5/2}=0.26(3)$ and $g_{7/2}=0.23(2)$ adopting the same B_{TF} as measured in platinum,[5] which however, is known to deviate from the general trend. Alternatively adopting the CR calibration in Fe or the equivalent Rutgers one, we deduce $g_{5/2}=0.21$ and $g_{7/2}=0.18$, values in good agreement with the present experiment.

IV. DISCUSSION

A. The transient field

Based on the present experimental results the following conclusions were made:

(i) The precessions for W and Pt in gadolinium were in agreement with the predictions of the CR parametrization which is capable of reproducing all the reported data for heavy ions.

(ii) The agreement achieved in the case of Pt in Gd clearly contradicts the suggestion[16] that the g factors in Pt isotopes have a value of about 0.2. This assumption, in disagreement with all of the previous existing measurements, was made with the purpose of avoiding the appearance of an anomalous low field for Pt in Fe. The anomaly is indirectly confirmed by the present experiment.

(iii) For Au in Fe no striking anomaly occurs as for Pt in Fe. In fact the gold g factors obtained in Fe (Ref. 17) are consistent with ours in Gd under the assumption of a standard CR or Rutgers parametrization.

These results should not allow one to overlook the fact that the understanding of the atomic processes governing the TF, in particular for heavy ions, is still not satisfactory. Following the rather qualitative interpretation presented in Ref. 4, the transient field at heavy ions is mainly given by polarized $4s$ electron vacancies as described by the generally accepted relation

$$B_{\text{TF}}=\sum_n q_{ns} p_{ns} B_{ns}\ ,$$

where q_{ns} and p_{ns} are the electron vacancy fractions and

the polarizations in the *ns* orbit with hyperfine field B_{ns}. The quantity q_{ns} has been estimated using a crude approximation and by excluding any molecular orbital (MO) mechanism. Referring to the polarization p_{ns} it is possible, with the present knowledge of the atomic collisions, to suggest some possible mechanisms. In this context the anomaly of the B_{TF} for Pt in Fe is an additional difficulty. As suggested in Ref. 5, the only plausible explanation of that anomaly is to relate it to the energy matching of the 4*s* electrons in Pt with the 2*p* electrons in Fe in the framework of a MO mechanism. The consequent vacancy quenching would be large at low velocity ($\approx 2v_0$) and small at higher velocity ($\approx 5v_0$). From this interpretation one derives the fact that the contribution of the 5*s* shell to the transient field is in general small. Strictly speaking the energy matching should not be considered as a necessary condition for a MO mechanism. One could draw a detailed correlation diagram as in Ref. 18, which is complicated in the present situation. Within this framework the success of the CR parametrization in gadolinium may be fortuitous; however, awaiting a more extensive experimental work, we have temporarily relied on it in reproducing the experimental data.

B. *g*-factors value

The two investigated levels have been interpreted within the framework of the weak-coupling core-excitation model[3,19,20] as belonging to the multiplet $\frac{1}{2}^+$, $\frac{3}{2}^+$, $\frac{5}{2}^+$, $\frac{7}{2}^+$ generated by the coupling of a 2^+ core with a $d_{3/2}$ proton.

Considering empirically ^{196}Pt as a core ($g_c=0.31$) and assuming for the $d_{3/5}$ proton the Schmidt value $g_p=0.082$, a value close to that of the ^{197}Au ground state, one obtains $g_{5/2}=0.225$ and $g_{7/2}=0.212$. These values can be considered consistent with our experimental values. Using the same parameters for the $\frac{1}{2}^+$ state at 77 keV one calculates $g_{calc}=0.538$ which is to be compared with the experimental value of 0.84(8).[2] This difference could be attributed to a mixing of the $s_{1/2}$ proton state, as evidenced in the stripping reaction (^{3}He,d).[21] Taking $g_p=3.20$ for the $s_{1/2}$ proton, as deduced from thallium isotopes,[2] one reproduces the experimental value with a 12 percent mixing.

Of course, in order to be complete, the comparison should include all of the spectroscopic properties of the multiplet. This has been done recently in Ref. 3, where particular emphasis was given to the fact that ^{198}Hg is likely to be a better core than ^{196}Pt. Under this hypothesis the theoretical *g* factors become larger than the experimental ones. Assuming $g(^{198}\text{Hg})=0.38(5)$,[2] one obtains $g_{5/2}=0.269$ and $g_{7/2}=0.252$. It is clear, however, that one cannot expect too much from such a simple description. The next step in a comparison could be with more realistic models (multishell, interacting boson fermion model calculations, etc.).

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