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November 1972

Prepared for the U. S. Atomic Energy
Commission under Contract W-7405-ENG-48

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EFFECTS OF TEMPERATURE ON THE ENERGY OF THE 6.2-keV MÖSSBAUER GAMMA RAYS OF ^{181}Ta*

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November 1972

Abstract:

Strong temperature dependence of the energy of the 6.2-keV gamma rays was found for dilute impurities of ^{181}Ta in transition metal hosts. The observed temperature shifts cover a range of -32 to +8 times the expected thermal redshift, and exhibit large variations with the hosts.

- - -

The effects of temperature on the energy of Mössbauer gamma rays have been studied up to now in detail only for ^{57}Fe[1-4] and ^{119}Sn.[5] For both these Mössbauer resonances the observed variations with temperature are mainly caused by the second-order Doppler (SOD) effect (thermal redshift).[6] Accordingly, information on the variation of the total electron density at the nucleus with temperature could be derived only after dominant corrections for the thermal redshift had been made;[5,7] therefore, this procedure may have introduced large systematic errors, limiting the accuracy of the derived results.

The case of the 6.2-keV gamma resonance of ^{181}Ta is quite different, as will be reported in the present paper. Recently this resonance has been

applied extensively to high-resolution studies of hyperfine interactions,[8] and its especially high resolving power in the field of isomer shifts has been recognized.[8,9] We have now found that the energy of the 6.2-keV gamma rays, emitted from ^{181}Ta as a dilute impurity in transition metals, exhibits a strong temperature dependence far beyond the expected SOD shift. The results underline the exceptional sensitivity of the 6.2-keV gamma resonance, and open new possibilities in solid-state applications of isomer shift studies.

The host metals investigated in this study are Ta, W, Ir, Pt, Nb, Mo, Pd, and Ni. Sources of ^{181}W diffused into these metals were studied at temperatures up to 1000 K, using a single-line Ta metal absorber at room temperature ($\simeq$ 4 mg/cm^2 thick). Details of the experimental technique have been presented elsewhere.[10]

Figure 1 shows the experimental variations with temperature of the line positions for five of the sources. It is striking that in the case of the nickel host the transition energy increases with temperature with a slope which is 32 times larger, and of opposite sign, than the one expected from the SOD shift alone. While the slopes of the temperature shifts for W, Ta, and Pt hosts are of the same sign as the SOD shift, they are up to 8 times larger. Within the accuracy of the present experiments the data can be described by a linear relationship between the lineshift S and the source temperature T. The solid lines are the results of a least-squares-fit of straight lines to the data.

We may write for the experimentally observed temperature variation of the line position S

$$\left(\frac{\partial S}{\partial T}\right)_P = \left(\frac{\partial S_{SOD}}{\partial T}\right)_P + \left(\frac{\partial S_{IS}}{\partial T}\right)_V + \left(\frac{\partial S_{IS}}{\partial \ \ell nV}\right)_T \left(\frac{\partial \ \ell nV}{\partial T}\right)_P \tag{1}$$

The first term accounts for the temperature variation of the SOD shift which is given for a Debye-solid in the limit of high temperatures by $-2k/2Mc$ in cm/s, amounting to $-2.30 \cdot 10^{-4}$ mm/s per degree for the present gamma transition. The second term represents the explicit temperature dependence of the isomer shift at constant volume due to temperature induced changes of the total electron density at the nucleus. The third term describes the volume dependence of the isomer shift caused by thermal expansion of the lattice.

Table I summarizes the experimental data, with the lineshifts S for both source and absorber at room temperature listed in column 2, and the experimental results for the isobaric temperature variation of the transition energy, $(\partial S/\partial T)_P$, presented in column 3. The values for the isobaric temperature dependence of the isomer shift, $(\partial S_{IS}/\partial T)_P$, were derived by subtracting the contribution due to SOD effect from $(\partial S/\partial T)_P$. In view of the fact that these corrections are small compared to the total temperature shifts, and that the measurements were carried out in the temperature range 300 to 1000 K, where the high temperature Debye model should approximately hold, this procedure should be satisfactory within the present accuracy. Also presented are representative values for the thermal expansion coefficients, $(\partial \ \ell nV/\partial T)_P$ (column 5).

Until now temperature shifts of the 6.2-keV gamma rays have been reported only for a W host by Taylor et al.,[11] and their results agree well with the present measurements. In the case of ^{57}Fe temperature shifts of the energy of the 14.4-keV gamma rays have been measured for dilute impurities of

^{57}Fe in 3d, 4d, and 5d transition metals.[3,4] Even though these shifts arise mainly from the SOD effect, the derived values for $(\partial S_{IS}/\partial T)_P$ exhibit characteristics similar to the present case.[7]

A separation of $(\partial S_{IS}/\partial T)_P$ into the explicitly temperature dependent part and the volume dependent part of Eq. (1) cannot be carried out quantitatively with the present results alone. The necessary additional information could be obtained from high-pressure isomer-shift studies, which would directly provide values for $(\partial S_{IS}/\partial \ln V)_T$.

For a qualitative discussion we use a value of $\Delta\langle r^2 \rangle \simeq -5\cdot 10^{-2}$ fm^2 for the change of the mean-squared nuclear charge radius, as recently derived from isomer shift studies in transition metal hosts.[9] Since the electron density at the nucleus, $|\psi_o|^2$, should decrease with increasing volume, we expect positive values for $(\partial S_{IS}/\partial \ln V)_T$ in all cases, even though their magnitudes might exhibit large variations, as observed in the case of ^{57}Fe. There, isomer shifts have been measured as a function of pressure for impurities of ^{57}Fe in a series of 3d, 4d, and 5d transition metal hosts,[12] and $(\partial S_{IS}/\partial \ln V)_T$ was found to increase with decreasing isomer shift (or increasing $|\psi_o|^2$), as expected from a scaling of $|\psi_o|^2$ with volume. We may expect a similar behaviour of $(\partial S_{IS}/\partial \ln V)_T$ in the ^{181}Ta case. This means that the negative values of $(\partial S_{IS}/\partial T)_P$, observed for the Pd, Ta, W, Ir, and Pt hosts, originate from an overcompensation of the positive volume shifts by negative contributions due to an explicit temperature dependence of the isomer shift.

Since $|\psi_o|^2$ is found to increase from 5d to 4d and to 3d hosts in a vertical column of the periodic system,[9] it is expected that $(\partial S_{IS}/\partial \ln V)_T$ is

larger for 3d than for 5d hosts. The large positive value of $(\partial S_{IS}/\partial T)_P$ observed for the nickel host may then be explained by a dominant contribution due to thermal expansion, especially since the thermal expansion coefficient is so large for this metal. For an order of magnitude estimate of $(\partial S_{IS}/\partial T)_V$ we take for the conduction electron contribution to $|\psi_o|^2$ in Ta metal a value of $|\psi_o|^2_{c.e.} \simeq 3.0 \cdot 10^{26}$ cm^{-3}, and at ^{181}Ta impurities in nickel metal a value of $|\psi_o|^2_{c.e.} \simeq 3.75 \cdot 10^{26}$ cm^{-3} as estimated from the results of Dirac-Fock calculations for free-ion configurations of Ta [13] and from the measured difference in isomer shifts between hosts of nickel and tantalum metal. With the simple volume scaling assumption

$$\Delta|\psi_o|^2 \simeq -\frac{\Delta V}{V}|\psi_o|^2_{c.e.} \qquad (2)$$

we then estimate for $(\partial S_{IS}/\partial \ln V)_T(\partial \ln V/\partial T)_P$ values of $\sim +103 \cdot 10^{-4}$ mm/s per degree for the nickel host and $\sim +32 \cdot 10^{-4}$ mm/s per degree for the tantalum host. This results in values of $-38 \cdot 10^{-4}$ mm/s per degree and $-27 \cdot 10^{-4}$ mm/s per degree for $(\partial S_{IS}/\partial T)_V$ for the nickel and tantalum hosts, respectively.

We may conclude from this estimate for $(\partial S_{IS}/\partial T)_V$, that the electron density at the nucleus increases in tantalum metal explicitly with temperature by $\simeq 5 \cdot 10^{21}$ cm^{-3} per degree, which corresponds to a $d \rightarrow s$ electron transfer with increasing temperature of approximately 10^{-5} electrons per degree. Such effects have been discussed theoretically in connection with the temperature dependence of the Knight shift, and have been interpreted as arising from an effective decrease in the strength of the lattice potential caused by lattice vibrations.[14] In this way, the energy bands become more free-electron like,

leading to an increase in the s character of the wavefunctions. This effect should exhibit a strong dependence on the electronic structure of the metals. It is to be expected that, as soon as pressure data will be available for the ^{181}Ta gamma resonance, the present results will provide a very detailed insight into these subtle effects.

The authors would like to thank D. A. Shirley for his constant interest in this work. They are also indebted to L. M. Falicov, D. Schroeer, and G. Wortmann for valuable discussions.

FOOTNOTES AND REFERENCES

*Work performed under the auspices of the U. S. Atomic Energy Commission.

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Table 1. Summary of experimental results and derived quantities for dilute impurities of ^{181}Ta in transition metal hosts.

host metal	S (mm/s)	$(\partial S/\partial T)_P$ (10^{-4} mm·s^{-1}·deg^{-1})	$(\partial S_{IS}/\partial T)_P$ (10^{-4} mm·s^{-1}·deg^{-1})	$(\partial \ln V/\partial T)_P$ (10^{-5} deg^{-1})
Ni	-39.5±0.2[a]	73.2±3.5	75.5±3.5	5.2
Nb	-15.3±0.1	9.2±1.0	11.5±1.0	2.5
Mo	-22.5±0.1	3.6±0.6	5.9±0.5	1.7
Pd	-27.6±0.3	-16.7±7.0	-14.4±7.0	3.5
Ta	-0.075±0.004	-8.0±0.5	-5.7±0.5	2.0
W	-0.86±0.01	-7.1±0.2	-4.8±0.2	1.4
Ir	-1.84±0.04	-10.7±3.3	-8.4±3.3	2.0
Pt	+2.66±0.04	-17.6±0.9	-15.3±0.9	2.9

[a]Extrapolated to room temperature from the temperature dependence of the line position, measured in the range 685 to 1003 K.

FIGURE CAPTIONS

Fig. 1. Temperature dependence of line positions for sources of ^{181}W diffused into Ni, Nb, W, Ta, and Pt. For comparison, the SOD shift, expected for a Debye-solid in the limit of high temperatures, is also shown. All curves are plotted on the same scale.

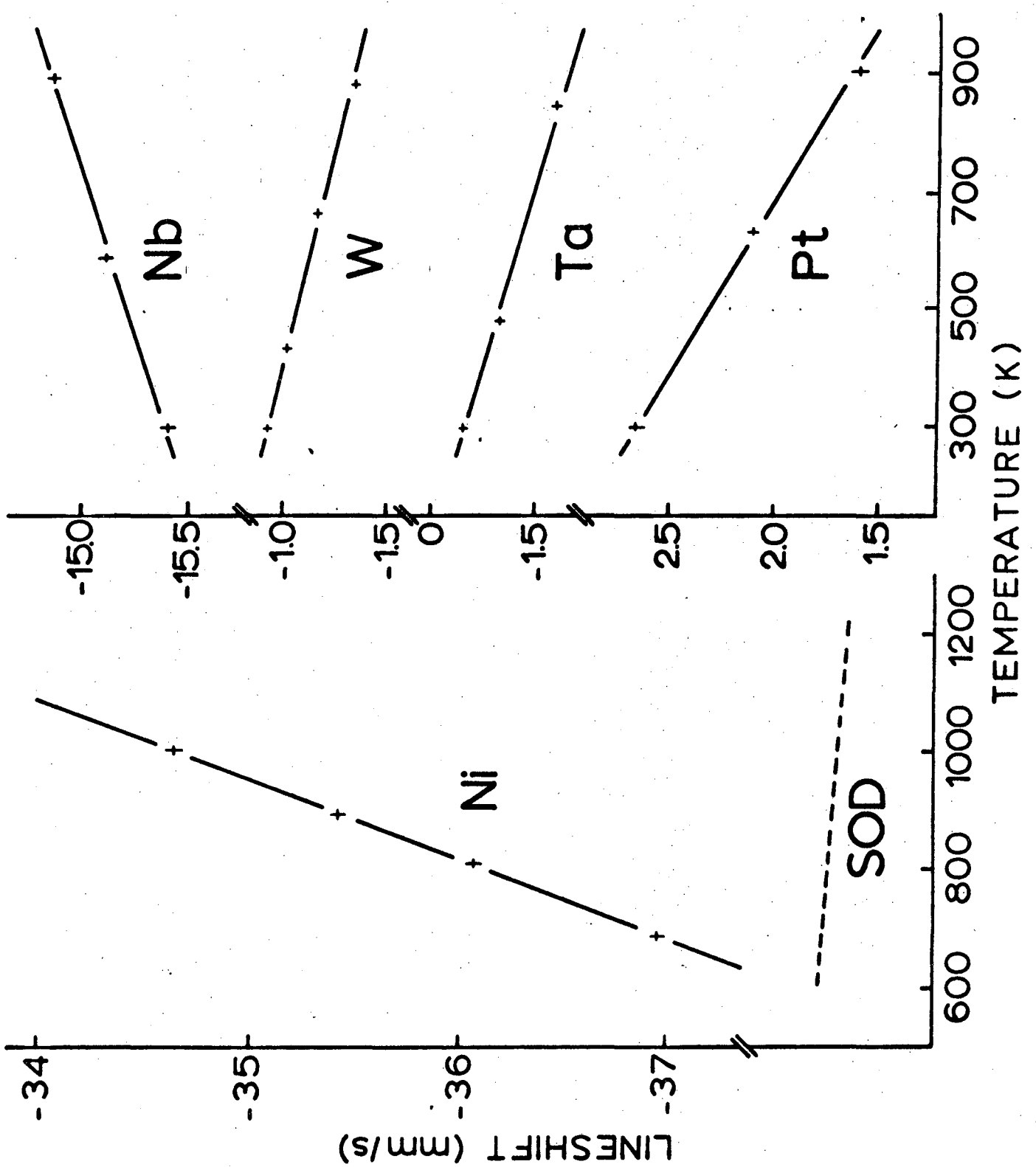
Nb
W
Ta
Pt
Ni
SOD
-15.0
-15.5
-1.0
-1.5
0
-1.5
2.5
2.0
1.5
-34
-35
-36
-37
300
500
700
900
600
800
1000
1200
TEMPERATURE (K)
LINESHIFT (mm/s)

Fig. 1

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