Determination of the nuclear magnetic moment of ^{175}Hf by nuclear orientation*

K. S. Krane
Department of Physics, Oregon State University, Corvallis, Oregon 97331

S. S. Rosenblum and W. A. Steyert
Los Alamos Scientific Laboratory of the University of California, Los Alamos, New Mexico 87545

(Received 17 November 1975)

The angular distribution of the 343-keV transition of ^{175}Lu has been measured following the decay of ^{175}Hf polarized at temperatures down to 0.004 K in ferromagnetic $Hf_{0.1}Zr_{0.9}Fe_2$. The ^{175}Hf nuclear magnetic moment has been deduced to be $|\mu| = (0.70 \pm 0.10)\mu_N$. The ^{180}Hf^m hyperfine splitting has been remeasured to be $\Delta = 8.2 \pm 0.2$ mK.

[NUCLEAR MOMENTS ^{175}Hf, ^{180}Hf^m; measured $\gamma(\theta)$ from polarized nuclei; ^{175}Hf, ^{180}Hf^m—deduced magnetic moment μ.]

Since the magnetic moments of odd-mass deformed nuclei can be calculated quite accurately using the Nilsson model, measurements of these moments provide detailed information about the Nilsson wave function for the nuclear state in question. The odd-mass Hf isotopes are particularly interesting in this regard since they are characterized by a number of low-lying intrinsic states (each of the five odd-mass isotopes of Hf for $173 \leq A \leq 181$ has a different ground state configuration). The magnetic moments of two of these (^{177,179}Hf) have been measured previously.[1] In the present work we extend the knowledge of this region with a measurement of the magnetic moment of ^{175}Hf.

The determination of the ^{175}Hf magnetic moment was accomplished by observing the anisotropy of the 343-keV γ radiation emitted following the decay of ^{175}Hf polarized at low temperature. The relevant features of the ^{175}Hf decay scheme are illustrated in Fig. 1.

Polarization of the ^{175}Hf was achieved by preparing the activity in the ferromagnetic lattice $ZrFe_2$. An alloy of $Hf_{0.1}Zr_{0.9}Fe_2$ was prepared as described in previous work.[2] The sample was cooled to temperatures of 4 mK by contact with a cerium magnesium nitrate adiabatic demagnetization apparatus coupled to the mixing chamber of a ^{3}He-^{4}He dilution refrigerator. The temperature was determined using a thermometer of ^{125}Sb in Ni, soldered with pure indium to the cold-finger along with the Hf sample. The ferromagnetic alloys were aligned in an external field of 0.3 T provided by either of two pairs of mutually perpendicular Helmholtz coils.

In earlier experiments we have established that this magnetic field is sufficient to completely align the nuclei of interest. For the ^{125}Sb, variation of the applied field from 0.21 to 0.36 T at 4 mK caused no change in the anisotropy of the 428-keV γ ray. For the Hf in $ZrFe_2$, in the course of earlier experiments on ^{180}Hf^m, variation of the applied field from 0.28 to 0.49 T at 30 mK caused no change in the anisotropy of the 332-keV γ ray. The γ rays were counted using two Ge(Li) detectors, each placed along the axis of one of the coil pairs.

The sample, in the form of a disk 6 mm in diameter by 0.5 mm thick, was activated in the Los Alamos Omega West reactor. The Hf activities resulting from the irradiation were ^{175}Hf, ^{180}Hf^m, and ^{181}Hf. Because of possible uncertainties in the hyperfine parameters and in the effective sample temperature, the ^{175}Hf moment was measured by a direct comparison of the ^{175}Hf hyperfine splitting with that of the ^{180}Hf^m.[2] Since the ^{175}Hf and ^{180}Hf^m are produced in the same sample, they ought to experience the same hyperfine field, and observation of the anisotropies of the γ rays following the respective decays should provide a means of comparing the hyperfine splittings. (The ^{181}Hf has a ground-state spin of $\frac{1}{2}$; thus the γ rays following the ^{181}Hf decay have isotropic angular distributions.)

A typical γ-ray spectrum taken near the beginning of the run is illustrated in Fig. 2. The ^{180}Hf^m γ rays decay with a half-life of 5.5 h; the half-lives of the ^{175}Hf (70 days) and ^{181}Hf (40 days) are considerably longer. The extraction of the anisotropy of the 343-keV peak was complicated by the presence of the 346-keV peak of the ^{181}Hf decay. Normally the anisotropy of either member of such a partially resolved doublet can only be deduced with a rather large uncertainty arising from

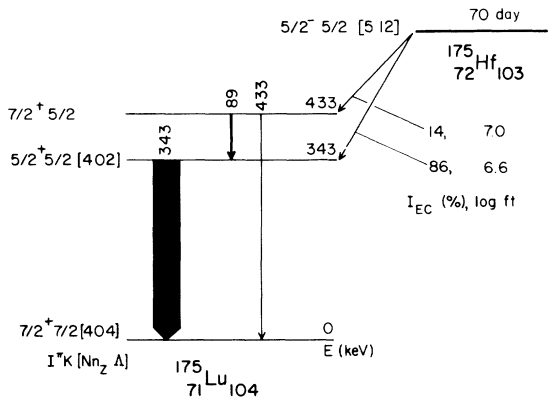

FIG. 1. Partial decay scheme of ^{175}Hf.

the correction for the anisotropy of the fraction of the intensity of the other member included in the integration interval; this is particularly true when the peak of interest is the lower-energy one. However, in the present case this correction introduces only a rather small uncertainty, since (1) the 346-keV transition has an isotropic angular distribution, and (2) the ^{175}Hf and ^{181}Hf half-lives are both long compared with the duration of the data accumulation (a few hours), and so the relative intensities do not change measurably over the course of the experiment.

The 343-keV anisotropy was computed in three independent ways as a check on the correction for the 346-keV impurity. (1) The counting rate of the 343-keV region was computed directly by a minicomputer-based data acquisition system. The ratio of the counting rates parallel and perpendicular to the field directions were then computed. (2) The 343- plus 346-keV region of the spectrum was printed out and the points plotted so that a correction could be made for the effects of the 346-keV low-energy tail on the deduced 343-keV counting rates. (3) The combined 343- plus 346-keV intensity was calculated by the computer and the deduced anisotropy of the combination was corrected for the isotropic fraction deduced from the intensity of the 346-keV component (which in turn was deduced from the intensities of other transitions in the ^{181}Hf decay using the known detector efficiencies). Within experimental error these three methods gave identical results.

The interpretation of the observed angular distributions is done according to the relationship

$$W(\theta) = \sum_{k=0,2,4} Q_k B_k U_k A_k P_k(\cos\theta). \qquad (1)$$

A description of the nuclear orientation formalism is given in a preceding paper.[3] The $k=4$ term is negligible for the ^{175}Hf decay but must be included for the ^{180}Hf^m decay.

In the ^{180}Hf^m decay, the 444-, 332-, and 215-keV transitions are all pure $E2$ radiation, and the multipolarities of all unobserved intermediate radiations are known with great precision.[2,4] Thus A_k and U_k are known, and the angular distribution anisotropy gives the B_k directly. In the ^{175}Hf decay, the 343-keV transition is mixed $M1+E2$ multipolarity and the first-forbidden β decay to the 343-keV level may have $L=0$, 1, or 2. The mixing ratio of the 343-keV transition has been determined in a previous nuclear orientation experiment by Kaindl, Bacon, and Soinski[5] to be $\delta(343) = -0.27 \pm 0.03$, a value in good agreement with that deduced from conversion coefficient measurement[6] ($|\delta| = 0.26 \pm 0.03$). Taking the average of these two values yields $A_2 = -0.197 \pm 0.022$. The U_2 coefficient may be estimated to sufficient accuracy by making two assumptions regarding the β decay to the 343-keV level: (1) The $L=2$ term (B_{ij}) does not contribute significantly to the decay (less than a few percent of the decay intensity); and (2) the intensity of the $L=1$ component can be deduced based on the intensity of the (assumed) $L=1$ decay to the 433-keV level (the first rotational state built on the 343-keV level) using the Alaga rules.[7] We allow for mixing and other possible effects resulting in deviations from these assumptions by assigning a 50% uncertainty to the intensities of the multipole components so deduced, yielding, for the β decay, $U_2 = 0.859 \pm 0.073$. (The complete U_2 value for the 343-keV transition must also include a 10% contribution for populations of the 343-keV level via the 433-keV level.) Thus U_2 and A_2 can be regarded as sufficiently well known, and the angular distribution anisotropy analyzed to give B_2.

The γ ray angular distributions were measured at temperatures down to 4 mK. Because of the

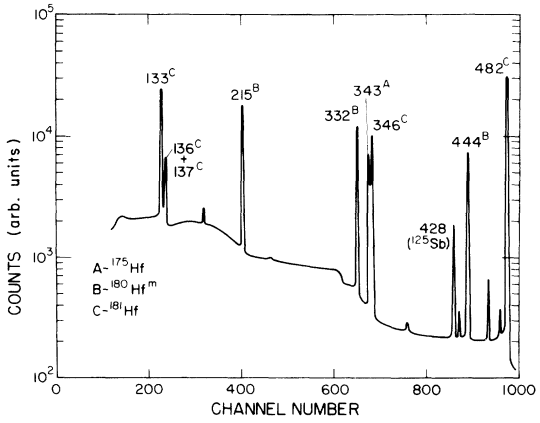

FIG. 2. γ-ray spectrum of ^{175}Hf, ^{180}Hf^m, and ^{181}Hf.

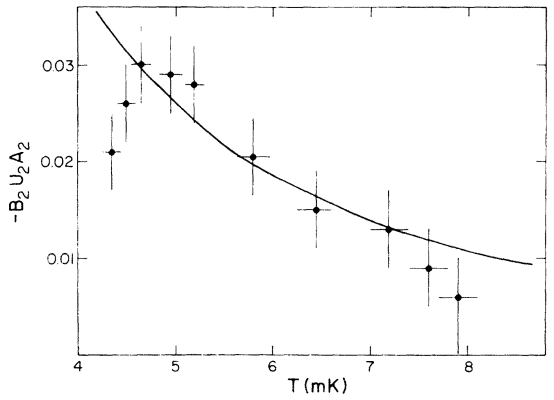

FIG. 3. Temperature dependence of the anisotropy of the 343-keV transition of the decay of ^{175}Hf.

small values of B_2 and A_2 for the ^{175}Hf decay, the anisotropies obtained were small, and the only useful data were obtained between 4 and 8 mK. The ^{180}Hf^m, however, gives sizable anisotropies up to 20 mK, the highest temperature at which the anisotropies were measured.

The temperatures were deduced using either the ^{125}Sb in Ni γ ray anisotropy or the ^{180}Hf^m γ ray anisotropy. At temperatures above 10 mK, good agreement was obtained between the two thermometers. Below 10 mK, the Hf γ rays indicated a temperature 1–1.5 mK (20–30%) higher; the largest discrepancies were obtained for the lowest temperatures. There are two possible explanations for this effect; the comparison of the ^{175}Hf and ^{180}Hf^m results to deduce the ^{175}Hf moment depends on which of these two explanations is the correct one. The first explanation interprets this effect as a true temperature discrepancy, resulting perhaps from the poor thermal conductivity of the $ZrFe_2$. As the temperature is decreased, an increasing thermal gradient is induced across the $ZrFe_2$ sample. In this case the ^{175}Hf and ^{180}Hf^m would be similarly affected and the ^{175}Hf should be analyzed by direct comparison with the ^{180}Hf^m for each data point. The second explanation concerns an interpretation in terms of the magnetic saturation of the internal hyperfine field. As was shown in a previous work,[8] the approach to magnetic saturation of impurities in ferromagnetic hosts is remarkably slow, even for reasonably large applied fields. (One possible explanation of this effect is in terms of a "cone angle" between the orientation of the nuclear spins and the direction of the applied field.) In the present case, at $T<10$ mK, the ^{180}Hf^m is quite close to full polarization and thus the apparent higher temperature deduced from the ^{180}Hf^m may in fact be simply a slow approach to magnetic saturation. In this case the ^{175}Hf, which is far from full polarization, would not be similarly affected, and the proper comparison would thus be between the ^{175}Hf at 4–8 mK and the ^{180}Hf^m at 20 mK, away from full polarization. The ^{175}Hf data at $T<10$ mK may therefore be compared with the ^{180}Hf^m data at either $T<10$ mK or $T>10$ mK; the difference in the deduced ^{175}Hf moment is the order of 25%. Although we favor the explanation based on magnetic saturation (partly because it is a well-documented effect), the present data cannot distinguish between the two effects and the analysis will be done using both methods.

In Fig. 3 is shown the anisotropy of the 343-keV γ ray as a function of the temperature deduced from the ^{125}Sb. A point-by-point computation of the B_2 yields an average value for the hyperfine splitting of

$$\Delta = 1.87 \pm 0.14 \text{ mK}.$$

The theoretical curve of Fig. 3 is calculated with this value. Using the ^{180}Hf^m data at $T>10$ mK (i.e., a hyperfine field of 20 ± 2 T, as measured in Mössbauer studies[9]), we obtain $|\mu(^{175}\text{Hf})| = (0.64\pm0.08)\mu_N$. Based on a direct comparison with ^{180}Hf^m with $T<10$ mK, our data yield $|\mu(^{175}\text{Hf})| = (0.80\pm0.10)\mu_N$. The assumption of nonsaturation of the hyperfine field suggests a preference for the former value over the latter, and we take $|\mu| = 0.70\pm0.10$ as our final result. It is to be noted that the error limit spans both of the above results, thus making our value independent of which explanation is really correct.

The ^{175}Hf ground state is interpreted as the $\frac{5}{2}^-[512]$ Nilsson state. The present experimental result agrees well with the moments of the identical Nilsson state in the $N=103$ isotones [$\mu(^{173}\text{Yb}) = (-0.67993\pm0.00003)\mu_N$, $|\mu(^{175}\text{Er})| = (0.70\pm0.05)\mu_N$].[1] A moment of $-0.70\mu_N$ requires (taking $g_R = 0.26$) a value of the intrinsic g factor of $g_K = -0.50\pm0.06$. The intrinsic g factor is described in terms of the angular momentum of the odd particle by

$$Kg_K = g_s\langle s_z\rangle + g_l\langle l_z\rangle, \tag{2}$$

where $\langle s_z\rangle$ can be computed from the Nilsson wave function to be 0.393 (we take a deformation $\eta = 5.5$). With $g_l = 0$ for an odd-neutron state, the deduced g_K requires $g_s = -3.2\pm0.4 = (0.8\pm0.1)(g_s)_{\text{free}}$; this g_s differs from other nuclei in this region, which generally have $g_s = 0.6(g_s)_{\text{free}}$.[10]

The ^{180}Hf^m anisotropies measured in the present work can also be used to derive a more precise value for the ^{180}Hf^m hyperfine splitting using the temperatures deduced from the ^{125}Sb in nickel. We deduce

$$\Delta^{180} = 8.2 \pm 0.2 \text{ mK},$$

compared with our previous value[2] of 7.9 ± 0.5 mK. From the above splitting we obtain, using $H = 20 \pm 2$ T, $|\mu(^{180}\text{Hf}^m)| = (9.0 \pm 0.9)\mu_N$. The 10% uncertainty in the value[9] of the hyperfine field precludes an interpretation of this value of the moment in terms of, for example, an anomalous orbital g factor of the proton, assuming a two-proton character for the $^{180}\text{Hf}^m$.

---

*Work performed under the auspices of the U. S. Energy Research and Development Administration.

[1]V. S. Shirley and C. M. Lederer, Lawrence Berkeley Laboratory Report No. LBL-3450, 1974 (unpublished) [*Proceedings of the International Conference on Hyperfine Interactions Studied in Nuclear Reactions and Decay, Uppsala, 1974* (Upplands Grafiska AB, Uppsala, 1974)].

[2]K. S. Krane, J. R. Sites, C. E. Olsen, and W. A. Steyert, Phys. Rev. C 4, 1906 (1971).

[3]K. S. Krane, S. S. Rosenblum, and W. A. Steyert, preceding paper, Phys. Rev. C 14, 653 (1976).

[4]K. S. Krane, C. E. Olsen, and W. A. Steyert, Phys. Rev. C 5, 1663 (1972).

[5]G. Kaindl, F. Bacon, and A. J. Soinski, Phys. Lett. 46B 62 (1973).

[6]P. Erman, B. I. Deutsch, and C. J. Herrlander, Nucl. Phys. A92, 241 (1967).

[7]G. Alaga, K. Alder, A. Bohr, and B. R. Mottelson, K. Dan. Vidensk. Selsk. Mat.-Fys. Medd. 29, No. 9 (1955).

[8]K. S. Krane, B. T. Murdoch, and W. A. Steyert, Phys. Rev. Lett. 30, 321 (1973).

[9]H. J. Körner, F. E. Wagner, and B. D. Dunlap, Phys. Rev. Lett. 27, 1593 (1971).

[10]Z. Bochnacki and S. Ogaza, Nucl. Phys. 69, 186 (1965).