(1970).
[3]W. Lichten, Phys. Rev. 164, 131 (1967).
[4]W. Brandt, R. Laubert, and I. Sellin, Phys. Rev. 151, 56 (1966).
[5]W. F. van der Weg, to be published.
[6]D. L. Walters and C. P. Bhalla, in *Seventh International Conference on the Physics of Electronic and Atomic Collisions, Abstracts of Papers*, edited by L. M. Branscomb *et al.* (North-Holland, Amsterdam, 1971), p. 404.
[7]E. J. McGuire, Phys. Rev. A 3, 587 (1971).
[8]D. Burch and P. Richard, Phys. Rev. Lett. 25, 983 (1970).
[9]W. Brandt and S. Lundqvist, J. Quant. Spectrosc. Radiat. Transfer 7, 411 (1967).
[10]F. W. Saris, Physica (Utrecht) 52, 290 (1971).

Nuclear Magnetic Resonance on Oriented Platinum-195*m* in Iron*

F. Bacon, G. Kaindl, H.-E. Mahnke,† and D. A. Shirley
Lawrence Berkeley Laboratory, University of California, Berkeley, California 94720
(Received 13 January 1972)

The magnetic hyperfine splitting of ^{195m}Pt(*Fe*) was determined by the technique of nuclear magnetic resonance on oriented nuclei as $\mu H/kI = 89.5 \pm 0.5$ MHz. With additional γ-ray anisotropy data for the 129- and 99-keV γ rays, we derived the spin, $I = \frac{13}{2}$, and the magnetic moment of the isomeric state, $\mu(\frac{13}{2}) = \pm (0.597 \pm 0.015)\mu_N$, as well as the $E2/M1$ mixing ratio of the 99-keV γ transition, $\delta = -0.16 \pm 0.02$.

Nuclear magnetic resonance on oriented nuclei (NMR-ON)[1] provides precise information on the magnetic splitting of nuclear sublevels ($\mu H_{\mathrm{eff}}/I$). On the other hand, the magnetic hyperfine interaction (μH_{eff}) results from an analysis of the temperature dependence of γ-ray anisotropies. By a combination of both measurements the spin of the nuclear state can therefore be obtained directly. The present paper reports on the first application of this method to an isomeric state in determining the spin of the 259-keV state ($T_{1/2} = 4.1d$) of ^{195}Pt. In addition, the magnetic moment of the isomeric state and the mixing ratio of the 98.8-keV γ transition of ^{195}Pt were derived.

The ^{195m}Pt activity was produced by neutron irradiation of 57%-enriched ^{194}Pt metal in a neutron flux of 2.5×10^{15} n/cm^2 sec. Samples containing 1-at.% Pt in an iron matrix were prepared by melting the ^{195m}Pt activity under a hydrogen atmosphere with high-purity iron, already containing a matched amount of ^{60}Co activity to be used for thermometry. Thin foils (~ 20 000 Å thick), produced by cold rolling and annealing, were attached to both sides of the Cu fin of an adiabatic demagnetization apparatus. γ-ray spectra were taken at 0 and 90 deg relative to the external polarizing field H_{ext} with high-resolution coaxial Ge(Li) diodes. For the NMR-ON experiment an rf field H_1 was applied perpendicular to H_{ext}, and the amplitude of H_1 was measured by a pickup coil.

Figure 1 shows the results of the NMR-ON experiment, with the counting rate of the 98.8-keV γ rays, observed at 0 deg, plotted versus the rf frequency. The temperature of the sample increased during the run from $1/T = 145 \pm 5$ K^{-1} to 125 ± 5 K^{-1}, causing the sloping background noticeable in Fig. 1(b). Despite a total time span of 3.5 min between adjacent data points, the reso-

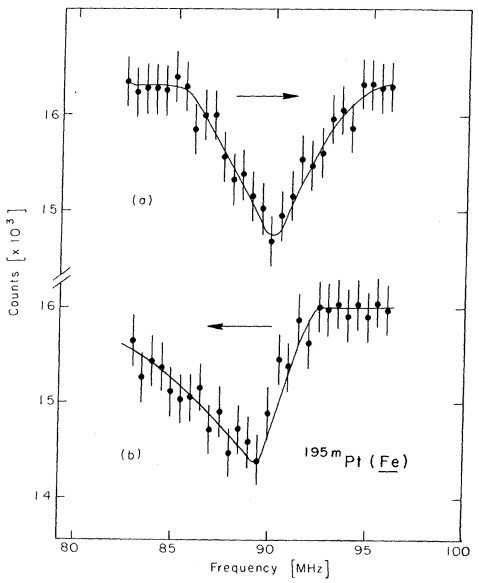

FIG. 1. Frequency dependence of the 99-keV γ-ray intensity, observed in the direction of the polarizing field $H_{\mathrm{ext}} = 1$ kOe, for (a) increasing and (b) decreasing frequency. The rf frequency was modulated with 100 Hz over a bandwidth of 1 MHz, and the rf amplitude was ~ 0.8 Oe. The time span between neighboring points is 3.5 min.

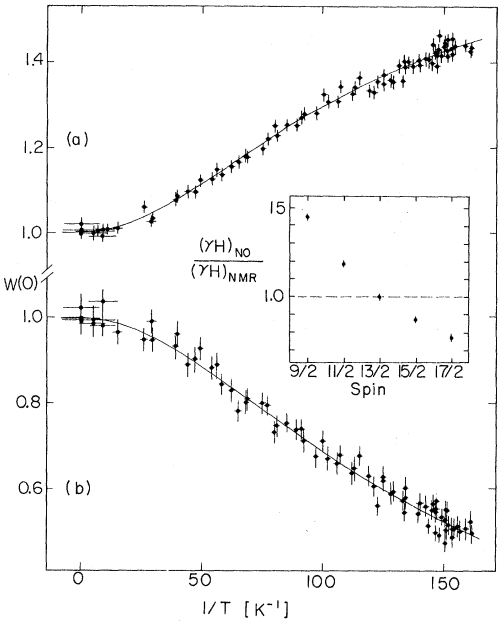

FIG. 2. Temperature dependence of the γ-ray anisotropy $W(\theta=0)$ of the (a) 99-keV and (b) 129-keV γ rays of ^{195}Pt(Fe) for $H_{ext}=4$ kOe. The solid curves are the results of least-squares fit procedures (see text). In the inset the ratio $(\gamma H)_{NO}/(\gamma H)_{NMR}$ is plotted versus the value of the assumed spin.

nance curves measured for increasing versus decreasing frequencies in steps of 1 MHz are shifted relative to each other by more than 1 MHz. This is because of the rather long nuclear spin-lattice relaxation time T_1' for ^{195m}Pt(Fe), which was determined in a separate experiment[2] to be $T_1'=10\pm1$ min at a temperature of $1/T=150\pm5$ K^{-1}, using a single-exponential fit.[3] The observed resonance effect represents a 30% destruction of the γ-ray anisotropy. The same resonance curves were simultaneously observed for the 129-keV γ rays of ^{195}Pt. From the results in Fig. 1 we determine the resonance frequency

$$\mu H_{eff}/hI = 89.5\pm0.5 \text{ MHz},$$

corresponding to $(5.930\pm0.033)\times10^{-19}$ erg.

In a separate experiment the temperature dependence of the anisotropies of the 99- and 129-keV γ rays of ^{195}Pt was measured at angles of 0 and 90 deg relative to the polarizing field. During the warmup of the samples over a typical period of 7 h, spectra were taken continuously for periods of 15 min. The anisotropy of the ^{60}Co γ lines was used for thermometry. The data shown in Fig. 2 are the results of three individual demagnetizations of the same ^{195m}Pt source. The anisotropy curves were fitted by least squares with

$$W(\theta)=1+\sum_{k=2,4} B_k U_k F_k Q_k P_k(\cos\theta),$$

using suitable solid-angle correction factors Q_k for each case.[4] In the analysis of the anisotropy of the 129-keV γ rays, the influence of the 129.6-keV $M4$ γ transition estimated from the decay scheme[5] was taken into account. The anisotropy curve of the 129-keV γ rays, shown in Fig. 2(b), was fitted for various values of the spin I of the isomeric state with μH_{eff} and an amplitude factor as the only free parameters. As expected, the results obtained for μH, given in Table I, are independent from the assumed spin within the limits of error, clearly demonstrating that from anisotropy curves only a value for the magnetic moment can be obtained. Only for a spin $I=\frac{13}{2}$ does $(\gamma H)_{NO}$ agree with $(\gamma H)_{NMR}$. The sensitivity of the method is shown by a plot of the ratio $(\gamma H)_{NO}/(\gamma H)_{NMR}$ versus the assumed spin, given in the insert of Fig. 2.

TABLE I. Results of a two-parameter fit of the anisotropy curve of the 129-keV γ rays for various values of the spin I of the isomeric state.

I	μH_{eff} (10^{-18} erg)	$\frac{(\gamma H)_{NO}}{(\gamma H)_{NMR}}$
9/2	3.87 ± 0.05	1.45 ± 0.03
11/2	3.87 ± 0.05	1.19 ± 0.02
13/2	3.87 ± 0.05	1.01 ± 0.02
15/2	3.86 ± 0.05	0.87 ± 0.02
17/2	3.90 ± 0.05	0.77 ± 0.02

The anisotropy curve of the 98.8-keV γ rays [Fig. 2(a)] was fitted by least squares with the $E2/M1$ mixing ratio[6] δ as the single free parameter, taking $\mu H/I$ from the NMR experiment. This leads to a value of

$$\delta=-0.16\pm0.02$$

for the mixing ratio of the 98.8-keV γ transition. The absolute value of δ is in good agreement with previous measurements,[7,8] but the negative sign is opposite to the one given by Ref. 8.

For a derivation of the magnetic moment of the $\frac{13}{2}^+$ state, we use the hyperfine field $H_{hf}=-1280\pm26$ kOe, measured for the $\frac{1}{2}^-$ ground state of ^{195}Pt in iron.[9] This leads to

$$\mu(\tfrac{13}{2})=\pm(0.597\pm0.015)\mu_N$$

for the magnetic moment of ^{195m}Pt, with the negative sign assumed from systematics. The error is mostly due to the 2% uncertainty in the value

for the hyperfine field. A correction for a possible hyperfine anomaly between the $\frac{13}{2}^+$ isomeric state and the $\frac{1}{2}^-$ ground state has not been applied. In the neighboring odd mercury isotopes ^{195}Hg and ^{197}Hg, however, the hyperfine anomalies between the $\frac{13}{2}^+$ isomeric states and the $\frac{1}{2}^-$ ground states have been measured[10]: $^{195m}\Delta^{195} = (+0.91 \pm 0.02)\%$ and $^{197m}\Delta^{197} = (+0.97 \pm 0.07)\%$. A hyperfine anomaly of this size can also be expected between the analogous states of ^{195}Pt. Thus the quoted value for $\mu(\frac{13}{2})$ should perhaps be decreased by 1%.

Our result for the spin of the isomeric state, $I = \frac{13}{2}$, confirms the spin assignment made on the basis of the $M4$ multipolarity of the 129.6-keV isomeric transition.[11] For ^{195}Pt a neutron configuration $(i_{13/2})^{13}(f_{5/2})^4$ outside of the $N = 82$ core and the filled $f_{7/2}$ and $h_{9/2}$ neutron shells is expected, since the $p_{3/2}$, $p_{1/2}$, $f_{5/2}$, and $i_{13/2}$ levels lie very close together, and hence the neutron pairs are expected to fill the states of higher angular momentum first as a result of the pairing energy. Following the core-polarization approach of Arima and Horie,[12] we obtain for this neutron configuration a value of $-0.64\mu_N$ for the magnetic moment, in rather good agreement with our experimental result. The magnetic moment may be compared with the known magnetic moments of other $\frac{13}{2}^+$ states in neighboring even-odd nuclei[10,13]: ^{193}Hg $[\mu = -1.0416(3)\mu_N]$, ^{195}Hg $[\mu = -1.0280(2)\mu_N]$, ^{197}Hg $[\mu = -1.0112(3)\mu_N]$, and ^{205}Pb $[\mu = -0.975(39)\mu_N]$. Going from Pt to Hg, the effect of two additional protons, filling up the $d_{3/2}$ shell, on the magnetic moment is obviously quite drastic, and much larger than expected on the basis of the single-particle model with configuration mixing. For the Hg isotopes the magnetic moments of the $\frac{13}{2}^+$ states have been interpreted assuming mixed neutron configuration with less than thirteen neutrons in the $i_{13/2}$ shell. This interpretation is in agreement with the small spectroscopic factor ($S = 7.4$) for the $\frac{13}{2}^+$ state of ^{199}Hg derived from (d, p)-stripping and (d, t)-pickup reactions on ^{198}Hg and ^{200}Hg, respectively.[14] The question of whether such a difference in the neutron configuration or drastic changes in the collective admixtures are responsible for the large difference in the magnetic moments of the $\frac{13}{2}^+$ state of ^{195}Pt and the even-odd Hg isotopes cannot be clarified at the present time, since too little is known about the wave functions of these states.

One of the authors (H.-E.M.) wants to thank the Deutscher Akademischer Austauschdients for granting a NATO fellowship.

---

*Work performed under the auspices of the U. S. Atomic Energy Commission.

†On leave from Hahn-Meitner Institut, Berlin, Germany.

[1]E. Matthias and R. J. Holliday, Phys. Rev. Lett. 17, 897 (1966).

[2]F. Bacon, G. Kaindl, H.-E. Mahnke, and D. A. Shirley, to be published.

[3]F. Bacon, J. A. Barclay, W. D. Brewer, D. A. Shirley, and J. E. Templeton, UCRL Report No. 20465, 1971 (unpublished).

[4]D. C. Camp and A. L. van Lehn, Nucl. Instrum. Methods 76, 192 (1969).

[5]R. Schöneberg, D. Gföller, and A. Flammersfeld, Z. Phys. 203, 453 (1967).

[6]We used the definition of K. S. Krane and R. M. Steffen, Phys. Rev. C 2, 724 (1970).

[7]B. Ahlesten and A. Bäcklin, Nucl. Phys. A154, 303 (1970); L. Grodzins, R. R. Borchers, and G. B. Hagemann, Nucl. Phys. 88, 474 (1966).

[8]D. Ashery, A. E. Blaugrund, and R. Kalish, Nucl. Phys. 76, 336 (1966).

[9]M. Kontani and J. Itoh, J. Phys. Soc. Jap. 22, 345 (1967).

[10]P. A. Moskowitz, C. H. Lin, G. Fulop, and H. H. Stroke, Phys. Rev. C 4, 620 (1971).

[11]*Nuclear Data Sheets 1959-1961*, compiled by K. Way *et al.* (Academic, New York, 1961), Part 10, p. 2324.

[12]A. Arima and H. Horie, Progr. Theor. Phys. 12, 623 (1954).

[13]K. H. Maier, J. R. Leigh, and R. M. Diamond, Nucl. Phys. A176, 497 (1971).

[14]M. J. Martin, Nucl. Data, Sect. B 6, 387 (1971).