Magnetic Moment and Electric Quadrupole Moment of the Anomalous $^{186}$Ir Ground State

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The ground state nuclear moments of $^{186}$Ir ($j^o = 5^{(+)}$) have been determined with NMR on oriented $^{186}$Ir in Ni as $\mu = 3.80^{+0.12}_{-0.02}$ $\mu_N$ and $Q = -3.00$ (15)b. The quadrupole moment is consistent with an anomalous $j^o K = 5^{+} 0$ or $5^{+} 1$ ground state configuration. The explanation of the magnetic moment in terms of pure $5^{+} 0$ or $5^{+} 1$ configurations would require a high collective $g_R$-factor of $g_R \geq 0.76$. On the other hand the magnetic moment can be explained with a “normal” $g_R$ and a mixed ground state configuration.

1. Introduction

There have been many speculations [1--6] about the structure of the ground state of $^{186}$Ir ($j^o = 5^{(+)}$ [4]; $T_{1/2} = 16$ h). From $\beta$-decay properties Hofstetter et al. [3] proposed $j^o K = 5^{+} 1$ as the coupling of a proton in a $1/2^-$ [541] Nilsson state and a neutron in a $1/2^-$ [510] state. Emery et al. [7] had anticipated theoretically that rotational bands built on these states should be strongly disturbed, and that $j=4.5$ states would lie energetically lower than the corresponding band heads. Recently, the spectroscopic quadrupole moment has been measured by nuclear orientation (NO) on $^{186}$IrOs as $Q = -2.41$ (20)b [6]. Applying the Bohr-Mottelson formula

$$Q = Q_0 \frac{3K^2 - j(j+1)}{(j+1)(2j+3)}$$

where $Q_0$ is the intrinsic quadrupole moment, which is fixed by deformation parameters in the frame of the rotational model, $K = 0$ or $K = 1$ has been found to be consistent with reasonable $Q_0$-values in this mass region. This result has been interpreted as confirmation of the $j^o K = 5^{+} 1$ configuration proposed by Hofstetter et al. [3]. The magnetic moment of an odd-odd nucleus with configuration $j^o K$ is given by

$$\mu = g_R \cdot j + \frac{K}{j+1} \left( g_{K_1} \cdot K_1 + g_{K_2} \cdot K_2 - g_R \cdot K \right).$$

Here $g_R$ is the collective g-factor and $g_{K_1}, g_{K_2}$ are the single particle contributions of the valence proton and neutron. Spanhoff et al. [5] reported a first attempt to derive the magnetic moment of $^{186}$Ir from NO on $^{186}$Ir in Fe$_{90}$Re$_{10}$ using the temperature dependence of the observed $\gamma$-anisotropies. They argued that their experimental value of 2.8 (3) $\mu_N$ would be in contradiction with $K = 0, 1$ and they considered several other couplings of Nilsson orbits. Their NMR-ON data on $^{186}$IrFe [8] giving a magnetic moment of 3.79 (5) $\mu_N$ supported this assumption.

To clarify the situation an experiment has to be performed with which $\mu$ and $Q$ can be determined simultaneously. Only in this way it can be assured that the NO-measurements on $^{186}$IrOs and $^{186}$IrFe have probed the same nuclear state. (In principle the decay of $^{186}$Ir could take place via an up to now unobserved isomeric state with a half life of $\sim 10 \ldots 100$ s. Because of the different spin-lattice relaxation times a NO measurement would then yield $Q$ of the long-lived state but $\mu$ of the short-lived state. For example, such conditions are present for the decay of $^{191}$Os [10]).

2. Principle of Measurement

The NMR-ON method (nuclear magnetic resonance on oriented nuclei detected via the aniso-
tropy of radiation) [11] with Ni as host lattice is well suited for a measurement of $\mu$ and $Q$, as for IrNi a small electric field gradient (EFG) is present besides a large magnetic hyperfine field. The EFG originates from an unquenched orbital momentum of the 5$d$ electrons (at the impurity site) and is thus collinear with the direction of the hyperfine field [12]. The magnetic interaction causes a high degree of polarization at the “convenient” temperature of $10 \text{ mK}$ while the quadrupole interaction splits the resonance into $2j$ subresonances. The center of the subresonance corresponding to rf-transitions between state $|m\rangle$ and $|m+1\rangle$ is given by

$$v_{m \to m-1} = v_M + \Delta v_Q(m+1/2) + b(1+K)B_0$$

$$v_M = |g\mu_N| H_{\text{HF}}/h$$

$$\Delta v_Q = 3v_Q/[2j(2j-1)]$$

$$b = |g\mu_N/h| \cdot \text{sign}(H_{\text{HF}})$$

(3)

Here $g$ is the nuclear g-factor, $H_{\text{HF}}$ is the magnetic hyperfine field, $eq$ is the electric field gradient, $Q$ is the spectroscopic quadrupole moment, $K$ is the Knight-shift parameter, and $B_0$ is the external magnetic field.

For the actual experiment the resonance line width $\Gamma$, which is caused entirely by inhomogeneous broadening, plays an essential role: For $\Gamma/\Delta v_Q << 1$ the subresonances can be resolved, for $\Gamma/\Delta v_Q \approx 1$ an asymmetric structure is expected, from which $\Delta v_Q$ can be deduced with less accuracy, while for $\Gamma/\Delta v_Q > 1$ all quadrupole effects are smeared out. Recently it has been demonstrated for $^{192}$IrNi that, with the use of highly pure Ni and very dilute alloys, $\Gamma$ can be reduced so far that well-resolved quadrupole spectra are obtained [13].

3. Experimental Details

Samples of $^{186}$IrNi were prepared by recoil-implantation in the following way: A target stack consisting of 12 Re foils ($d=12 \mu\text{m}$; natural abundance) each being followed by a Ni foil ($d=2 \mu\text{m}$; purity >99.995%) was irradiated for 8h with 67 MeV $\alpha$-particles ($I=2 \mu\text{A}$) at the cyclotron in Karlsruhe. At this energy mainly $^{184}$Ir ($T_{1/2}=3.4 \text{ h}$) and $^{186}$Ir ($T_{1/2}=15.8 \text{ h}$) are produced via the nuclear reactions $^{185,187}$Re($\alpha$, 5$n$)$^{184,186}$Ir with cross sections of $\sim 700 \text{ mb}$. All $^{184,186}$Ir nuclei which are produced in the rear surface layer within $\sim 0.2 \mu\text{m}$ thickness can leave the Re foils and are thus implanted homogeneously into the following Ni foil within a layer of about the same thickness. (The $^{184}$Ir activities do not disturb the experiment because of the relatively fast decay to stable $^{184}$Os. The activities produced in situ in the Ni foils do not disturb either) During the irradiation the Ni-foils are heated via the energy loss of the $\alpha$-particles; thus a simultaneous annealing step takes place. After the irradiation the most active parts of the Ni-foils were cut out, and soldered to both sides of the cold finger of a demagnetization cryostat, and cooled to a temperature of $\sim 10 \text{ mK}$. A small external magnetic field $B_0$ ($0.435 \text{ kG} \leq B_0 \leq 4.78 \text{ kG}$) was applied to orient the ferromagnetic domains and thus to establish a unique direction of the hyperfine field with respect to which the $\gamma$-anisotropy is present. The rf field was applied perpendicular to $B_0$ with a single-turn coil, the direction of both fields being parallel to the foil plane. The $\gamma$-counts of the 137 keV, 297 keV, and 435 keV transitions, measured at 0°, 90°, 180°, and 270° with respect to $B_0$, were recorded as a function of the rf-frequency, which was 1 kHz frequency modulated and swept continuously over the resonance region; the sweep rate was chosen so small that no significant asymmetry of the measured resonance spectrum due to the finite spin-lattice-relaxation time was observed. Details of the NMR-electronics are described in [9]. All measurements were performed during the warm-up of the cryostat between $\sim 10$ and $\sim 20 \text{ mK}$. 

4. Results and Discussion

The resonance was searched between 200 and 320 MHz with a large modulation width $\Delta f = \pm 0.75 \text{ MHz}$ and a frequency resolution of 1 MHz/channel. A resonance for the 296 keV transition measured at 0° is shown in the upper part of Fig. 1. The spectrum shown in the lower part of Fig. 1 has been recorded with a higher frequency resolution of 40 kHz/channel and a smaller modulation width $\Delta f = \pm 50 \text{ kHz}$. The solid line represents the results of a least-squares fit, performed with the assumption of 7 equidistant quadrupole subresonances with constant line widths. The arrows show the center of these resonances, the height being directly proportional to the corresponding amplitudes. The $\nu_1$-resonance corresponds to the energetically lowest sublevel transition. The occurrence of $\sim 4$ resonances with decreasing amplitudes is expected according to the degree of orientation at $\sim 10 \text{ mK}$. This has been verified with model calculations as described in [9]. The large arrow in Fig. 1 indicates the position of the "pure" magnetic resonance $\nu_m$ which is si-