Nuclear Properties and Magnetic Hyperfine Interaction of Os^{189}†

B. PERSSON,* H. BLUMBERG,‡ AND M. BENT
California Institute of Technology, Pasadena, California 91109
(Received 31 May 1968)

Mössbauer absorption of the 69.6-keV γ rays from Os^{189} has been studied in various absorbers at 4.2°K. The following quantities have been determined: the half-life of the 69.6-keV state, $t_{1/2} \geq 1.8 \pm 0.2$ nsec; the magnetic moment of the 69.6-keV state, $\mu(69.6) = (0.988 \pm 0.010)\mu_N$; the mixing ratio of the 69.6-keV transition, $\delta = \langle \|E2\| \rangle / \langle \|M1\| \rangle = +0.71 \pm 0.08$; and the hyperfine field at the Os nuclei dilutely dissolved in Fe, $H_{hf} = 1100 \pm 20$ kOe. The results pertaining to the nucleus are compared with calculations in terms of the rotational model.

INTRODUCTION

THE ground state of $Os^{189}(I^\pi = \frac{3}{2}^-)$ is deformed, but it has not been possible to account for the low-lying excited states of this nucleus in terms of a pure rotational excitation.[1–4] It is expected from systematics[5] that in Os^{189} the two Nilsson states [512] $K = \frac{3}{2}$ and [510] $K = \frac{1}{2}$ are most strongly bound and that the difference of their energies is small. Band mixing caused by the Coriolis interaction could therefore strongly disturb the level separation. Also, the proximity of Os^{189} to the region of nuclei where transition from deformed to spherical equilibrium shapes occurs leads one to expect collective excitations other than rotational to be of importance for the low-lying states.

Obviously a great deal of knowledge of the properties of the various states of Os^{189} is required for an understanding of the character of their excitation. The present experiment contributes to the knowledge of the magnetic moment of the 69.6-keV state ($I^\pi = \frac{5}{2}^-$), its lifetime, and the multipole mixture of the transition to the ground state.

EXPERIMENT

The γ-rays emitted without recoil in the de-excitation of the 69.6-keV state in Os^{189} have been studied in resonance absorption experiments at 4.2°K. The source was moved with constant acceleration and the transmitted γ rays were detected with a thin-window Ge(Li) detector. A full description of the experimental arrangement has been given elsewhere.[6]

Ir^{189} in Ir metal lattice was used as source. The cubic symmetry and high Debye temperature of the source lattice should ensure a narrow linewidth and a large recoilless fraction of the emitted γ rays. However, the observed Mössbauer effect was greatly reduced because the intense $K\beta$ x rays (≥ 70.8 keV) could not be resolved from the γ rays, nor could they be suppressed with the use of a critical absorber. Ir^{189} was produced by the irradiation of Os^{189} metal with 13-MeV protons. Other Ir isotopes were also produced; the $K\beta$ x rays from their decay further attenuated the observed Mössbauer effect to 1–2%.

The following procedure was used to separate the radioactive Ir isotopes from Os and incorporate them into Ir metal. After irradiation the Os metal was mixed with Ir metal and NaCl and heated in chlorine at 500°C to yield the complex $NaIr(Os)Cl_6$. In subsequent heating to 900°C in oxygen, the osmium was removed as OsO_4, leaving IrO_2. Finally, the iridium oxide was placed on an iridium foil and reduced to the metal by heating to 1200°C in an argon atmosphere.

Commercially obtained K_2OsCl_6 and $K_2Os(CN)_6$ were used for absorbers. The point symmetry at the Os nucleus in these compounds is sufficiently high to ensure vanishing electric field gradients at the Os nucleus. Therefore these compounds are expected to provide unsplit absorption lines.

The magnetic hyperfine interaction was studied with a dilute (1 at%) solid solution of Os^{189} in Fe, prepared by levitational melting in an argon atmosphere. The homogeneity of the alloy was checked with x-ray diffraction and electron microprobe analyses. No evidence for clustering was found. In the measurement, the disk-shaped Os-Fe absorber was magnetized in directions parallel and transverse to the x-ray beam. Magnetization in the longitudinal direction was obtained with a field of 40 kOe, supplied by a superconducting solenoid. A C-magnet providing 2.5 kOe was used to magnetize the absorber in the plane of the disk. Absorbers containing 20 and 40 mg Os^{189}/cm^2 were used for the measurements in the longitudinal and the transverse field configurations, respectively.

† This work was performed under the auspices of the U.S. Atomic Energy Commission. Prepared under Contract No. AT(04-3)-63 for the San Francisco Operations Office, U.S. Atomic Energy Commission.
* On leave from the University of Lund, Sweden.
‡ On leave from the Institut für Strahlen- und Kernphysik of the University of Bonn, Germany.
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ANALYSIS AND RESULTS

The velocity spectrum obtained with the K_2OsCl_6 absorber (3.2 mg Os^{189}/cm^2) is shown in Fig. 1 together with a least-squares fitted Lorentzian. The width, full-width at half-maximum (FWHM), was determined to be 2.21 ± 0.25 mm/sec. With the $K_2Os(CN)_6$ absorber (3.2 mg Os^{189}/cm^2) the width 2.54 ± 0.43 mm/sec was obtained. Correcting these results for thickness broadening, which amounts to 6% if $\theta_p=375°K$ is assumed, we derive an upper limit for the natural linewidth, $2\Gamma\leq 2.1\pm0.25$ mm/sec. Since hyperfine interactions should not be present in the source or the absorbers, one might expect $2\Gamma=2.15\pm0.25$ mm/sec.

The velocity spectra obtained with the Os-Fe absorbers in the two field configurations are shown in Fig. 2. Since the $\frac{3}{2}^-\rightarrow\frac{5}{2}^-$ transition is of mixed multipolarity ($M1+E2$) the nuclear Zeeman spectra may be composed of as many as 16 components, all of which appear in the transverse field configuration. The number of component absorption lines is reduced in the longitudinal field configuration, since only transitions for which $\Delta m=\pm1$ can then be observed. For either field configuration only partially resolved hyperfine spectra were observed.

The dependence of the relative positions of the hyperfine lines on the ratio (g_e/g_g) of the g factors of the excited and ground states is demonstrated in Fig. 3. A comparison of the measured two dip velocity pattern (Fig. 2) for the longitudinal Zeeman effect with Fig. 3 immediately suggests $g_e\sim g_g$. An exact evaluation of the g factor of the excited state, however, depends particularly on the mixing ratio $|\delta|$, the relative phase φ of the $E2$ and $M1$ matrix elements, and on the magnetic hyperfine splitting of the ground state.

For a mixed $M1,E2$ transition the absorption strengths of the various hyperfine components are[7]

$$I(\theta)_{\Delta m=0}=\tfrac{3}{2}\sin^2\theta\begin{pmatrix} j_e & 1 & j_g \\ m_e & 0 & -m_g\end{pmatrix}^2 + (15/8)\sin^2 2\theta\begin{pmatrix} j_e & 2 & j_g \\ m_e & 0 & -m_g\end{pmatrix}^2\delta^2,$$

$$I(\theta)_{\Delta m=\pm1}=\tfrac{3}{4}(1+\cos^2\theta)\begin{pmatrix} j_e & 1 & j_g \\ m_e & \mp1 & -m_g\end{pmatrix}^2 \pm\tfrac{1}{2}(\sqrt{15})\cos\varphi(\cos^2\theta+\cos 2\theta) \times\begin{pmatrix} j_e & 1 & j_g \\ m_e & \mp1 & -m_g\end{pmatrix}\begin{pmatrix} j_e & 2 & j_g \\ m_e & \mp1 & -m_g\end{pmatrix}|\delta| + (5/4)(\cos^2\theta+\cos^2 2\theta)\begin{pmatrix} j_e & 2 & j_g \\ m_e & \mp1 & -m_g\end{pmatrix}^2\delta^2,$$

$$I(\theta)_{\Delta m=\pm2}=(5/4)(\sin^2\theta+\tfrac{1}{4}\sin^2 2\theta)\begin{pmatrix} j_e & 2 & j_g \\ m_e & \mp2 & -m_g\end{pmatrix}^2\delta^2.$$

Here $\Delta m=m_e-m_g$ and θ is the angle between the direction of magnetization and the γ-ray beam. For

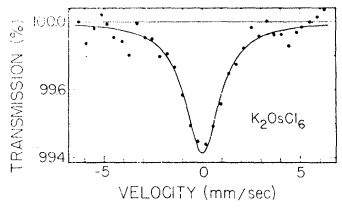

FIG. 1. Velocity spectrum obtained with a source of Ir^{189} in Ir metal and an absorber of K_2OsCl_6.

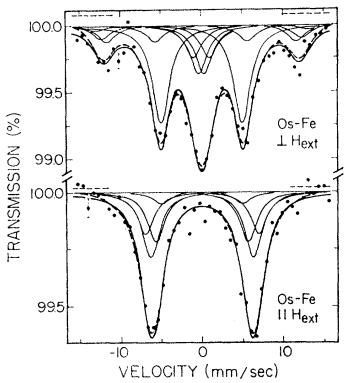

FIG. 2. Velocity spectra obtained with absorbers of 1 at.% Os dissolved in Fe. The solid curves indicate synthetized spectra and component Lorentzians corresponding to the best fit with the widths of the Lorentzians constrained to the value 2.5 mm/sec. The dashed curves indicate the best-fitting synthetized spectrum with this constraint removed. The constraint $H_{hf}=1120$ kOe applies to both solid and dashed curves.

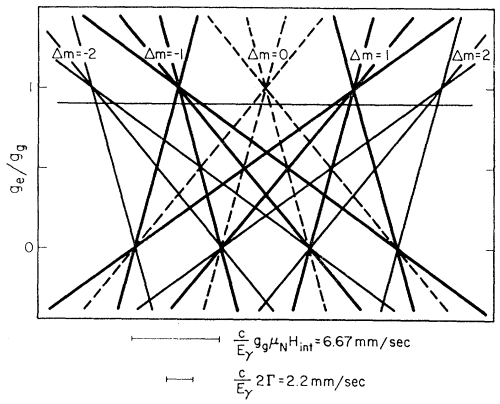

FIG. 3. Plot of the relative positions of the magnetic hyperfine absorption lines as function of the ratio of the g factors of the excited and ground states. The horizontal line indicates the fit to the experimental spectrum.

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time-reversal invariance to hold there are only two possible values for φ, i.e., $\varphi=0$ and 180°.

The relative intensities and positions of the Zeeman components as calculated for $g_e=1.1g_g$, $0.9g_g$, and $\varphi=0$ and 180° are shown in Fig. 4. The value of the mixing ratio used for the calculation, $\delta^2=0.43$, is derived[1] from subshell internal conversion coefficients.

Inspection of Fig. 2 reveals the groups of components corresponding to $\Delta m=1$ and $\Delta m=-1$ to be somewhat more separated in the longitudinal Zeeman pattern than in the transverse pattern. Therefore (cf. Fig. 4), $g_e>g_g$ is compatible only with $\varphi=180°$ and $g_e<g_g$ is compatible only with $\varphi=0°$. The first of these two alternatives is excluded since a hyperfine field of 840±17 kOe is required to fit the data. This is inconsistent with the NMR value 1120±23 kOe.[8] With $\varphi=0$ the hyperfine field determined by fitting the spectra is 1090±11 kOe, in good agreement with the NMR value. Hence, the $M1$ and $E2$ matrix elements are determined to be in phase, i.e., $\delta>0$.

TABLE I. Results from the study of magnetic hyperfine interaction in Os-Fe alloy. Indicated errors are standard deviations obtained from the fit. Where no error is indicated the parameter was constrained in the fitting procedure to the given value.

W (mm/sec)	H_{hf} (kOe)	g_e/g_g	δ	x^2 $\Delta x^2=0.10$
3.22±0.14	1090±11	0.916±0.006	0.75±0.03	0.82
3.12±0.13	1120[a]	0.905±0.004	0.72±0.03	0.84
2.5[b]	1120[a]	0.901±0.003	0.66±0.03	0.89
2.5[b]	1110±12	0.904±0.005	0.65±0.03	0.92

[a] NMR value from Ref. 8.
[b] The natural linewidth with estimated correction for thickness broadening.

To determine the g factor of the excited state (g_e) and the mixing ratio (δ) the velocity spectra for the two field configurations were simultaneously least-squares fitted to superpositions of Lorentzians. In the fitting procedure the nonresonant background, the total area of the dips, the center shift, g_e, and δ were varied to minimize χ^2. The ground-state g factor and the $E2/M1$ phase angle were constrained to the values $g_g=0.4377$ [9] and $\varphi=0$. In various fits the hyperfine field H_{hf} and the width W of the Lorentzian components were constrained to specific values or adjusted. Some results of these fits are given in Table I.

The width of the component Lorentzians determined by the fits is rather large ($W\sim1.35\times2\Gamma$), probably to a great extent because of correlations among the width, the background, and δ. Examination of the dependence of χ^2 on these parameters made us accept all values of g_e/g_g, δ, and H_{hf} for widths in the range 2.5–3.5 mm/sec. For the derivation of the final results the hyperfine field was constrained, where appropriate, to the independently determined value of 1120±23 kOe[8] to reduce the effect of correlations. The results of the measurements are

$$g_e/g_g=0.905\pm0.009,$$

hence

$$\mu(\tfrac{5}{2})=0.988\pm0.010\,\mu_N,$$

$$\delta=+0.71\pm0.08,$$

and

$$H_{hf}=1100\pm20\text{ kOe}.$$

The errors quoted are the square roots of the sum of the squares of the following quantities: the statistical error, the systematic error from the interpretation of the spectra estimated from the width dependence, the error in the velocity calibration, and the error in the hyperfine field. The uncertainty in the hyperfine field is the main contribution to the error in the ratio g_e/g_g, and the uncertainty concerning what linewidth should be used to fit the data is the main source of error in δ and H_{hf}.

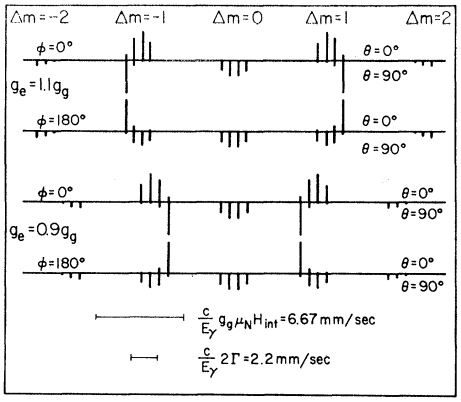

FIG. 4. Plots of the relative positions and intensities of the Zeeman lines for $\delta^2=0.43$ and indicated parameter values.

DISCUSSION

The width of the 69.6-keV state, $2\Gamma=2.15\pm0.25$ mm/sec, determined in the present experiment corresponds to the half-life 1.83±0.20 nsec. The presently determined mixing ratio is $\delta^2=0.50\pm0.10$. These results are in good agreement with the corresponding values $t_{1/2}=1.7$ nsec[10] and $\delta^2=0.43$ [1] derived from the $B(E2)$ value and the internal conversion coefficients. From the half-life, the mixing ratio, and the total internal conversion coefficient $\alpha_t=8.2\pm0.8$,[10] we determine $B(M1, \frac{5}{2}^-\rightarrow\frac{1}{2}^-)=(4.6\pm0.7)\times10^{-3}\,\mu_N^2$.

A few remarks can be made concerning the interpretation of the 69.6-keV state in the framework of the rotational model. Assuming the 69.6-keV state to be the lowest excited state belonging to a pure rotational band, one may use the magnetic moments of these states

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to determine the gyromagnetic ratios g_K and g_R. The derived values $g_K=0.49$ and $g_R=0.37$ appear to be in fair agreement with the theoretical values[11,12] $g_K=0.48$, $g_R=0.30$ and 0.32. Also the theoretical values for the reduced $M1$ transition probability, $B(M1, \frac{5}{2}^- \rightarrow \frac{3}{2}^-) = 4.7$ and 3.7, agree with the experimental result.

The magnetic moments and the $B(M1)$ value have also been calculated considering Coriolis admixture of the [510] $K=\frac{1}{2}$ Nilsson state. However, this did not improve the agreement between the observed and calculated values. These calculations were performed with recent Nilsson matrix elements[12] treating g_K as an adjustable parameter.

Upon closer inspection, however, it appears that the mentioned agreement with a pure rotational assignment is quite accidental. This can be seen as follows. If the rotational motion is undisturbed, the second excited state of the $K=\frac{3}{2}$ ground-state band is expected to be at about 170 keV. No level of this energy has been observed.[10] Coulomb excitation experiments[13] indicate that the collective excitations of the ground state have the energies 69.6 and 219.4 keV, deviating strongly from those of a pure rotor. It appears that a more adequate description of these states can only be achieved by resorting to an elaborate bandmixing calculation, probably also including vibrational interactions.

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PHYSICAL REVIEW VOLUME 174, NUMBER 4 20 OCTOBER 1968

Resonant and Nonresonant Capture of Slow Neutrons in $Tm^{169}(n,\gamma)Tm^{170}$†

M. A. Lone,* R. E. Chrien, O. A. Wasson, M. Beer, M. R. Bhat, and H. R. Muether‡
Brookhaven National Laboratory, Upton, New York 11973
(Received 11 June 1968)

The intensities of radiative transitions following slow-neutron capture in $Tm^{169}(n,\gamma)Tm^{170}$ have been measured for neutron energies up to ~136 eV. From the determination of the strengths of transitions feeding final states in Tm^{170}, the partial radiative widths of resonances below 136 eV are determined, and the partial cross sections $\sigma_{n\gamma f}$ below 30 eV are fitted with a simple Breit-Wigner multilevel formula. A direct amplitude is necessary to achieve good fits for several transitions, including that to the ground state. The correlation of the direct amplitude to the strength of the state as observed in (d,p) is investigated.

INTRODUCTION

THE availability of high-resolution radiation detectors and intense neutron sources has made feasible more detailed studies of the radiative de-excitation of states formed in slow-neutron capture. By measuring the decay characteristics of the compound nucleus as a function of the incident neutron energy, it is possible to study the (n,γ) reaction mechanism. By virtue of populating the final states in the residual nucleus, information relating to the nuclear structure of the residual nucleus is obtained.

In this experiment, the partial radiative widths in the reaction $Tm^{169}(n,\gamma)Tm^{170}$ have been measured. The spectra in the "between-resonance" regions have been obtained, and by combining this data with the partial widths of the resonances, multilevel analyses of the partial cross-section ratios in these regions have been performed. The strong interference effects seen in the off-resonance region can only partly be accounted for by interfering levels; a direct amplitude term is necessary to get good fits in general.

Lane and Lynn[1] have discussed the possibility of the direct capture mechanism in the (n,γ) reaction, where an incident s-wave neutron is scattered into a final state without the formation of a compound nucleus. This direct capture can be encompassed by the R-matrix theory by formally identifying it with the faraway levels contribution to the dispersion sum. Similar considerations lead to an entrance channel contribution from the external region.[2] Although this process has the same resonant-energy dependence as the ordinary compound-nucleus contribution, it is proportional to the single-particle component of the capturing state. The channel resonance contribution arises from the part of the dipole integral for which $r \geq R$, and for which the initial wave function may be simply regarded as the target nucleus plus a single neutron. This situation

* State University of New York, Stony Brook, N. Y.; present address: Department of Physics, Indiana University, Bloomington, Ind.
† This work was supported by the U. S. Atomic Energy Commission.
‡ State University of New York, Stony Brook, N. Y.

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