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Measurement of the sign and magnitude of the electric field gradients at Re and Os nuclei as impurities in a hexagonal Lu single crystal

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The nuclear orientation technique has been applied to dilute alloys of ^{182}Re ($j^\pi = 2^+$) and ^{183}Os ($j^\pi = \frac{9}{2}^+$) nuclei in a hexagonal Lu single crystal, the activities being produced *in situ* via the heavy-ion-induced nuclear compound reaction (^{12}C,xn) with $x = 4, 5$. From the γ anisotropy at temperatures down to 6 mK the quadrupole interaction frequencies of ^{182}Re*Lu* and ^{183}Os*Lu* have been determined as +311(24) and +403(20) MHz, respectively. The electric field gradients (EFG) are deduced to be $eq(\mathrm{Re}Lu) = +6.8(6) \times 10^{17}$ V/cm^2 and $eq(\mathrm{Os}Lu) = +5.3(5) \times 10^{17}$ V/cm^2. The positive sign in both cases indicates that the direction of the EFG at the impurity sites is fixed by the properties of the host lattice.

I. INTRODUCTION

Systematic investigations of the nuclear quadrupole interaction in noncubic materials has gained considerable interest in recent years. From the measured quadrupole splitting $\Delta E_Q = h\nu_Q = e^2qQ$ either the nuclear quadrupole moment Q or the electric field gradient (EFG) eq can be determined if the other quantity is known. Most experiments have been done for a better understanding of the EFG's in noncubic metals. This is due to the fact that no theoretical model exists with which a large part of the EFG data could be described properly. Only for a few cases of simple nontransition metals the theoretical description has been performed successfully.[1] A review of the present situation, together with all EFG data through 1977, has been given recently by Kaufmann and Vianden.[2] There exist, however, phenomenological models, with which the empirically observed systematic trends are described. Raghavan *et al.*[3,4] have proposed the so-called "universal correlation" between the total EFG, which can be measured, and the lattice gradient, which can be calculated easily using lattice sum methods.[5,6] This correlation is given by

$$eq = K(1-\gamma_\infty)eq_{\mathrm{latt}} + e\bar{q} \quad . \tag{1}$$

Here γ_∞ is the Sternheimer antishielding parameter and K is a constant, which was empirically found to be $K \sim -2$. Small deviations due to the individual properties of different host-impurity systems are taken into account by the correction $e\bar{q}$, which is outlined in detail in Ref. 4. For all hexagonal transition metals negative EFG's would be expected according to Eq. (1), as the corresponding lattice gradients are all positive. This is due to the fact that the c/a ratios of all known hexagonal transition metals are smaller than 1.633. There exist, however, hexagonal transition metals such as Gd, Lu, or Hf for which the sign of the EFG is unambiguously positive. This observation has led to the recent proposal[7] that Eq. (1) holds, but with $K \sim -2$ for all Group IIb, VIIb, and VIIIb hexagonal metals, and $K \sim +3$ for all Group IIIb and IVb metals. All EFG data on pure systems are then described properly. No predictions on impurity systems had been made in this framework, but it is an interesting question whether the impurity systems follow this trend, too.

A first experiment on ^{175}Hf*Lu* showed the EFG of Hf*Lu* being positive.[8] This is not so astonishing, however, as the EFG of both pure systems Lu*Lu* and Hf*Hf* is positive. A more interesting aspect would be the sign of the EFG of impurity-host combinations, the one belonging to Group IIb, VIIb, or VIIIb, with a negative sign for the EFG's of the pure systems, and the other belonging to Group IIIb or IVb, with a positive sign of the EFG's of the pure systems. Such conditions are fulfilled for Re and Os nuclei as impurities in Lu.

The low-temperature nuclear orientation technique (NO) is well applicable for the measurement of magnitude and sign of electric quadrupole splittings; several experiments have been performed recently, both for the determination of nuclear quadrupole moments of ground states of radioactive nuclei,[9-12] and for the determination of EFG's.[7,8,13-16] The isotopes ^{182}Re ($j^\pi = 2^+$) and ^{183}Os ($j^\pi = \frac{9}{2}^+$) are well suited for NO experiments with Lu as host lattice, as NO data[17] on ^{182}Re*Re* and ^{183}Os*Re* are available according to which reasonably large γ anisotropies can be expected. Normally, the sample preparation is one of the most difficult parts of the experiment. We have solved this problem by preparing the activities *in situ* via the heavy-ion-induced nuclear compound reactions $^{175}\mathrm{Lu}(^{12}\mathrm{C},5n)^{182}\mathrm{Ir} \rightarrow {}^{182}\mathrm{Os} \rightarrow {}^{182}\mathrm{Re}$

and ^{175}Lu(^{12}C, 4n)^{183}Ir$\rightarrow$^{183}Os. Moreover, these experiments have shown that the use of heavy-ion-induced reactions is very powerful for the preparation of selected impurity-host systems. With the use of the appropriate heavy-ion beam a large series of neutron-deficient isotopes can be produced selectively, thus opening a wide field, both, for the determination of EFG's and of ground-state quadrupole moments of short-lived neutron-deficient nuclei.

II. NUCLEAR ORIENTATION

The angular distribution of γ rays emitted in the decay of oriented radioactive nuclei is most conveniently written as[18]

$$W(\theta)=\sum_k B_k\left(\frac{h\nu_Q}{k_B T}\right)A_k P_k(\cos\theta)Q_k \ . \qquad (2)$$

The parameters B_k describe the degree of orientation, they depend on the spin of the oriented state and on ν_Q/T. Here T is the temperature of the system. The parameters A_k depend on the characteristics of the nuclear decay. They are normally products of the usual angular correlation coefficients U_k and F_k, which, e.g., are tabulated in Ref. 19. The $P_k(\cos\theta)$ are Legendre polynomials, θ being the angle between the direction of observation and the c axis of the single crystal which is the quantization axis of the nuclear spin system. The Q_k in Eq. (2) are correction coefficients for the solid angle of the detectors; they are normally near 1. The basic features in the context with quadrupole nuclear orientation have been described in detail in Refs. 7 and 11. There are, however, some special features which are important for the present work; these are outlined shortly in the following.

In the high-temperature region, $h\nu_Q << k_B T$, only the $k=2$ contribution in Eq. (2) plays an essential role, as the orientation parameter B_4 is very much smaller than B_2. The $B_2(h\nu_Q/k_B T)$ can then be expanded in powers of $h\nu_Q/k_B T$, which yields

$$B_2 \sim h\nu_Q/k_B T \ . \qquad (3)$$

The γ anisotropy is then given by

$$W(\theta)=1+A_2P_2(\cos\theta)Q_2\nu_Q/T \ . \qquad (4)$$

Here A_2 contains all information about the nuclear decay [spins, multipolarities, mixing ratios of multipolarities, tensor ranks of the preceding β^-, β^+ or electron capture (EC) transitions, and mixing ratios of different tensor ranks] as well as some numerical factor. It is obvious that it is the product A_2e^2qQ which can be determined most precisely from a quadrupole NO experiment. For an absolute determination of eq a precise value for the product A_2Q has to be available. This information can be obtained from a NO experiment with the same isotope in a host lattice for which the EFG is known. The ratio of the corresponding γ anisotropies yields the ratio of EFG's:

$$\frac{W^{(1)}(\theta)-1}{W^{(2)}(\theta)-1}=\frac{(A_2e^2qQ)^{(1)}}{(A_2e^2qQ)^{(2)}}=\frac{eq^{(1)}}{eq^{(2)}} \ . \qquad (5)$$

This means that a detailed knowledge of the single quantities A_2 and Q is not necessary. (For the determination of nuclear quadrupole moments, however, information about A_2 is necessary. Sometimes this may be the most important limitation for the accuracy to which quadrupole moments can be determined, the largest factor of uncertainty normally arising from imprecisely known mixing ratios of different tensor ranks of the β decays preceding the observed γ transition.) Equation (5) holds exactly for the temperature range where the $k=4$ terms of Eq. (2) can be neglected. If the measurements are extended to such low temperatures that the $k=4$ terms have to be taken into account, the ratio $eq^{(1)}/eq^{(2)}$ can be determined as a function of the nuclear parameters. It is found that this quantity remains nearly constant in most cases, at least for reasonable variations of the nuclear parameters, thus allowing a precise determination of ratios of EFG's. Normally the γ anisotropies are measured at 0° and 90° with respect to the axis of orientation. The ratio

$$\epsilon=\frac{W(0)}{W(90)}-1 \ , \qquad (6)$$

which is normally denoted as anisotropy also, is then used for the further analysis of the data. It is obvious that $eq^{(1)}/eq^{(2)}$ can also be determined from those ϵ's without a precise knowledge of the nuclear decay parameters.

This feature will be utilized for the determination of the EFG's from the γ anisotropies of ^{182}Re*Lu* and ^{183}Os*Lu*, as precise NO data are available for ^{182}Re*Re* and ^{183}Os*Re* and the EFG's of Re*Re* and Os*Re* are well known.

III. (^{12}C,xn) REACTION ON ^{175}Lu

The ^{12}C induced nuclear compound reactions with the highest cross sections in the energy range between 60 MeV (Coulomb barrier of ^{12}C+^{175}Lu) and 81 MeV (the energy at which the experiment has been performed) on ^{175}Lu are

$$^{175}\text{Lu}(^{12}\text{C},xn)^{187-x}\text{Ir}, \quad x=3,4,5 \ .$$

Thus the Ir isotopes ^{182,183,184}Ir are produced which decay with relatively small half-lives to the corresponding Os isotopes:

$$^{182}\text{Ir}\ (15\ \text{min}) \xrightarrow{\text{EC},\beta^+} {}^{182}\text{Os}\ (22\ \text{h}) \xrightarrow{\text{EC}} {}^{182}\text{Re}\ (12.7\ \text{h})\ ,$$

$$^{183}\text{Ir}\ (0.9\ \text{h}) \xrightarrow{\text{EC},\beta^+} {}^{183}\text{Os}\ (13\ \text{h}) \xrightarrow{\text{EC}} {}^{183}\text{Re}\ (71\ \text{d})\ ,$$

$$^{184}\text{Ir}\ (3\ \text{h}) \xrightarrow{\text{EC},\beta^+} {}^{184}\text{Os}\ (\text{stable})\ .$$

For a calculation of the obtainable radioactivities the reaction cross sections have to be known. Absolute values for $\sigma(E)$ on ^{12}C induced reactions on ^{175}Lu have not been found in the literature; an estimate for $\sigma(E)$ can be made, however, using experimental cross sections on ^{12}C induced reactions on other isotopes (^{181}Ta, ^{197}Au) in this mass region.[20] The result is listed in Table I, together with the energy loss of ^{12}C in lutetium, which has been obtained by proper interpolation of the data of Ref. 21. The (^{12}C,3n) reaction will not be considered as the half life of ^{184}Ir is too short for an off-line NO measurement. As the energy loss of ~ 80 MeV ^{12}C in Lu is ~ 1 MeV/(mg/cm^2) (~ 1 MeV/μm) the (^{12}C, 4n) reaction takes place in a surface layer of ~ 20 μm thickness with an average cross section $\bar{\sigma} \sim 200$ mb. The (^{12}C, 5n) reaction is fixed to an ~ 10 μm layer at the surface with $\bar{\sigma} \sim 200$ mb. The activity N (in μCi) after an irradiation is given by

$$N[\mu\text{Ci}] = \frac{100}{A} p I(\mu\text{A}) \sigma(\text{mb}) \times d(\text{mg/cm}^2)[1 - \exp(-T_s \ln 2 / T_{1/2})]\ . \quad (7)$$

Here A is the atomic number, p is the abundance of the target nuclei, I is the beam particle current, σ is the reaction cross section, d is the (effective) target thickness, T_s is the duration of irradiation, and $T_{1/2}$ is the half life of the produced isotope. Taking the values for d and σ from above and assuming $T_s = 12$ h and $I = 150$ particle nA, the activities of ^{182}Os and ^{183}Os are estimated to be 54 and 138 μCi, respectively. After a time interval of 2 days activities of ~ 12-μCi ^{182}Os and ~ 11-μCi ^{183}Os are left, which is exactly the right order of magnitude for quadrupole NO experiments.

IV. SAMPLE PREPARATION AND EXPERIMENTAL DETAILS

The sample was prepared in the following way: From a lutetium single crystal rod purchased from Ames Laboratory, in Iowa, a disk of about 4 mm diameter and a thickness of ~ 0.3 mm was spark cut. The crystal c axis was oriented perpendicularly to the disk plane, the accuracy of the orientation being $\sim 1°$. During another experiment at the Munich MP-tandem accelerator the sample was irradiated parasitically with 20-MeV deuterons to produce ~ 15-μCi ^{175}Hf ($j^\pi = \frac{5}{2}^-$; $T_{1/2} = 70$ d) via the nuclear reaction ^{175}Lu(d, 2n)^{175}Hf. (The quadrupole splitting of ^{175}Hf*Lu* has been known only with a large experimental error[9]; thus more precise data on ^{175}Hf*Lu* have been desirable.) The crystal was then irradiated directly with ^{12}C, the energy and the current of the beam being chosen at 81 MeV and 150 particle nA, respectively. After this second irradiation the crystal was annealed for 1 h at a temperature of 1400 °C under vacuum atmosphere with a pressure of $< 10^{-7}$ torr. Special care was taken in slowly cooling down to room temperature. Using the eutectic alloy Ga-In as soldering material and a high-power ultrasonic soldering device the crystal was then soldered to one side of the cold finger of a two-step demagnetization cryostat the details of which are described in Ref. 22. For thermometry a ^{60}Co*Ni* foil was soldered to the other side of the cold finger. To be able to detect a possible temperature gradient a ^{57}Co*Ni* thermometer foil was soldered to the surface of the Lu crystal. With Cr-K-alum and the van Vleck paramagnetic compound PrCu$_6$ as cooling materials the sources were cooled to final temperatures of ~ 6 mK. An external magnetic field of 4 kG was applied, both to orient the ferromagnetic domains of the thermometer foils, and to establish a good thermal conductivity of the soldered joints.

TABLE I. Estimated minimum cross sections for ^{175}Lu(^{12}C,xn) reactions and energy loss of ^{12}C in ^{175}Lu.

	σ (mb)		
E (MeV)	^{175}Lu(^{12}C, 4n)	^{175}Lu(^{12}C, 5n)	dE/dx [MeV/(mg/cm^2)]
50	0		1.12
60	100	0	1.04
70	300	100	0.96
80	200	300	0.88

During four warm-up periods of the cryostat from 6 to ~ 30 mK, each of which took place in a time interval of ~ 6 h, γ spectra were measured with 4 coaxial Ge(Li) detectors which were placed at 0°, 90°, 180°, and 270° with respect to the *c* axis of the single crystal. Every 1000 sec the spectra were recorded onto magnetic tape. Four normalization spectra were taken at "high" temperatures before and after each cooling run. The final analysis was done on the PDP 10 computer of the accelerator laboratory, using fit routines with the assumption of Gaussian line shapes and a linear background.

Figure 1 shows the inverse temperature $1/T$ at the surface of the Lu crystal, as determined from the γ anisotropy of ^{57}Co*Ni*, vs $1/T$ of the cold finger, which is determined from the γ anisotropy of ^{60}Co*Ni*. The solid line holds for the ideal case that both temperatures are equal. The temperature at the surface of the Lu crystal is obviously slightly higher than the temperature of the cold finger. Similar but very much larger temperature gradients have been observed in previous experiments with Lu as host lattice.[7,8] In these experiments an ultrasonic soldering device with smaller power had been used. Thus we conclude that such temperature gradients are caused by bad heat contacts at the soldering joints and not by a bad thermal conductivity of Lu at ultralow temperatures. For the further analysis the mean value of the two thermometers is adopted as average temperature of the Lu crystal. The error in this temperature has been estimated in such a way that both single values are included.

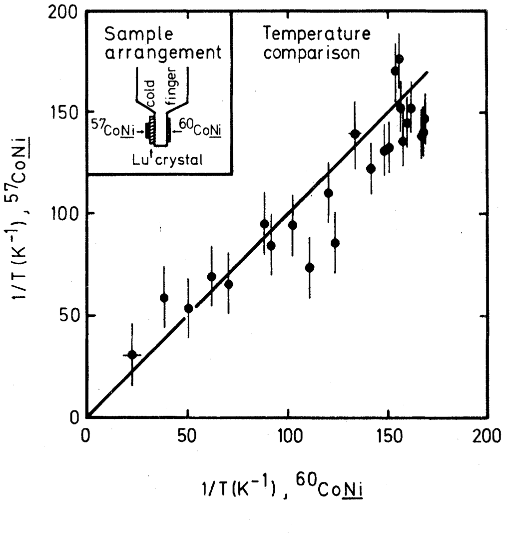

FIG. 1. Reciprocal temperature $1/T$ at the surface of the Lu crystal vs $1/T$ of the cold finger. The solid line represents the ideal case that no temperature gradients are present.

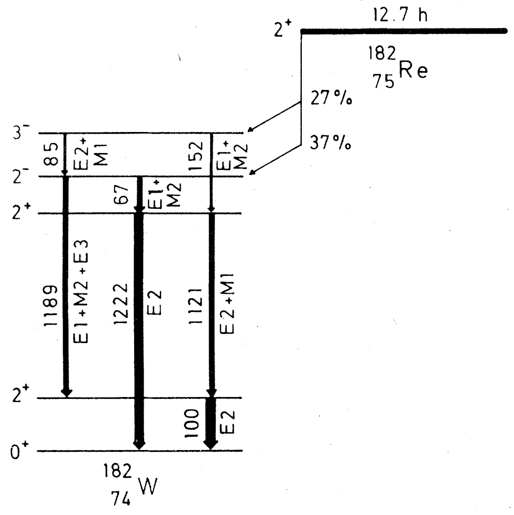

FIG. 2. Simplified decay scheme of ^{182}Re.

V. RESULTS

A. ^{182}Re*Lu*

A simplified decay scheme of ^{182}Re is illustrated in Fig. 2. From NO measurements on ^{182}Re*Re* it has been known that the largest γ anisotropies are expected for the 1189- and the 1222-keV transitions.[17] Figure 3 shows the corresponding γ anisotropies for

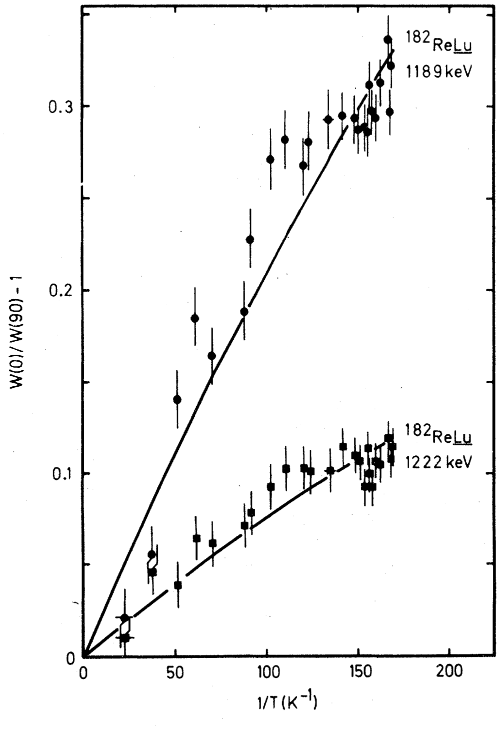

FIG. 3. γ anisotropies of the 1189- and 1222-keV γ transitions of ^{182}Re*Lu* vs $1/T$.

TABLE II. Nuclear parameters of ^{182}Re decay.

Energy (keV)	$j_i \rightarrow j_f$	type	Multipolarity	Mixing ratio[a]
	$2^+ \rightarrow 3^-$	EC	1,2	$\lvert\langle T2\rangle/\langle T1\rangle\rvert^2 \approx 0.2$
	$2^+ \rightarrow 2^-$	EC	1,2	$\lvert\langle T2\rangle/\langle T1\rangle\rvert^2 \approx 0.1$
67	$2^- \rightarrow 2^+$	γ	$M2/E1$	$\delta = 0.003(2)$
85	$3^- \rightarrow 2^-$	γ	$E2/M1$	$\delta = 0.30(2)$
152	$3^- \rightarrow 2^+$	γ	$M2/E1$	$\delta = 0.014(13)$
1121	$2^+ \rightarrow 2^+$	γ	$E2/M1$	$\delta = +15^{+5}_{-2}$
1189	$2^- \rightarrow 2^+$	γ	$E3/M2/E1$	$M2/E1{:}\delta = +0.46(2)$ $E3/E1{:}\delta = -0.69(4)$
1222	$2^+ \rightarrow 0^+$	γ	$E2$	

[a] EC transition: mixing ratio of different tensor ranks; γ transition: mixing ratio of different multipolarities.

Lu as host lattice. The full curves have been obtained from least squares fits utilizing Eqs. (2) and (6). With the nuclear parameters listed in Table II the quadrupole interaction frequency is found to be $\nu_Q(^{182}\mathrm{Re}Lu) = +311(24)$ MHz. The quoted error represents the statistical error plus the uncertainty from the temperature assignment. The quadrupole frequency for ^{182}Re*Re* has been deduced with the same nuclear parameters to be $-223(7)$ MHz. The EFG for Re*Re* is obtained from the quadrupole splitting of the stable isotopes ^{185,187}Re*Re*. With $\nu_Q = -246(2)$ MHz as mean value[23] for ^{185}Re and ^{187}Re with natural abundance and the known ground-state quadrupole moments[24] of $Q(^{185}\mathrm{Re}) = +2.16(6)$ b and $Q(^{187}\mathrm{Re}) = +2.05(6)$ b the EFG is found to be $eq(\mathrm{Re}Re) = -4.87(15) \times 10^{17}$ V/cm^2, which can now be used to calculate the EFG for Re*Lu*. The result is $eq(\mathrm{Re}Lu) = +6.8(6) \times 10^{17}$ V/cm^2.

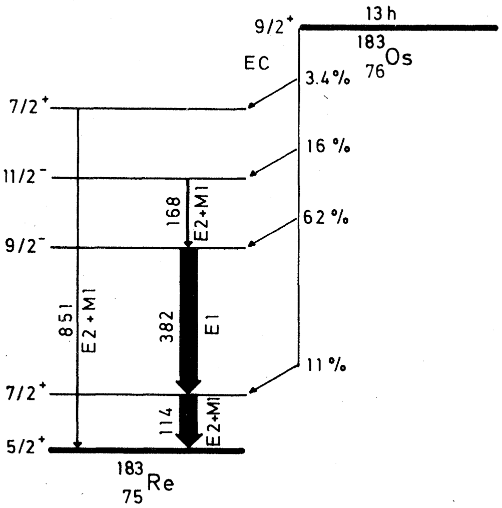

FIG. 4. Simplified decay scheme of ^{183}Os.

B. ^{183}Os*Lu*

In the decay of ^{183}Os (see Fig. 4) two strong γ transition with energies of 114 and 382 keV take place. As the 114-keV γ anisotropy has been found to be significantly smaller than that of the 382-keV transition, only the anisotropy of the latter has been investigated in this experiment. The result is shown in Fig. 5. Assuming the EC decays to be of pure tensor-rank 1 and taking the $E2/M1$ γ-mixing ratio of the 168-keV transition as $\delta = 0.16(3)$ (Ref. 17) the quadrupole frequency of ^{183}Os*Lu* is found to be

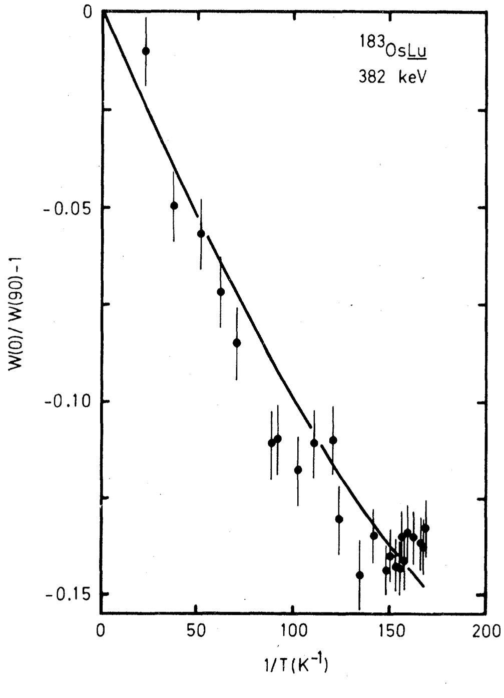

FIG. 5. γ anisotropy of the 382-keV γ transition of ^{183}Os*Lu* vs $1/T$.

$\nu_Q(^{183}\mathrm{Os}Lu) = +403(20)$ MHz. With the same assumption for the nuclear parameters the quadrupole splitting of $^{183}\mathrm{Os}Re$ had been determined as $-289(10)$ MHz. The electric field gradient of Os*Re* is known from a Mössbauer-effect measurement on the first excited 2^+ state of ^{186}Os in Re. With the quadrupole frequency $\nu_Q(^{186}\mathrm{Os}Re) = +151(13)$ MHz (Ref. 25) and the quadrupole moment $Q_{2^+}(^{186}\mathrm{Os}) = -1.63(3)$ b (Ref. 11) the EFG is calculated as $eq(\mathrm{Os}Re) = -3.83(33) \times 10^{17}$ V/cm^2. The EFG for Os in Lu is then found to be $eq(\mathrm{Os}Lu) = +5.3(5) \times 10^{17}$ V/cm^2.

C. ^{175}Hf*Lu*

In a previous NO experiment on ^{175}Hf*Lu* (Ref. 8) the quadrupole splitting had been determined as +307(50) MHz, the relatively large error being due to the fact that a large temperature gradient between the cold finger and the surface of the Lu crystal had been observed. The temperature gradient in this experiment (see Fig. 1) was found to be much smaller, thus leading to a more precise quadrupole splitting of ^{175}Hf*Lu*: $\nu_Q(^{175}\mathrm{Hf}Lu) = +364(24)$ MHz. Taking all nuclear parameters as discussed in Ref. 8 the EFG is deduced to be $eq(\mathrm{Hf}Lu) = +5.6(9) \times 10^{17}$ V/cm^2.

VI. DISCUSSION

A compilation of all known quadrupole splittings for Group IIIb, IVb, VIIb, and VIIIb hexagonal metals is given in Table III, together with the corresponding EFG's. References for quadrupole moments appear in Table IV. All EFG's of systems with Hf and Lu as host lattice, for which the sign is known from experiment, are positive, in contradiction to Raghavan's universal correlation,[4] according to which negative EFG's would be expected. On the other hand, the positive sign is in agreement with the correlation of EFG's in pure systems,[7] if the essential

TABLE III. Experimental quadrupole frequencies and electric field gradients for Group IIIb, IVb, VIIb, and VIIIb hexagonal metals. With the exception of ^{57}Fe*Ti* all EFG's for Group IIIb and IVb systems are positive. The results on impurity-host combinations with ^{57}Fe as impurity are partly contradicting. For all other systems only the most precise data are given. (ME: Mössbauer effect; NMR: nuclear magnetic resonance; NO: nuclear orientation; SH: specific heat; TDPAC: time differential perturbed angular correlation.)

Group	System	Method	T (K)	ν_Q (MHz)	Q (b)	eq_{expt} (10^{17} V/cm^2)
IIIb	^{45}Sc*Sc*	NMR	295	2.02(3)[a]	−0.22(1)	(+)0.38(2)
	^{181}Ta*Sc*	TDPAC	295	313.0(1.3)[b]	+2.51(15)	(+)5.16(38)
	^{45}Sc*Y*	NMR	295	5.20(8)[a]	−0.22(1)	(+)0.98(5)
	^{57}Fe*Y*	ME	295	7.0(7)[c]	+0.19(2)	(+)1.52(22)
	^{111}Cd*Y*	TDPAC	295	14.2(3)[d]	+0.80(7)	(+)0.73(7)
	^{181}Ta*Y*	TDPAC	295	358.1(1.7)[b]	+2.51(15)	(+)5.90(35)
	^{57}Fe*Lu*	ME	295	7.0(9)[c]	+0.19(2)	(+)1.52(25)
	^{111}Cd*Lu*	TDPAC	295	14(1)[e]	+0.80(7)	(+)0.72(8)
	^{175}Hf*Lu*	NO	0	+364(24)[f]	+2.7(4)	+5.6(9)
	^{177}Lu*Lu*	NO	0	+294(37)[g]	+3.39(2)	+3.6(5)
	^{181}Ta*Lu*	TDPAC	4.2	333(10)[b]	+2.51(15)	(+)5.49(37)
	^{182}Re*Lu*	NO	0	+311(24)[f]	. . .	+6.8(6)
	^{183}Os*Lu*	NO	0	+403(20)[f]	. . .	+5.3(5)
IVb	^{44}Sc*Ti*	TDPAC	295	6.07(8)[h]	−0.21(2)	(+)1.20(12)
	^{47,49}Ti*Ti*	NMR	4.2	7.7(1)[i]	+0.29(1) +0.24(1)	(+)1.20(5)
	^{57}Fe*Ti*	ME	295	7.4(7)[c]	+0.19(2)	(+)1.61(23)
	^{57}Fe*Ti*	ME	295	−2.3(5)[j]	+0.19(2)	−0.51(12)
	^{111}Cd*Ti*	TDPAC	295	+27.5(5)[k]	+0.80(7)	+1.42(13)
	^{181}Ta*Ti*	TDPAC	295	345(3)[l]	+2.51(15)	(+)5.68(34)
	^{197}Hg*Ti*	TDPAC	295	13.8(1.0)[m]	0.081(6)	(+)7.0(7)
	^{57}Fe*Zr*	ME	295	7.7(7)[c]	+0.19(2)	(+)1.68(23)
	^{91}Zr*Zr*	NMR	4.2	18.7(3)[n]	−0.21(2)	(+)3.68(36)
	^{92}Mo*Zr*	TDPAC	295	16(1)[o]	0.35(2)	(+)1.89(16)
	^{181}TaZr-α	TDPAC	295	314.3(1.4)[p]	+2.51(15)	(+)5.18(31)
	^{57}Fe*Hf*	ME	295	7.7(9)[c]	+0.19(2)	(+)1.68(26)
	^{178}Hf*Hf*	ME	4.2	−443(15)[q]	−1.95(2)	+9.40(33)
	^{181}Ta*Hf*	ME	295	+443(24)[r]	+3.29(5)	+5.57(31)

TABLE III. (*continued*).

Group	System	Method	T (K)	ν_Q (MHz)	Q (b)	eq_{expt} (10^{17}V/cm^2)
VIIb	^{57}Fe*Tc*	ME	295	−3.0(5)[s]	+0.19(2)	−0.65(13)
	^{99}Tc*Tc*	NMR	295	5.75(4)[t]	0.34(17)	(−)0.70(35)
	^{57}Fe*Re*	ME	295	8.1(9)[c]	+0.19(2)	1.76(27)
	^{57}Fe*Re*	ME	295	−2.32(46)[j]	+0.19(2)	−0.51(11)
	^{111}Cd*Re*	TDPAC	295	−29.2(6)[k]	+0.80(7)	−1.51(14)
	^{181}Ta*Re*	ME	295	−520(5)[r]	+3.29(5)	−6.54(12)
	^{185,187}Re*Re*	SH	0	−246(2)[u]	+2.16(6) +2.05(6)	−4.87(15)
	^{186}Os*Re*	ME	4.2	+151(13)[v]	−1.63(3)	−3.83(34)
	^{186}Ir*Re*	NO	0	+198(8)[w]	−2.41(20)	−3.40(31)
	^{197}Hg*Re*	NO	0	−110(15)[m]	+1.61(13)	−2.83(45)
VIIIb	^{57}Fe*Fe*	ME	295	3.9(7)[x]	+0.19(2)	(−)0.85(18)
	^{57}Fe*Co*	ME	295	−0.762(37)[y]	+0.19(2)	−0.17(2)
	^{59}Co*Co*	NMR	4.2	−2.90(7)[z]	+0.38(4)	−0.32(3)
	^{111}Cd*Co*	TDPAC	295	5.94(42)[aa]	+0.80(7)	(−)0.31(3)
	^{57}Fe*Ru*	ME	295	−3.31(12)[j]	+0.19(2)	−0.72(8)
	^{99}Ru*Ru*	TDPAC	295	2.7(5)[bb]	+0.23(5)	(−)0.49(14)
	^{181}Ta*Ru*	ME	295	−377(10)[r]	+3.29(5)	−4.74(14)
	^{57}Fe*Os*	ME	295	−3.55(7)[j]	+0.19(2)	−0.77(8)
	^{181}Ta*Os*	ME	295	−568(10)[r]	+3.29(5)	−7.14(17)
	^{186}Os*Os*	ME	4.2	+179(9)[v]	−1.63(3)	−4.54(24)
	^{193}Ir*Os*	ME	4.2	−56.5(2.4)[cc]	+0.78(3)	−3.00(17)

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TABLE IV. References for quadrupole moments used in Table III. GS stands for ground state.

Element	E (keV)	j^π	Q(b)	Reference
^{44}Sc	68	1^-	−0.21(2)	H. Haas and D. A. Shirley, J. Chem. Phys. 58, 3339 (1973).
^{45}Sc	GS	$\frac{7}{2}^-$	−0.22(1)	G. Fricke, H. Kopfermann, S. Penselin, and K. Schlüpmann, Naturwissenschaften 46, 106 (1959).
^{47,49}Ti	GS	$\frac{5}{2}^-,\frac{7}{2}^-$	+0.29(1) +0.24(1)	K. H. Channappa and J. M. Pendlebury, Proc. Phys. Soc. London 86, 1145 (1965).
^{57}Fe	14	$\frac{3}{2}^-$	+0.19(2)	R. R. Sharma, Phys. Rev. Lett. 26, 563 (1971).
^{59}Co	GS	$\frac{7}{2}^-$	+0.38(4)	L. Niessen and W. J. Huiskamp, Physica (Utrecht) 57, 1 (1972).
^{91}Zr	GS	$\frac{5}{2}^+$	−0.21(2)	S. Büttgenbach, R. Dicke, H. Gebauer, R. Kuhnen, and F. Träber, Z. Phys. A 286, 125 (1978).
^{92}Mc	2761	8^+	0.35(2)	C. V. K. Baba, D. B. Fossan, T. Faestermann, F.v. Feilitzch, K. E. G. Löbner, and C. Signorini, Phys. Lett. B 48, 218 (1974).
^{99}Ru	90	$\frac{3}{2}^+$	+0.23(5)	O. C. Kistner and A. H. Lumpkin, Phys. Rev. C 13, 1132 (1976).
^{99}Tc	GS	$\frac{9}{2}^+$	0.34(17)	K. G. Kessler and R. E. Trees, Phys. Rev. 92, 303 (1952).
^{111}Cd	247	$\frac{5}{2}^+$	+0.80(7)	H. Ernst, E. Hagn, and E. Zech (unpublished).
^{175}Hf	GS	$\frac{5}{2}^-$	+2.7(4)	G. Kaindl, F. Bacon, and A. Soinski, Phys. Lett. B 46, 62 (1973).
^{177}Lu	GS	$\frac{7}{2}^+$	+3.39(2)	H. Ernst, E. Hagn, E. Zech, and G. Eska, Phys. Rev. B 19, 4460 (1979).
^{178}Hf	93	2^+	−1.95(2)	K. E. G. Löbner, M. Vetter, and V. Hönig, Nucl. Data Tables A 7, 495.
^{181}Ta	GS	$\frac{7}{2}^+$	+3.29(5)	J. Konijn, J. K. Panman, W. van Doesburg, G. T. Ewan, J. Johnson, L. Tauscher, and G. Tibell, Verh. Detsch. Phys. Ges. 3, 1979, 800 (1979).
^{181}Ta	482	$\frac{5}{2}^+$	+2.51(15)	G. Netz and E. Bodenstedt, Nucl. Phys. A 208, 503 (1973).
^{185,187}Re	GS	$\frac{5}{2}^+,\frac{5}{2}^+$	+2.16(6) +2.05(6)	J. Konijn, J. K. Panman, W. van Doesburg, G. T. Ewan, J. Johansson, L. Tauscher, and G. Tibell, Verh. Detsch. Phys. Ges. 3, 1979, 800 (1979).
^{186}Os	137	2^+	−1.63(3)	H. Ernst, E. Hagn, and E. Zech, Nucl. Phys. A 332, 41 (1979).
^{186}Ir	GS	5^+	−2.41(20)	H. Ernst, E. Hagn, U. Schneider, and E. Zech, Phys. Lett. B 86, 154 (1979).
^{193}Ir	GS	$\frac{3}{2}^+$	+0.78(3)	L. A. Schaller and W. Dey, Helv. Phys. Acta 47, 482 (1974).
^{197}Hg	299	$\frac{13}{2}^+$	+1.61(13)	H. R. Hirsch, J. Opt. Soc. Am. 51, 1192 (1961).
^{197}Hg	134	$\frac{5}{2}^-$	0.081(6)	P. Herzog, K. Krien, K. Freitag, M. Reuschenbach, and H. Walitzki, Nucl. Phys. A 337, 261 (1980).

assumption is made that the sign of the EFG of impurity-host systems is fixed by the properties of the host lattice, independent of the type of the impurity nuclei. To our knowledge, only one system is known at present which does not follow this rule: the EFG of Cd*Ti* is positive,[26] as expected for Ti as a Group IV metal, but the EFG of Fe*Ti* is negative.[27] This exception should not be overinterpreted, especially as the absolute value of the EFG is very small, so that the correction $e\bar{q}$ of Eq. (1) can be responsible for the change of the sign. As a further test of the proposed scheme the sign of inverse systems would be interesting. Experiments with ^{175}Hf and ^{177}Lu as impurities in Re and Os single crystals are in progress.

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