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 ($j^* = 5^{+}$) 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 $j^*K = 5^+0$ 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 ($j^* = 5^{+}$) [4]; $T_{1/2} = 16$ h). From $\beta$-decay properties Hofstetter et al. [3] proposed $j^*K = 5^+1$ 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 $j^*K = 5^+1$ configuration proposed by Hofstetter et al. [3].

The magnetic moment of an odd-odd nucleus with configuration $j^*K$ is given by

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

Here $g_R$ is the collective $g$-factor and $g_{K_1,2}K_{1,2}$ 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 $\sim 10 \cdots 100$ 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-
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entropy 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 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

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

$$v_M = \frac{|g\mu_N H_{HF}|}{h}$$
$$v_Q = \frac{e^2 qQ}{h}$$
$$\Delta v_Q = \frac{3vQ}{2j(2j-1)}$$
$$b = \frac{|g\mu_N/h| \cdot \text{sign}(H_{HF})}{(3)}$$

Here $g$ is the nuclear g-factor, $H_{HF}$ 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 $\Gamma/\Delta v_Q \ll 1$ 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 $\Gamma/\Delta v_Q \gg 1$ 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 ($d=12\,\mu$m; natural abundance) each being followed by a Ni foil ($d=2\,\mu$m; purity $>99.9995\%$) was irradiated for 8h with 67 MeV $\alpha$-particles ($I=2\,\mu$A) at the cyclotron in Karlsruhe. At this energy mainly $^{184}$Ir ($T_{1/2} = 3.4\,h$) and $^{186}$Ir ($T_{1/2} = 15.8\,h$) are produced via the nuclear reactions $^{185,187}$Re($\alpha,5n$)$^{184,186}$Ir with cross sections of $\sim 700\,mb$. All $^{184,186}$Ir nuclei which are produced in the rear surface layer within $\sim 0.2\,\mu$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 $\approx 10\,mK$. A small external magnetic field $B_0$ ($0.435\,kG \leq B_0 \leq 4.78\,kG$) 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 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 $\sim 20\,mK$.

4. Results and Discussion

The resonance was searched between 200 and 320 MHz with a large modulation width $\Delta f = \pm 0.75\,MHz$ 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 $\Delta f = \pm 50\,kHz$. 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 $v_r$-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 $\sim 10\,mK$. 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 $v_M$ which is si-