PHYSICAL REVIEW C VOLUME 12, NUMBER 6 DECEMBER 1975

Magnetic moment of the $I^{\pi} = \frac{25}{2}^-$ isomer in ^{179}Hf and anomalous orbital proton g factor

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(Received 17 March 1975)

The magnetic moment of the $I^{\pi} = \frac{25}{2}^-$ isomeric state at 1106 keV in ^{179}Hf was measured by the technique of low-temperature nuclear orientation. From the result $\mu(\frac{25}{2}) = (7.43 \pm 0.34)\ \mu_N$ the value $g_l = 1.08 \pm 0.05$ for the effective proton g_l factor is deduced.

[RADIOACTIVITY ^{179}Hf^m, ^{177}Lu. Measured $\gamma(\Theta)$ polarized nuclei, $\gamma\gamma(\Theta, H)$. Deduced δ, μH, $\omega\tau$, μ, g_l. ^{3}He/^{4}He refrigerator, Ge(Li) detectors.]

Many theoretical investigations predict the effects of mesonic exchange currents on nuclear magnetic dipole moments. Since a fraction of these corrections can be renormalized into the orbital magnetism $g_l \cdot \vec{l}$, unambiguous experimental determinations of effective g_l factors are very important. The first such determination was made by Yamazaki *et al.*[1] who analyzed the magnetic moment of the $I^{\pi} = 11^-$ state of ^{210}Po and found $g_l = 1.09 \pm 0.02$. So far no such clear experimental evidence has been found for other nuclei—especially in the strongly deformed region.

In a recent publication Nagamiya and Yamazaki[2] analyzed a large number of experimental magnetic moments including some of strongly deformed nuclei. They found effective g_l factors for protons and neutrons in the deformed region of $g_{lp} = 1.07 \pm 0.04$ and $g_{ln} = -0.03 \pm 0.04$, respectively. A disadvantage of this determination of g_l is that uncertainties in the spin contribution and in the contribution of the collective motion to the magnetic moments are not easy to determine and admixtures to the wave function of the states are not always known.

Körner, Wagner, and Dunlap[3] reported on the determination of the magnetic moment of the 8^- two-quasiparticle state in ^{180}Hf. They pointed out that the spin magnetism does not contribute significantly to the magnetic moment of this state which makes it a favorable case for the detection of an anomalous g_l factor. These authors deduced $g_{lp} = 1.16 \pm 0.12$. Unfortunately, the experimental error is quite large in this case. Another very favorable case for the determination of an effective g_l value for protons is the $I^{\pi} = \frac{25}{2}^-$ isomeric state in ^{179}Hf with the Nilsson configuration $\{\pi\frac{7}{2}^+[404], \pi\frac{9}{2}^-[514], \nu\frac{9}{2}^+[624]\}\frac{25}{2}^-$ (Refs. 4 and 5). After a separation of the neutron contribution to the magnetic moment of this state the spin magnetism of the remaining two protons almost cancels out. Furthermore, owing to the high spin of this state, uncertainties in g_R are not important and the g factor is nearly equal to g_l. We have therefore determined the magnetic moment of this state by a low-temperature nuclear orientation measurement and deduced an effective g_l value from the result.

The decay scheme of ^{179}Hf^{m_2} is shown in Fig. 1. The activity was produced by bombarding natural tantalum with deuterons of 30 MeV in the Karlsruhe cyclotron using the reaction ^{181}Ta-$(d, \alpha)^{179}$Hf. After a chemical separation ^{179}Hf was implanted into Fe foils with an isotope separator. The implantation dose and energy were 4×10^{14} ions/cm^2 and 70 keV, respectively. The nuclear orientation experiments were performed with a ^{3}He-^{4}He dilution refrigerator. The ^{179}Hf(Fe) foils were soldered onto the copper cold finger of the dilution unit. ^{57}Co(Fe) was used as thermometer. The foils were polarized by an external magnetic field of 8 kG. γ ray spectra were measured with a Ge(Li) detector at 0° relative to the polarizing field.

In Fig. 2 we show as an example of our data the temperature dependence of the counting rate of the 453 keV γ radiation. From the temperature dependence of the γ ray counting rate of five pure $E2$ crossover transitions the magnetic hyperfine interaction μH was determined and for five $\Delta I = 1$ transitions the $E2/M1$ mixing ratios were deduced. The results are given in Table I. The $E2/M1$ mixing ratios can be compared to the previous

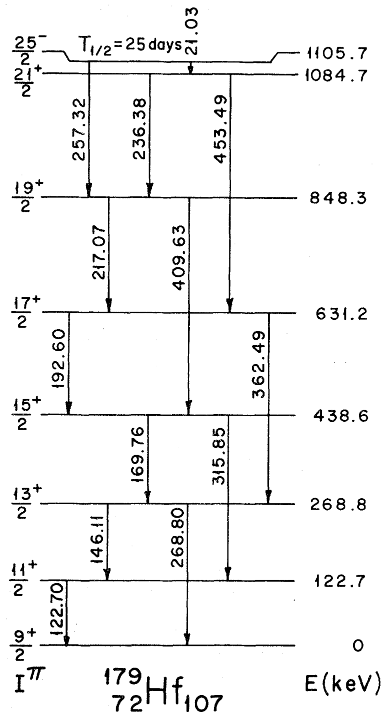

FIG. 1. Decay scheme of $^{179}Hf^{m_2}$.

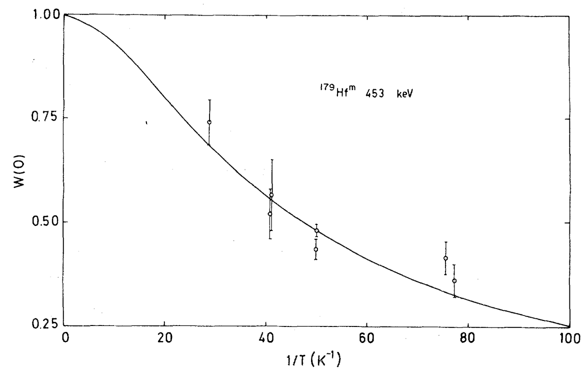

FIG. 2. Temperature dependence of the counting rate $W(0°)$ of the 453 keV transition in ^{179}Hf.

values of Hübel *et al.*[4] which are listed in the last column of Table I. The agreement is satisfactory.

In order to deduce the magnetic moment of the $I^\pi = \frac{25}{2}^-$ isomeric state in ^{179}Hf from the hyperfine interaction μH, the magnetic hyperfine field H must be known. However, several contradicting values exist in the literature for the hyperfine field of Hf in Fe. In order to calibrate the hyperfine field for our source we have implanted ^{177}Lu under conditions identical to the $^{179}Hf^m$ implantation into the same Fe foils and determined $\omega\tau = (\mu_n gH\tau)/\hbar$ for the 113 level in ^{177}Hf by a measurement of the perturbed directional correlation of the 208-113 keV $\gamma\gamma$ cascade. Since the nuclear orientation measurement was performed at low temperatures, the directional correlation measurement was carried out at liquid He temperatures. Figure 3 shows the result of this measurement. For the ^{177}Hf(Fe) source we obtain $\omega\tau = 0.337 \pm 0.011$. For the determination of the magnetic moment of the isomeric state in ^{179}Hf we use $g\tau$(^{177}Hf, 113 keV) = 0.170 ± 0.004 (from Ref. 6) and our average value for $\mu H(^{179}Hf^m)$. The result is

$$\mu(\tfrac{25}{2}) = (7.43 \pm 0.34)\mu_N .$$

The magnetic moment of a three-quasiparticle state in a deformed nucleus can be calculated from the single-particle gyromagnetic ratios g_K and g_R: $\mu = K/(K+1)(g_{K_1}K_1 + g_{K_2}K_2 + g_{K_3}K_3 + g_R)$(Refs. 7 and 8). If we use the single-particle values for g_K and g_R given by Schoeters *et al.*[8] we obtain $\mu(\frac{25}{2})_{calc} = 7.33\mu_N$. The excellent agreement with the experimental value given above confirms the Nilsson configuration of the $I^\pi = \frac{25}{2}^-$ isomer proposed by Hübel *et al.*[4]

In order to obtain information about the effective g_l factor for the protons of this state we have

TABLE I. Experimental results of nuclear orientation measurements on $^{179}Hf^m$.

E_γ (keV)	Multipolarity	μH (μ_N kG)	γ ray mixing δ This work	Ref. 4
146	$E2/M1$		−0.330(75)	−0.382(30) [a]
170	$E2/M1$		−0.327(45)	−0.407(18)
193	$E2/M1$		−0.262(56)	−0.416(46)
217	$E2/M1$		−0.365(33)	−0.391(40)
236	$E2/M1$		−0.301(30)	−0.404(22)
269	$E2$	2890(390)		
316	$E2$	2860(250)		
362	$E2$	3094 (90)		
410	$E2$	3610(390)		
453	$E2$	3200(190)		

[a] The sign of δ is taken from the present work.

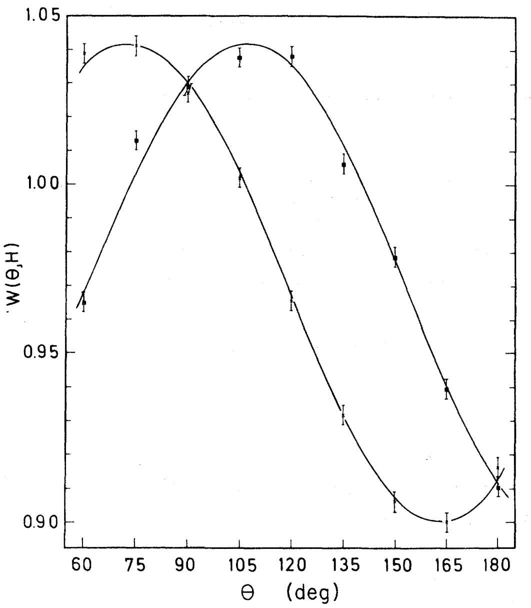

FIG. 3. Integral rotation of the 208–113 keV cascade in ^{177}Hf in the effective hyperfine field of He in Fe measured at 4.3 K.

to eliminate the neutron contribution to the experimental magnetic moment. Using the parameters of Ref. 8 we obtain $\mu(8^-)=(8.02\pm 0.33)\mu_N$ for the configuration $\{\pi\frac{7}{2}^+[404], \pi\frac{9}{2}^-[514]\}8^-$. The magnetic moment of such a two-particle state can be written as[7]

$$\mu=\frac{I}{I+1}(g_{s_1}\langle s_{z_1}\rangle + g_{l_1}\langle l_{z_1}\rangle + g_{s_2}\langle s_{z_2}\rangle + g_{l_2}\langle l_{z_2}\rangle + g_R).$$

Provided that the g_s factors are equal, the spin contributions cancel each other almost completely out for all reasonable values of deformation. We denote the small correction to the moment due to incomplete cancellation of the spin terms by $\delta\mu_s$. We can then write

$$\mu(8^-)=\frac{I}{I+1}(Kg_1+g_R)+\delta\mu_s\,. \qquad (1)$$

We have calculated $\langle s_{z_1}\rangle$ and $\langle s_{z_2}\rangle$ for all reasonable choices of deformation parameters ϵ_1 and ϵ_2. Taking into account the small difference of g_s found experimentally[9] for states with $\langle s_z\rangle > 0$ and $\langle s_z\rangle < 0$, respectively, we obtain $\delta\mu_s = (0.02\pm 0.01)\mu_N$. With the experimental value for $\mu(8^-)$ given above we thus obtain for the effective g_l factor of the protons in ^{179}Hf

$$g_l = 1.08\pm 0.05$$

This result suggests the presence of an anomalous orbital contribution to the magnetic moment of the proton in a strongly deformed nucleus. This result is quite reliable for the following reasons: Owing to the high K value uncertainties in g_R are negligible [see Eq. (1)]. Since the spin contributions cancel almost completely, the small remaining correction due to spin magnetism can be applied reliably. The wave function of the $I^{\pi}=\frac{25}{2}^-$ state can be expected to be rather pure. However, small admixtures to the wave function, if present, do not affect the result. For instance, a 5% admixture of the state $I=\frac{25}{2}, K=\frac{23}{2}$ (where one proton is in the $\frac{5}{2}^+[402]$ orbit) can change the magnetic moment by less than 1% only.

The magnitudes of the observed g_l factors both in ^{210}Po (Ref. 1) and in ^{179}Hf agree with most theoretical predictions. However, more experimental data would be needed to discriminate among the different theoretical approaches.

ACKNOWLEDGMENTS

The irradiations were performed at the cyclotron of the Gesellschaft für Kernforschung, Karlsruhe. The authors wish to thank Dr. G. Schatz and the cyclotron operating crew for their help. We are grateful to F. J. Schröder and H. Toschinski for their help in the perturbed angular correlation measurements.

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