Measurements of spin, magnetic moment, and electric quadrupole moment of 41.5 h ^{188}Ir

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The techniques of nuclear orientation and nuclear magnetic resonance on oriented nuclei were applied to ^{188}Ir after recoil implantation into Fe and Ni. Combining the results of nuclear orientation and nuclear magnetic resonance on oriented nuclei, which are sensitive to the magnetic moment and the g factor, respectively, the spin of ^{188}Ir was determined to be $I=1$, in contradiction to $I=2$ adopted previously. In addition, the splitting of the nuclear magnetic resonance on oriented nuclei resonance into two subresonances due to quadrupole interaction was observed, which proves again $I=1$. The magnetic and electric hyperfine splitting frequencies, $\nu_M=|g\mu_N B_{HF}/h|$ and $\nu_Q=e^2qQ/h$, were determined for ^{188}Ir*Fe*, $\nu_M=315.8(3)$ MHz and for ^{188}Ir*Ni*, $\nu_M=104.8(1)$ MHz, $\nu_Q=-1.98(4)$ MHz. Taking into account a 3% uncertainty arising from hyperfine anomalies, the magnetic moment of ^{188}Ir is deduced to be $|\mu|=0.302(10)\,\mu_N$. With the electric field gradients of Ir in Fe and Ni, recalculated to be $-0.283(6)\times10^{17}$ V/cm^2 and $-0.151(4)\times10^{17}$ V/cm^2, respectively, the spectroscopic quadrupole moment of ^{188}Ir is deduced to be $+0.543(8)$ b. The β decay of ^{188}Ir to the 2214 keV level in ^{188}Os takes place to about 88% with tensor rank 0. Assuming the validity of the ξ approximation, the ratio of the remaining matrix elements is $|V/Y|=5.3(1.5)$. Our measurements show further that nuclear orientation experiments, from which γ-decay properties in ^{188}Os have been derived, will have to be reinterpreted. In addition, the spectroscopic quadrupole moments of ^{192}Ir and ^{194}Ir were redetermined to be $+2.28(6)$ b and $+0.339(12)$ b, respectively.

I. INTRODUCTION

The β decay of 41.5 h ^{188}Ir to levels in ^{188}Os and the ground state properties of ^{188}Ir had been the subject of several investigations.[1–4] For the ground state spin of ^{188}Ir, Yamazaki and Sato[3] assigned $I^\pi=2^-$ arising from the antiparallel coupling of a $\pi\frac{3}{2}^+[541]$ (^{187}Ir) and a $\nu\frac{1}{2}^-[510]$ (^{187}Os) Nilsson single particle state, although this coupling violates the Gallagher-Moszkowski rule.[5] This spin assignment had been based on logft values of rather weak β-decay branches to 4^+ levels in ^{188}Os. Thompson *et al.*[4] continued a refined study of these decay properties, again assuming $I^\pi=2^-$, which also was adopted in the Table of Isotopes.[6] Berkes *et al.*[7] reported a nuclear orientation (NO) measurement on ^{188}Ir*Fe*; assuming $I^\pi=2^-$ they derived $\mu(^{188}\text{Ir};2^-)=0.385(20)\,\mu_N$. Taking into account the magnetic moments of neighboring nuclei Berkes *et al.*[7] derived a "theoretical" magnetic moment $\mu(2^-)=0.36(4)\,\mu_N$, which was regarded to agree well with the experimental magnetic moment. This good agreement was viewed as a proof for the correct spin assignment. Murray *et al.*[8] reported quadrupole interaction nuclear orientation experiments on $^{186,188-190}$Ir in a Re single crystal. Assuming $I^\pi=2^-$ for ^{188}Ir, $L_\beta=1$ for the first-forbidden β decay to the 2214 keV level in ^{188}Os, and $L_\gamma=1$ for the 2214 keV γ transition, Murray *et al.*[8] derived a highly precise quadrupole splitting for ^{188}Ir*Re*, from which a spectroscopic quadrupole moment was deduced, which agreed well with the quadrupole moment expected in the framework of the rotational model.

Recently, Kreiner *et al.*[9] reported a study of excited states of ^{188}Ir by the $(\alpha,3n)$ reaction. Assuming $I^\pi=(2)^-$ for the ground state, spins of excited states were assigned consecutively.

In this paper we show that the spin of ^{188}Ir is 1. This means that the β-decay properties to levels in ^{188}Os have to be reinterpreted. We also present precise measurements of the magnetic moment and the quadrupole moment of ^{188}Ir. These are at variance with the results and conclusions drawn by Berkes *et al.*[7] and Murray *et al.*[8] A short description of these new results has been given elsewhere.[10]

After completion of this work we became aware that Ohya *et al.* had performed nuclear magnetic resonance on oriented nuclei (NMR-ON) experiments on ^{188}Ir*Fe*, too.[11] However, these authors did not resolve the quadrupole substructure. Although they reported that their magnetic moment disagreed with the NO result of Berkes *et al.*[7] they did not recognize that the spin assignment had been wrong. Consequently, their magnetic moment deduced with the assumption $I=2$ is incorrect, too. In our opinion it is accidental that their incorrect magnetic moment agrees with the theoretical expectation of Ekström *et al.*[12] based on the assumption of an incorrect ground state configuration.

Our spin determination is based on the combination of nuclear orientation (NO) and nuclear magnetic resonance on oriented nuclei (NMR-ON) (Ref. 13) measurements. This method had been proposed by Bacon *et al.*,[14] who stated that NO measurements yield the magnetic moment μ, while NMR-ON measurements yield the g factor, and that a combination of both methods thus yields $\mu/g=I$. The statement that the NO technique yields the magnetic

moment, independent of the spin, is (approximately) true only for high-spin parent states. For low-spin parent states the hyperfine interaction frequency deduced with a least-squares fit of the γ anisotropy depends characteristically on the spin assumed for the parent state. This means that a combination of NO and NMR-ON yields actually the spin of the parent state, independent of all decay parameters.

In addition, we applied a second independent method for the determination of the spin, namely quadrupole-interaction-resolved NMR-ON spectroscopy. In this method, which is well applicable to low-spin states in Ir, the spin is found by counting the number of NMR-ON subresonances, for which $2I$ is expected. In the present case two subresonances were found, again proving $I=1$ for ^{188}Ir.

II. NUCLEAR ORIENTATION AND NMR ON ORIENTED NUCLEI

The angular distribution of γ rays emitted in the decay of oriented nuclei is given by[15]

$$W(\theta)=1+\sum_{k\ \text{even}} B_k U_k F_k P_k(\cos\theta) Q_k \ . \tag{1}$$

The U_k and F_k are the normally used angular correlation coefficients which depend on the spins and multipolarities of the decay cascade. Tabulated values are given in Ref. 16. The $P_k(\cos\theta)$ are Legendre polynomials, θ being the angle between the quantization axis and the direction of observation, and Q_k are solid angle correction coefficients. The B_k describe the degree of orientation; in the case of "magnetic NO" they depend on

$$\beta=h\nu_M/k_B T \ , \tag{2}$$

where ν_M is the magnetic hyperfine (HF) splitting frequency,

$$\nu_M=|g\mu_N B_{\rm HF}/h| \ , \tag{3}$$

and T is the temperature of the system. It is reasonable to measure the angular distribution for $\theta=0°$ and 90°, $W(0°,T)$ and $W(90°,T)$. Then the following combinations can be calculated:

$$\epsilon(T)=\frac{W(0°,T)}{W(90°,T)}-1 \ ,$$
$$W_2(T)=\frac{3W(0°)-8W(90°)+5}{7}=A_2B_2(T)Q_2 \ , \tag{4}$$
$$W_4(T)=\frac{4W(0°)-8W(90°)-12}{7}=A_4B_4(T)Q_4 \ .$$

A simultaneous analysis of $W_2(T)$ and $W_4(T)$ yields ν_M, A_2, and A_4, completely independent of the knowledge of the specific decay properties (γ multipolarities, β-decay matrix elements, etc.). This is an essential advantage as no "reasonable" assumptions have to be made. The only parameter, which can be varied, is the spin I of the oriented state. If I is unknown, the γ anisotropy can be analyzed for different spins; the result for ν_M will then depend on the choice of I. The comparison of $\nu_M(I)$ with ν_M determined with the NMR-ON technique will then allow a direct determination of I, again completely independent of all decay parameters.

In the NMR-ON method[13] a rf-induced change of the sublevel populations is detected via the corresponding change of the radiation pattern of the γ rays. As the γ anisotropy influences only the resonance amplitude, the knowledge of $A_{2,4}$ is not necessary. The only criterion is that the γ anisotropy is large enough that the resonant destruction can be detected with statistical significance.

For ^{191}Ir and ^{193}Ir ($I^\pi=\frac{3}{2}^+$) as dilute impurities in Fe and Ni a small electric quadrupole interaction was detected to be superimposed to the magnetic interaction.[17,18] This is due to the interaction of the spectroscopic quadrupole moment with the local-moment-induced electric field gradient (EFG) of the $5d$ electrons at the impurity sites.[19,20] This effect causes a splitting of the NMR-ON resonance into $2I$ subresonances; the center of the subresonance corresponding to rf transitions between state $|m\rangle$ and $|m+1\rangle$ is, assuming that the $m=I$ state lies lowest in energy, given by

$$\begin{aligned}
&\nu_{m\to m+1}=\nu_M+\Delta\nu_Q(m+\tfrac{1}{2})+b(1+K)B_0 \ ,\\
&\nu_M=|g\mu_N B_{\rm HF}/h| \ ,\\
&\nu_Q=e^2qQ/h \ ,\\
&\Delta\nu_Q=3\nu_Q/[2I(2I-1)] \ ,\\
&b=|g\mu_N/h|\,\mathrm{sgn}(B_{\rm HF}) \ .
\end{aligned} \tag{5}$$

Here ν_M and ν_Q are the usually quoted magnetic and electric hyperfine splitting frequencies, respectively, $\Delta\nu_Q$ is the subresonance separation, K is the Knight shift parameter, and B_0 is the external magnetic field. Equation (5) holds also for "normal" NMR on the stable isotopes ^{191}Ir and ^{193}Ir in Fe and Ni, for which ν_Q is known experimentally with good accuracy.[17,18] As the spectroscopic quadrupole moments of ^{191}Ir and ^{193}Ir are known precisely from muonic hyperfine spectroscopy,[21] the field gradient of Ir in Fe and Ni can be deduced with good accuracy:

$$eq(\mathrm{Ir}Fe)=-0.283(6)\times10^{17}\ \mathrm{V/cm^2} \ ;$$

$$eq(\mathrm{Ir}Ni)=-0.151(4)\times10^{17}\ \mathrm{V/cm^2}$$

(see also Sec. V B). This means that for ^{188}Ir the quadrupole moment can be determined from the separation of the subresonances in addition to the spin which can be determined from the number of subresonances. In the following we will denote the resonance corresponding to transitions between the energetically lowest sublevels as ν_1 resonance, the next as ν_2 resonance, etc. In the case of $I=2$, four resonances will be expected, $\nu_1,\ldots,\nu_4$, while for $I=1$, two resonances are expected, ν_1 and ν_2. The theoretical amplitudes of the quadrupole subresonances can easily be calculated as described in earlier publications.[22,23] Figure 1 shows model calculations of the quadrupole subresonance structure for ^{188}IrFe (left) and ^{188}IrNi (right) for a temperature of 10 mK, both, for $I=1$ (top) and $I=2$ (bottom). [Parameters for the calculations: ^{188}IrFe: $\nu_M=315.8$ MHz, $\nu_Q(I=1)=-3.4$ MHz, $\nu_Q(I=2)=-9.8$ MHz, $\Gamma=2.4$ MHz; and ^{188}IrNi: $\nu_M=105.0$ MHz, $\nu_Q(I=1)=-1.8$ MHz, $\nu_Q(I=2)$

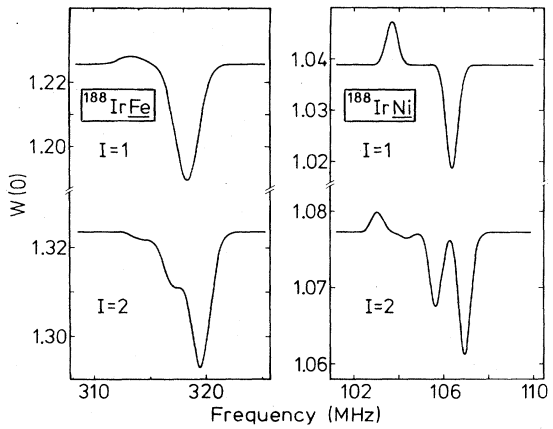

FIG. 1. Theoretical quadrupole subresonance structure for ^{188}Ir*Fe* (left) and ^{188}Ir*Ni* (right) as expected for $I=1$ (top) and $I=2$ (bottom) at a temperature of 10 mK.

$=-5.2$ MHz, $\Gamma=0.8$ MHz. The quadrupole frequencies were calculated assuming $K=I$ ground state configurations with an intrinsic quadrupole moment $Q_0=5$ b and the EFG's of above.] The following features deserve to be mentioned: For the resonance search Fe as host matrix will be better as the resonance strength is concentrated to a large degree in the ν_1 resonance, independent of the spin of ^{188}Ir. The amplitudes of the higher quadrupole subresonances drop rather rapidly because of the large value of $\beta=1.5$. (The ratio of the sublevel populations is given by the Boltzmann factor $e^{-\beta}$.) For a precise measurement of the quadrupole interaction substructure Ni will be the better host matrix because of the smaller $\beta=0.5$. In this case the spin of ^{188}Ir can be determined directly via the subresonance structure which is completely different for $I=1$ and 2.

III. EXPERIMENTAL DETAILS

The decay of 41.5 h ^{188}Ir can be investigated in two different ways, either by the direct decay or via the longer-lived isotope ^{188}Pt ($T_{1/2}=10.2$ d), which feeds 41.5 h ^{188}Ir. Both methods were applied for the present work: ^{188}Ir*Fe* was investigated with a ^{188}Pt*Fe* sample, while ^{188}Ir*Ni* was investigated directly. Both samples were prepared with the recoil-implantation technique. ^{188}Pt*Fe* was prepared at the cyclotron in Jülich by irradiating a sandwich target (16 ^{194}Pt foils, enrichment 97.4%, thickness 2.1 mg/cm^2, each followed by a Fe foil, thickness 1.5 mg/cm^2) with 125 MeV alpha particles (average current 1.5 μA, integral current 55 000 μAs). ^{188}Ir*Ni* was prepared at the cyclotron in Karlsruhe by irradiating a sandwich target (16 Cu foils, thickness 3.1 mg/cm^2, onto which Re had been evaporated with a thickness of 1.1 mg/cm^2, each followed by a Ni foil, thickness 2.0 mg/cm^2) with 43 MeV alpha particles (average current 2 μA, integral current 50 400 μAs). After the irradiations the Fe/Ni foils were annealed at 650 °C for 3 h in vacuum. The most active parts were soldered to the Cu coldfinger of an adiabatic demagnetization cryostat and cooled to a temperature of 8—10 mK. Details of the cryostat and the data acquisition system are described elsewhere.[22,24,25] For thermometry, Mn and Co isotopes were used, which were produced as contaminants in the Fe and Ni foils. These were ^{52}Mn, ^{54}Mn, and ^{57}Co in the ^{188}Pt*Fe* experiment. (The hyperfine splitting frequencies of these isotopes in Fe are well known.) For the NO experiment nonresonant rf eddy current heating was used for a controlled variation of the temperature between ~ 10 and ~ 50 mK. γ-ray spectra were accumulated for 500 s. All together 200 "cold" spectra were measured; after the warm-up of the cryostat to 1.1 K, 150 "warm" spectra were measured for normalization. In the ^{188}Ir*Ni* experiment, ^{56}Co was used for thermometry.

All NMR-ON measurements were performed in the temperature range between 10 and 15 mK. The center frequency was varied in steps of 0.1—1 MHz. After the accumulation of the γ-ray spectra the γ-ray intensities were analyzed immediately with least-squares fitting routines. In this way the γ anisotropy of the 2214 keV transition from ^{188}Ir*Fe* as well as the temperature of the sample were monitored continuously. NMR-ON spectra were obtained by summation of an even number of single spectra which were measured consecutively with opposite "sweep" direction. All together ~ 8000 γ-ray spectra were analyzed during the experiments within four weeks.

IV. RESULTS

A. γ anisotropies

The most intense γ rays emitted in the decay of oriented ^{188}Ir have small γ anisotropies, which have also been

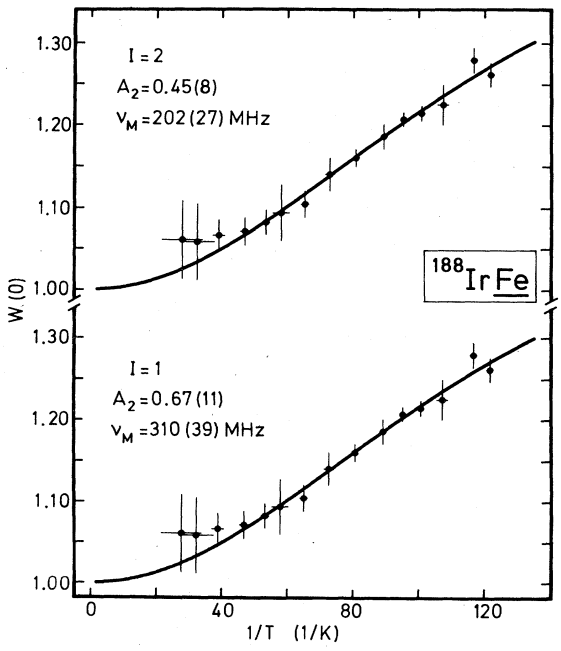

FIG. 2. γ anisotropy of the 2214 keV transition of ^{188}Ir*Fe* vs reciprocal temperature $1/T$. The solid lines are the results of least-squares fits assuming $I=2$ (top) and $I=1$ (bottom) for the ground state spin of ^{188}Ir. No assumptions on the β- and γ-decay properties were made.

recognized by Berkes *et al.*[7] and Murray *et al.*[8] The most suitable transition for γ-anisotropy studies is the 2214 keV transition [absolute γ intensity 13.0% (Ref. 26)]. Figure 2 shows the γ anisotropy $W(0°)$ vs $1/T$ measured in an external magnetic field $B_0=3.20(6)$ kG. (Additional measurements of the γ anisotropy for small external magnetic fields showed that the magnetization was saturated for $B_0 \geq 0.7$ kG.) The temperature was determined from the γ anisotropy of the 744 keV transition of ^{52}Mn. In addition, the temperature was determined from the 136 keV transition from ^{57}Co and from the 835 keV transition from ^{54}Mn. All temperature values were consistent within an accuracy of $\sim 3\%$. Assuming $I=2$, from an analysis of $W_2(T)$ and $W_4(T)$, the A_4 coefficient was found to be $|A_4| \leq 0.03$, which is consistent with the $L_\gamma=1$ character of the 2214 keV transition, for which $A_4=0$ is inferred. The solid lines in Fig. 2 represent the results of least-squares fits, performed with the assumption of $I=2$ (top) and $I=1$ (bottom) for the spin of ^{188}Ir, with A_2 and ν_M as free parameters ($A_4=0$). The results are

$$I=2: \quad \nu_M=202(27)\ \text{MHz}, \quad A_2=+0.45(8),$$

$$I=1: \quad \nu_M=310(39)\ \text{MHz}, \quad A_2=+0.67(11).$$

TABLE I. Experimental A_2 coefficients of γ lines from the decay of ^{188}Ir.

E (keV)	E_i (keV)	E_f (keV)	I_i	I_f	A_2
155	155	0	2^+	0^+	−0.03(1)
323	478	155	4^+	2^+	−0.08(7)
478	633	155	2^+	2^+	+0.06(1)
633	633	0	2^+	0^+	−0.27(2)
635	790	155	3^+	2^+	+0.12(6)
673	1463	790	2^-	3^+	−0.04(14)
757	2214	1457	1^+	2^+	+0.15(15)
825	1457	633	2^+	2^+	+0.2(3)
828[a]					−0.14(7)
830[a]	1463	633	2^-	2^+	−0.44(5)
1097	1730	633	$2,3^+$	2^+	−0.25(15)
1210	1842	633	1^+	2^+	−0.06(2)
1453	2086	633	$2,3^+$	2^+	−0.15(15)
1458	1458	0	2^+	0^+	−0.17(9)
1466	1620	155	3^+	2^+	+0.2(4)
1575	1730	155	$2,3^+$	2^+	+0.75(15)
1689					+0.15(25)
1717	2349	633	2^-	2^+	−0.26(8)
1803	1957	155	1,2	2^+	+0.3(2)
1812	1965	155	2^+	2^+	+0.05(20)
1945	2099	155	$1,2^+$	2^+	−0.11(7)
2050	2205	155	$2,3^+$	2^+	−0.26(4)
2060	2214	155	1^+	2^+	+0.01(5)
2098[b]					+0.13(3)
2194	2349	155	2^-	2^+	−0.4(2)
2214	2214	0	1^+	0^+	+0.67(2)

[a]Lines not well resolved.
[b]Double peak (not resolved).

It is obvious from Fig. 2, that no spin assignment can be made via the "quality" of the fit, i.e., χ^2. Moreover, none of both A_2 values can be excluded with nuclear structure arguments about the decay cascade. Therefore no spin assignment can be made from the NO measurement alone. On the other hand, as the magnetic hyperfine splitting frequencies are considerably different for $I=1$ and $I=2$, a unique spin determination can be made, if ν_M is measured with another technique. In Sec. IV B we present the results of our NMR-ON measurements, from which $\nu_M=315.8(3)$ MHz has been obtained. This definitely rules out $I=2$.

With the known NMR-ON value for ν_M, the A_2 coefficients of all γ transitions in ^{188}Os with moderate strengths were determined with least-squares fits from the respective γ anisotropies. The results are listed in Table I.

B. NMR-ON on ^{188}Ir*Fe*

The ^{188}Ir*Fe* NMR-ON resonance was first searched in the region 180—250 MHz. Within four days of continuous measurement time no resonance signal could be detected within an accuracy of 1%, which has to be compared with the γ anisotropy of $\sim 30\%$. Therefore further measurements were performed in the frequency regions 250—290 MHz and 290—330 MHz. A NMR-ON spectrum for the 290—330 MHz region is shown in Fig. 3. At ~ 318 MHz, the anisotropy was destroyed nearly completely, while the temperature remained constant. No satellite resonances due to quadrupole interaction were observed here because the temperature was too low. Figure 4 shows a NMR-ON spectrum measured at a temperature of ~ 20 mK. Here a second resonance becomes visible. The positions of the ν_1 and ν_2 resonance are marked in the figure. The small amplitude for the ν_2 resonance is again due to the relatively large $\beta \sim 1.0$. As we supposed that it would not be possible to resolve the quadrupole subresonance structure in Fe with good statistical accuracy, we confined ourselves to precise measurements of the ν_1 resonance. Figure 5 shows the ν_1 resonance measured with higher frequency resolution for two different external magnetic fields. Figure 6 shows the resonance frequencies

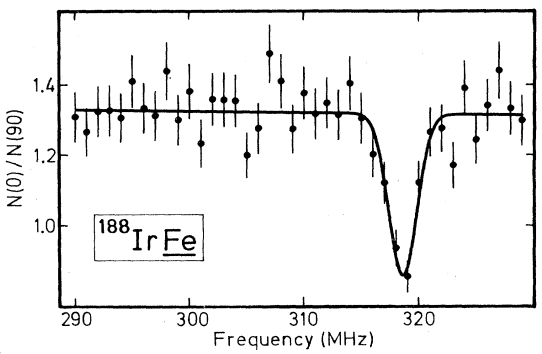

FIG. 3. NMR-ON resonance of the 2214 keV transition measured in an external magnetic field $B_0=0.80(2)$ kG. This result, together with the NO hyperfine splittings of Fig. 2, proves $I=1$ for the ^{188}Ir ground state.

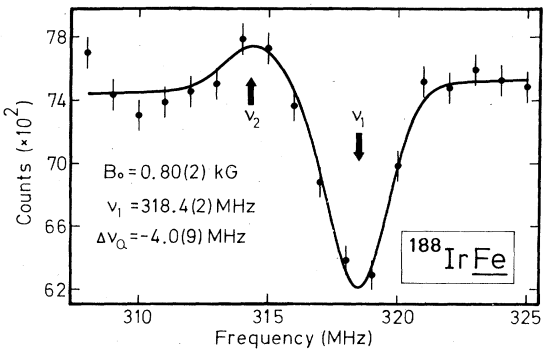

FIG. 4. ^{188}Ir*Fe* NMR-ON resonance of the 2214 keV transition measured at higher temperatures. The existence of two quadrupole subresonances is indicated, which are marked. The number of quadrupole subresonances cannot be deduced uniquely from this spectrum.

as a function of the external magnetic field B_0. The least-squares fit (solid line in Fig. 6) yields

$$\nu_1(B_0=0)=318.6(1)\ \text{MHz}\ ,$$

$$d\nu_1/dB_0=-0.29(6)\ \text{MHz/kG}\ .$$

C. NMR-ON on ^{188}Ir*Ni*

Because of the small γ anisotropy of the 2214 keV transition of only $\sim 3\%$ at $T=10$ mK, measurements were performed only for two values of the external magnetic field.

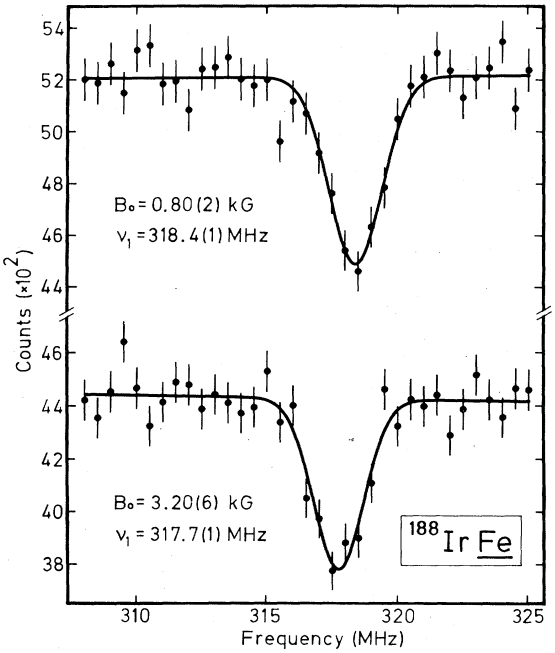

FIG. 5. ^{188}Ir*Fe* NMR-ON resonance of the 2214 keV transition measured with a total frequency modulation bandwidth 1 MHz. Only the ν_1 resonance is observed well.

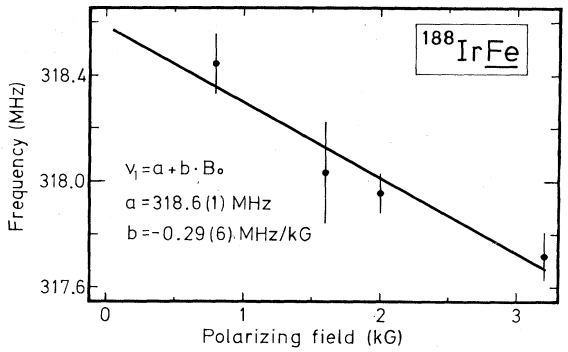

FIG. 6. Shift of the ν_1 resonance of ^{188}Ir*Fe* with the external magnetic field B_0.

Figure 7 shows a NMR-ON spectrum of ^{188}Ir*Ni* measured in an external magnetic field $B_0=0.80(2)$ kG. The linewidth (including the total frequency modulation bandwidth of 0.4 MHz) is 0.6(1) MHz, which is relatively small in comparison to the subresonance separation $\Delta\nu_Q=-3.02(9)$ MHz. The comparison of this spectrum with the model calculations of Fig. 1 definitely rules out the assignment $I=2$. This is a second independent proof that the ground state spin of ^{188}Ir is $I=1$. Further measurements were performed for $B_0=2.00(4)$ kG, the two resonances being measured separately. (In order to get the quadrupole subresonance separation as accurate as possible it is reasonable to measure the ν_2 resonance with better statistics because of its smaller resonance amplitude.) The results are $\nu_1=105.69(5)$ MHz, $\nu_2=102.77(7)$ MHz, $\Delta\nu_Q=-2.91(9)$ MHz. The dependence of the ν_1 resonance on B_0 is illustrated in Fig. 8; the least-squares fit yields

$$\nu_1(B_0=0)=106.27(7)\ \text{MHz}\ ,$$

$$d\nu_1/dB_0=-0.29(6)\ \text{MHz/kG}\ .$$

For the quadrupole subresonance separation and the quadrupole interaction frequency the final results are

$$\Delta\nu_Q=-2.97(6)\ \text{MHz}\ ,$$

$$\nu_Q=-1.98(4)\ \text{MHz}\ .$$

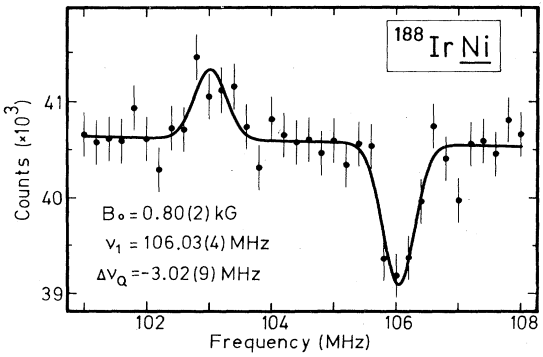

FIG. 7. ^{188}Ir*Ni* NMR-ON resonance structure of the 2214 keV transition. A comparison with the model calculations of Fig. 1 proves that the ground state spin of ^{188}Ir is $I=1$.

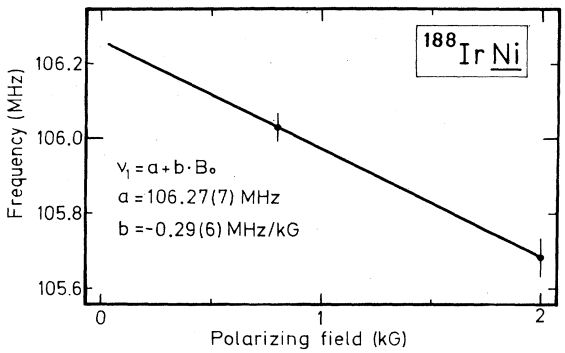

FIG. 8. Shift of the ν_1 resonance of ^{188}Ir*Ni* with the external magnetic field B_0.

The magnetic hyperfine splitting frequency is given by $\nu_1+\Delta\nu_Q/2$, i.e.,

$$\nu_M(^{188}\text{Ir}Ni)=104.8(1)\ \text{MHz}\ .$$

V. DISCUSSION

A. Decay properties

The decay of ^{188}Ir to levels in ^{188}Os has been discussed in several papers.[1–4] Here we want to confine ourselves to items which can be deduced from the A_2 coefficients (see Table I) of the present work.

2214 keV level: The 2214 keV level is fed directly by β decay and decays to the ground state via a 2214 keV γ transition. For the A_2 coefficient of the 2214 keV transition the following cascade has to be considered:

$$1^{(-)}\xrightarrow[\beta]{}I^{\pi}\xrightarrow[\gamma]{2214}0^{+}\ .$$

Originally $I^{\pi}=2^{+}$ had been assigned, i.e., multipolarity $E2$ for the 2214 keV transition. Assuming $I=2$, the theoretical A_2 coefficient is constricted to $A_2\leq+0.35$. This is in contradiction to the experimental value, $A_2=+0.67(2)$ (see Table I). Thus $I^{\pi}=2^{+}$ can be excluded. An assignment of $I=3$ yields the constriction $A_2\leq+0.49$, and can thus be excluded, too. With the assignment $I=1$ the measured A_2 coefficient can be analyzed to get information about β-decay matrix elements. In the most general case six different matrix elements with tensor ranks $L=0,1,2$ can contribute to a first forbidden $\Delta I=0$ transition. The theoretical A_2 coefficient is sensitive only to the tensor rank of the involved matrix elements. It is given by

$$A_2=U_2F_2=0.707(1.0X_0-0.5X_1+0.1X_2)\ , \tag{6a}$$

where X_0, X_1, and X_2 are the squares of the tensor rank L matrix elements,

$$\begin{aligned}X_0&=|\langle||L_\beta=0||\rangle|^2/\sum_{0,1,2}|\langle||L_\beta||\rangle|^2\ ,\\ X_1&=|\langle||L_\beta=1||\rangle|^2/\sum_{0,1,2}|\langle||L_\beta||\rangle|^2\ ,\\ X_2&=|\langle||L_\beta=2||\rangle|^2/\sum_{0,1,2}|\langle||L_\beta||\rangle|^2\ .\end{aligned} \tag{6b}$$

The experimental A_2 coefficient requires

$$X_0\geq0.88\ ,$$

$$X_1\leq0.06\ ,$$

$$X_2\leq0.12\ ,$$

which means that this β decay takes place with almost pure tensor rank 0. This result indicates that the ξ approximation,[33] in which the $L=2$ contribution vanishes and only two matrix elements V ($L=0$) and Y ($L=1$) remain, holds for this transition. Assuming the validity of the ξ approximation, the ratio of these matrix elements is deduced to be

$$|V/Y|=5.3(1.5)\ .$$

For the following γ transitions multipole mixing ratios δ were determined:

673 keV, $M2/E1$: $-\infty\leq\delta\leq+0.2$,

757 keV, $E2/M1$: $-\infty\leq\delta\leq-1.5$ or $-0.2\leq\delta\leq+0.4$,

830 keV, $M2/E1$: $+0.1\leq\delta\leq+1.5$,

1716 keV, $M2/E1$: $-0.2\leq\delta\leq+0.4$ or $+1\leq\delta\leq+5$,

2194 keV, $M2/E1$: $-0.2\leq\delta\leq+5.0$,

2060 keV, $E2/M1$: $-5\leq\delta\leq-2$ or $-0.2\leq\delta\leq+0.1$.

B. Hyperfine aspects and nuclear moments

The magnetic hyperfine splitting frequencies of Ir isotopes in Fe and Ni and the ratios of these frequencies are listed in Table II. This ratio, i.e., the ratio of the hyperfine fields is a highly selective quantity for each element. A determination of this ratio by measuring the resonance frequencies in Fe and Ni allows a unique assignment to the element. Especially for online measurements on nuclei far from stability this feature may be a useful tool for the assignment of γ rays to specific elements if the γ transitions cannot be assigned with conventional techniques. This ratio is 3.018(2) (see Table II) for Ir, while it is 3.87(1) for Os.[34] Thus we can decide whether the observed resonance originates from ^{188}Ir or from an isomeric state in ^{188}Os populated in the decay of ^{188}Ir. The measured value $R(^{188}\text{Ir})=3.013(4)$ proves uniquely that the NMR-ON signal originates from the ^{188}Ir ground state.

The electric quadrupole interaction frequencies of Ir isotopes in Fe and Ni are listed in Table III. For ^{188}Ir*Fe* the quadrupole subresonance structure was not resolved well, most probably due to the fact that the temperature could not be raised high enough so that the ν_2 resonance could be observed with reasonable statistical accuracy. However, the ν_1 resonance was measured with sufficient accuracy, and it is possible to correct for the quadrupole interaction as $\nu_Q(^{188}\text{Ir}Ni)$ and the ratio of the electric field gradients of Ir in Fe and Ni are known. Taking the ratio 1.88(4) of the electric field gradients in Fe and Ni, the quadrupole splitting of ^{188}Ir*Fe* is calculated to be 3.72(11) MHz. This corresponds to a quadrupole subresonance

TABLE II. Magnetic hyperfine splitting frequencies of Ir isotopes in Fe and Ni and ratios of these frequencies.

Isotope	$\nu^{(Fe)}$ (MHz)	$\nu^{(Ni)}$ (MHz)	$\nu^{(Fe)}/\nu^{(Ni)}$	Ref.
^{186}Ir	794.7(3)[a]	263.1(2)	3.021(4)	27,28
^{188}Ir	315.8(3)	104.8(1)	3.013(4)	This work
^{191}Ir^{m}	1174.9(2)[b]	389.70(2)[b]	3.015(5)[c]	29,30
^{192}Ir	503.5(1)	176.77(1)	3.019(1)	22
^{193}Ir	119.00(5)	39.56(3)	3.008(3)	31
^{194}Ir	408.54(23)	135.24(5)	3.021(2)	32
Average			3.018(2)	

[a]Corrected for displacement due to quadrupole interaction assuming $Q=-2.7(3)$b [Correction $+2.7(3)$ MHz.]
[b]Not corrected for resonance displacement due to quadrupole interaction as the quadrupole moment is unknown.
[c]Error estimated from model calculations with a reasonable assumption for the quadrupole moment. Because of this uncertainty this value was omitted for the calculation of the average ratio.

splitting of $-5.6(2)$ MHz. The magnetic hyperfine splitting frequency is thus found to be

$$\nu_M(^{188}\mathrm{Ir}Fe)=315.8(3)\ \mathrm{MHz}\ .$$

For the derivation of the nuclear g factor the hyperfine field has to be known. As the hyperfine field derived from the ground state splitting of stable ^{193}Ir in Fe is subject to a large hyperfine anomaly, it is more appropriate to use the hyperfine field acting on the 73 keV $\frac{1}{2}^+$ state of ^{193}Ir, for which the single-level hyperfine anomaly is expected to be small, $B_{\mathrm{HF}}=-1373(7)$ kG.[22] For the derivation of this hyperfine field the ground state g factor for ^{193}Ir, $g=0.1061(4)$ (Ref. 35), including corrections due to Knight shift [$K=1.3\%$ (Ref. 35)] and diamagnetic shielding [$(1/(1-\sigma)=1.1047$ (Ref. 36)] and the hyperfine anomaly between the $\frac{3}{2}^+$ ground state and the $\frac{1}{2}^+$ excited state, $^{1/2^+}\Delta^{3/2^+}_{\mathrm{Fe}}=0.072(4)$ (Ref. 37) had to be used. Meanwhile, there exist doubts whether the NMR value for the ground state g factor of ^{193}Ir, $g=0.1061(4)$, is correct. Recently Bürger *et al.* reported a direct measurement of this g factor by high-precision atomic beam magnetic resonance.[38] Their result, $g=0.1091(4)$, is about 3% larger than the NMR value. The origin for this discrepancy is not known at present. Bürger *et al.*[38] discuss that it might be due to an incorrect Knight shift correction in the NMR experiment or due to an incomplete treatment of off-diagonal perturbations in their g_I determination. As long as the origin for this discrepancy is not removed experimentally, we use the "old" hyperfine field for Ir*Fe*, $B_{\mathrm{HF}}=-1373(7)$ kG,[22] with which the g factor of ^{188}Ir is now deduced to be 0.3017(15). For an estimate of the single-level hyperfine anomaly of ^{188}Ir the respective nuclear wave function has to be known. Possible assignments are listed in Table IV, together with theoretical g factors calculated with Nilsson wave functions.

Although the measured g factor would support the second configuration we think that no final conclusion on the configuration should be drawn as long as the sign of the g factor is not known experimentally. We think, however, that an upper limit for the hyperfine anomaly is 3%. (Applying the empirical rule of Moskowitz and Lombardi,[39] a 2% hyperfine anomaly would be expected if the

TABLE III. Electric quadrupole splitting frequencies and spectroscopic quadrupole moments of Ir isotopes.

Isotope	$\nu^{(Fe)}$ (MHz)	$\nu^{(Ni)}$ (MHz)	$\nu^{(Fe)}/\nu^{(Ni)}$	Q (b)
^{186}Ir		$+10.6(3)$[a]		
^{188}Ir		$-1.98(4)$[b]		$+0.543(18)$
^{192}Ir	$-15.64(34)$[c]	$-8.307(19)$[c]	1.88(4)	$+2.28(6)$
^{193}Ir	$(-)5.1(1)$[d]	$(-)2.8(1)$[e]	1.82(7)	$+0.751(9)$[f]
^{194}Ir	$-2.47(20)$[g]	$-1.23(3)$[g]	2.01(12)	$+0.339(12)$
Average			1.88(4)	

[a]Reference 28; quadrupole subresonance structure not well resolved.
[b]This work.
[c]Reference 22.
[d]Reference 18.
[e]Reference 17.
[f]Reference 21; quadrupole moment taken for calibration of the EFG's.
[g]Reference 32.

TABLE IV. Ground state g factor of ^{188}Ir for different possible Nilsson configurations. The experimental value is $|g|=0.302(10)$.

Proton configuration $j^{\pi}[Nn_z\Lambda]$	Neutron configuration $j^{\pi}[Nn_z\Lambda]$	$I^{\pi}K$	g
$\frac{3}{2}^+[402]$	$\frac{1}{2}^-[510]$	1^-1	$+0.37\cdots+0.55$
$\frac{1}{2}^+[400]$	$\frac{3}{2}^-[521]$	1^-1	$+0.13\cdots-0.52$

sign of the magnetic moment of ^{188}Ir is positive.) Thus the g factor of the ^{188}Ir ground state is finally given by

$$|g(^{188}\mathrm{Ir})|=0.302(10)\ .$$

From the quadrupole splitting of ^{188}Ir in Ni the spectroscopic quadrupole moment can be derived. From the quadrupole splittings of ^{193}Ir in Fe and Ni and the quadrupole moment of ^{193}Ir, which was determined recently by muonic x-ray spectroscopy[21] (see Table III), the electric field gradients of Ir in Fe and Ni are deduced to be

$$eq(\mathrm{Ir}Fe)=-0.283(6)\times10^{17}\ \mathrm{V/cm^2}\ ,$$

$$eq(\mathrm{Ir}Ni)=-0.151(4)\times10^{17}\ \mathrm{V/cm^2}\ .$$

The spectroscopic quadrupole moment of ^{188}Ir is now found to be

$$Q(^{188}\mathrm{Ir})=+0.543(18)\ \mathrm{b}\ .$$

In the framework of the rotational model the intrinsic quadrupole moment Q_0 can be calculated via the projection formula

$$Q=Q_0\frac{3K^2-I(I+1)}{(I+1)(2I+3)}\ , \tag{7}$$

from which, with the assumption of a $I^{\pi}K=1^{(-)}1$ configuration, $Q_0=5.43(18)$ b is deduced. This value agrees well with the expectation, taking into account known spectroscopic quadrupole moments and $B(E2)$ transition probabilities in this mass region. Thus our value for the spectroscopic quadrupole moment may be regarded as a proof for a pure $I^{\pi}K=1^{(-)}1$ configuration, the amplitudes of $K=0$ admixtures being negligibly small.

In addition, the "new" electric field gradients of Ir in Fe and Ni are used to reinterpret the quadrupole splittings of ^{192}Ir and ^{194}Ir. The quadrupole moments are

$$^{192}\mathrm{Ir}(I^{\pi}=4^{(-)}):\ Q=+2.28(6)\ \mathrm{b}\ ,$$

$$^{194}\mathrm{Ir}(I^{\pi}=1^{(-)}):\ Q=+0.339(12)\ \mathrm{b}\ .$$

It should be mentioned that ^{188}Ir and ^{194}Ir seem to have the same ground state configuration. However, the spectroscopic quadrupole moment drops from $+0.543(18)$ b at $A=188$ to 0.339(12) b at $A=194$. This can be understood as the deformation decreases with increasing neutron number, and a prolate-oblate phase transition could occur for the heavier Ir isotopes. A measurement of the magnetic moment and the spectroscopic quadrupole moment of ^{196}Ir with quadrupole-interaction-resolved NMR-ON should be possible with on-line mass-separator implantation techniques.

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