Nuclear magnetic moment of ^{106}Rh

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Nuclear orientation and nuclear magnetic resonance measurements have been performed for ^{106}Rh oriented at low temperature in iron and nickel hosts. From the results of the temperature dependence measurements of nuclear orientation, the magnetic moment of ^{106}Rh was deduced as $|\mu(^{106}\mathrm{Rh}, 1^+)| = 2.52(5)\ \mu_N$, which is very different from the value of 3.07(9) μ_N reported previously. From the nuclear magnetic resonance on oriented nuclei measurements of ^{106}Rh*Ni*, the magnetic hyperfine splitting frequency $|g\mu_N B_{\mathrm{HF}}/h|$ was determined to be 441.5(7) MHz. Using the hyperfine field B_{HF} (Rh*Ni*) of $-22.49(5)$ T, the precise value of the magnetic moment of ^{106}Rh was deduced: $|\mu(^{106}\mathrm{Rh}, 1^+)| = 2.575(7)\ \mu_N$. The electric quadrupole interaction has been measured using modulated adiabatic passage on oriented nuclei in a nickel single-crystal host. A broad distribution of the quadrupole splitting $\Delta\nu_Q$ is found, extending from 0 to 300 kHz.

I. INTRODUCTION

The magnetic moment of odd-odd ^{106}Rh nuclei has been measured to be $|3.07(9)|\ \mu_N$ by Rüter *et al.*[1] using the low-temperature nuclear orientation method. 374 d ^{106}Ru*Fe* activity, which decays to the 30 s ^{106}Rh ground state, was used in their measurements. They assumed incomplete orientation and analyzed their data using an assumed relaxation time of 5 s. However, Nishimura *et al.*[2] reported recently that the relaxation time of ^{101}Rh^m*Fe* is faster than 3 s. For a ^{106}Rh*Fe* source it is faster than 0.5 s. In order to decide, the magnetic moment with high precision nuclear orientation of ^{106}Rh*Fe* and nuclear magnetic resonance on oriented nuclei (NMR-ON) of ^{106}Rh*Ni* have been performed. The presence of well-defined electric quadrupole interaction (EQI) at 5*d* impurity nuclei in iron and nickel has enabled the determination of spectroscopic quadrupole moments Q of Ir and Au nuclei by NMR-ON.[3] The MAPON technique[4] is also applied to the present system to extend the knowledge of unresolved EQI at 4*d* nuclei in cubic ferromagnetic hosts.

II. EXPERIMENTAL PROCEDURE

The 1^+ ground state of 30 s ^{106}Rh is populated by the β decay of 374 d ^{106}Ru. A radioactive source of carrier-free ^{106}Ru in a dilute HCl solution was obtained from Amersham International. Samples of ^{106}Rh*Fe* and ^{106}Rh*Ni* were prepared by diffusion of the ^{106}Ru activity into pure Fe ($\sim 100\ \mu$m) and Ni ($\sim 1.5\ \mu$m) foils at 850 °C for 24 h in an atmosphere of hydrogen. After diffusion, surface activity was removed by etching the foils in dilute-HCl. For the measurement of the EQI an 0.8-mm-thick Ni single-crystal disk was cut with a (110) face, and polished with 1 μm alumina paste. The activity was deposited from a HCl solution and diffused at 800 °C for 1 h. The sample was mounted with the ⟨111⟩ easy axis parallel to the polarizing field. The samples were soldered to the copper cold finger using Woods metal and top-loaded into a dilution refrigerator. Sample temperatures were measured by ^{54}Mn*Ni* and ^{60}Co*Fe* thermometry. The intensity of γ rays emitted parallel and perpendicular to an external magnetic field B_0 was measured using two Ge(Li) detectors.

III. RESULTS AND DISCUSSION

A. NO experiments

The angular distribution of γ radiation from oriented ^{106}Rh nuclei is given by

$$W(\theta) = 1 + f A_2 B_2 U_2 Q_2 P_2(\cos\theta) ,$$

where the parameter f denotes the fraction of nuclei experiencing a magnetic hyperfine field B_{HF}, A_2 is the directional correlation coefficient, B_2 is the orientation parameter, U_2 is the deorientation parameter which corrects for effects of unobserved intermediate radiation, Q_2 is the solid angle correction, and P_2 is the second Legendre polynomial.

In Fig. 1 the data of $W(0)$ for the 512-keV and 1051-keV γ transitions obtained with the external field $B_0 = 0.7$ T are shown as a function of temperature. The solid lines represent least-squares fits to the data. From these analyses, the values of μB_{HF} and $f A_2 U_2$ can be determined. Neglecting a possible hyperfine anomaly we used the measured B_{HF} value of $-55.66(12)$ T.[5] The results are

512-keV γ ray: $|\mu| = 2.53(5)\ \mu_N$,

$$f U_2 A_2 = -0.148(2) ,$$

1051-keV γ ray: $|\mu| = 2.46(9)\ \mu_N$,

$$f U_2 A_2 = -0.357(11) .$$

The weighted average moment value is $|2.52(5)|\ \mu_N$. The effective relaxation time of ^{101}Rh^m*Fe* was reported to be faster than 3 s by Nishimura *et al.*[2] So, the relaxation time for ^{106}Rh*Fe* could be estimated to be faster than 0.5

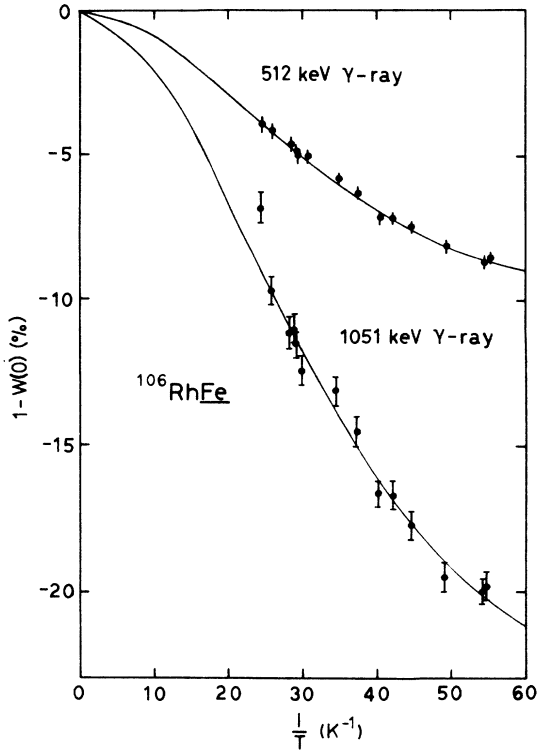

FIG. 1. $1-W(0)$ vs $1/T$ for the 512-keV and 1050-keV γ rays.

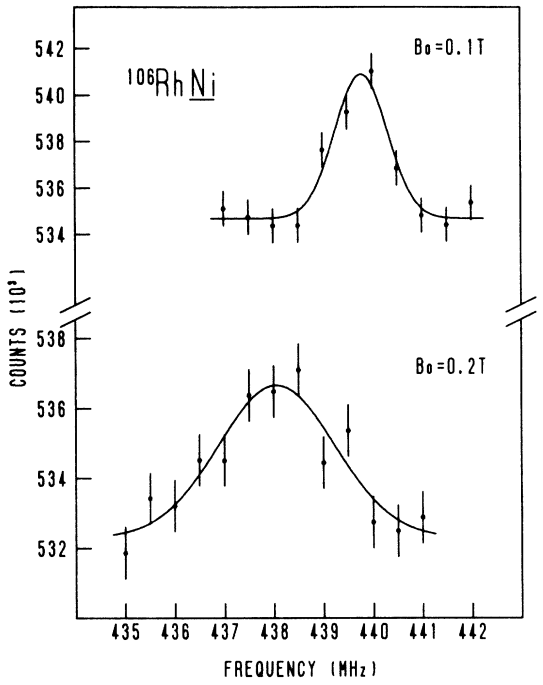

FIG. 2. NMR-ON spectra of ^{106}Rh*Ni* for $B_0=0.1$ and 0.2 T taken with FM of ± 0.5 MHz.

s. Correction for this short relaxation time is small and included in the uncertainty quoted.

The present magnetic moment result is very different from the value of 3.07(9) μ_N reported by Rüter *et al.*[1] using the same method. They assumed a relaxation time of 5 s and corrected their data accordingly for incomplete relaxation during the early part of the 30 s half-life. The above disagreement of the magnetic moment may be due to the misestimation of the relaxation time.

The 1562-keV level is populated by β^- (GT-type) decay of ^{106}Rh (95.8%) and via other 0^+ states. The 1051-keV transition has a mixing ratio of $\delta=0.24(1)$.[6] Using these parameters U_2A_2 (1051-keV transition) can be calculated to be 0.378(26). With this value our experimental result yields the fraction f to be $0.94(^{+6}_{-7})$. The solubility of the Rh in Fe is therefore very good. Using this value of f, the experimental U_2A_2 value for the 512-keV transition is $-0.157(23)$. We note that the anisotropies observed in this work are 15–20 % larger than those reported by Rüter *et al.*[1]

B. NMR-ON experiments

For the NMR-ON experiments, a sample of ^{106}Rh*Ni* has been used because the resonance frequency of ^{106}Rh*Fe* is expected to be greater than 1 GHz. Figure 2 shows the NMR-ON spectrum of ^{106}Rh*Ni* for $B_0=0.1$ T measured at 13 mK. The strong 512-keV γ transition was used to detect the resonances. The solid lines in Fig. 2 represent the results of a Gaussian curve with a constant background. The observed linewidths were 1.2(2) and 2.8(7) MHz with a FM width of ± 0.5 MHz for $B_0=0.1$ and 0.2 T, respectively. The resonance frequencies for $B_0=0.1$ and 0.2 T were 439.8(2) and 438.1(3) MHz, respectively. From these results, the resonance frequency for $B_0=0$ was obtained:

$$\nu(B_0=0)=441.5(7)\ \text{MHz}\ .$$

The hyperfine field $B_{\rm HF}$ for ^{105}Rh*Ni* is known to be $-22.49(5)$ T.[5] Neglecting a possible hyperfine anomaly, the magnetic moment was deduced as

$$|\mu(^{106}\text{Rh},1^+)|=2.575(7)\ \mu_N\ .$$

This value is in agreement with the present nuclear orientation experimental results from the Fe alloy.

The shell model configuration for the ^{106}Rh 1^+ state is $[\pi(g\frac{9}{2})^n\frac{7}{2},\nu(d\frac{5}{2})\frac{5}{2}]1^+$ or $[\pi(g\frac{9}{2})^n\frac{9}{2},\nu(g\frac{7}{2})\frac{7}{2}]1^+$. The empirical magnetic moment can be estimated using empirical g factors derived from neighboring odd-even and even-odd nuclei.

For the first case the empirical g factor of the $\frac{7}{2}$ odd proton was taken from the observed value $g(^{105}\text{Rh},\frac{7}{2}^+)=1.272(3)$ (Ref. 5) and that of odd neutron from $g(^{105}\text{Pd},\frac{5}{2}^+)=-0.257(1)$.[2] Assuming simple additivity, the empirical magnetic moment of ^{106}Rh was calculated to be $\mu(^{106}\text{Rh},1^+)=3.18\ \mu_N$ which is in relatively poor agreement with the experimental results.

For the second case the empirical g factor of the $\frac{9}{2}^+$ odd proton was taken to be $g(^{101}\text{Rh}^m,\frac{9}{2}^+)=1.216(3)$.[2] Since the g factor of the $\frac{7}{2}^+$ state in Ru or Pd nuclei has not yet been measured, the value of $g(^{111}\text{Sn},\frac{7}{2}^+)=0.608(4)$ (Ref. 7) was used for the odd neutron. With these g factors, the calculated g factor of ^{106}Rh is $\mu(^{106}\text{Rh},1^+)=3.00\ \mu_N$, which is still larger than the ex-

perimental value of 2.575(7) μ_N. Thus, at the present time the measured moment cannot clearly indicate the predominant configuration. The energy of the first excited states of even Ru decreases near $A=106$, indicating that the effect of changing deformation should be included in the moment calculation. Such an effect has been observed in the 1^+ states of ^{108,110}Ag.[8]

C. MAPON results

The resonance frequency and linewidth of ^{106}Rh in the Ni single crystal were consistent with the foil result within experimental error. The quadrupole splitting $\Delta\nu_Q$ is defined by

$$\Delta\nu_Q = 3eQV_{zz}/2I(2I-1)h \ ,$$

where V_{zz} is the electric field gradient. This was measured in applied field of 0.1 T by sweeping the rf center frequency from 438.5 to 440.5 MHz in 0.25 s, using a frequency separation Δf in the range 2–500 kHz. The change in anisotropy, $\Delta[1-W(0)]$, was recorded following the sweep. The post-passage signal was 2% at 2 kHz, rising steadily to 15% at 300 kHz, with no clearly defined transition region (Fig. 3). The distribution of $\Delta\nu_Q$ extends from 0 to 300 kHz. No sweep asymmetry was found. This indicates a broad distribution of V_{zz} which is randomly oriented with respect to the hyperfine field. This is in contrast to V_{zz} arising from magnetostriction or incomplete quenching of orbital angular momentum.[9] If we estimate $0.2<Q(^{106}\text{Rh})<0.8$ b we obtain $3>V_{zz}>0.7\times10^{19}$ V m^{-2} which is an order-of-magnitude smaller than those observed at 5*d* impurities and is comparable to the values for 3*d* impurities.[10] Further study of the intrinsic origins of V_{zz} at 4*d* sites would be valuable.

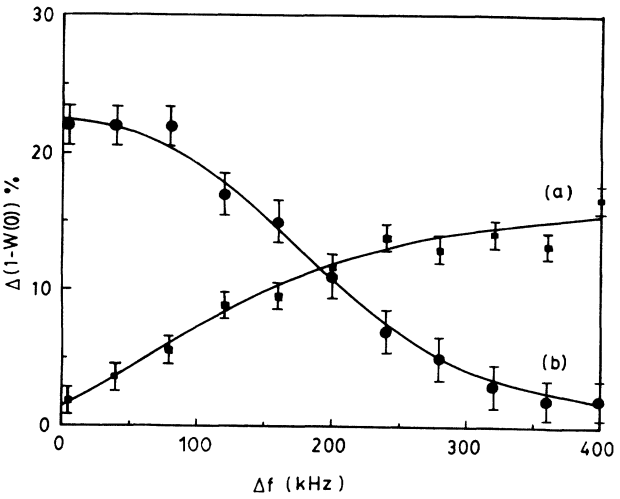

FIG. 3. MAPON spectrum for ^{106}Rh*Ni* ⟨111⟩ in 0.1 T. (a) Integral spectrum and (b) distribution of $\Delta\nu_Q$.

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