

# PHYSICAL REVIEW B

## CONDENSED MATTER

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### Observation of the room-temperature $^{125}\text{Te}$ Mössbauer effect in $\text{Mg}_3\text{TeO}_6$ : Linewidth, recoil-free fraction, and isomer shift

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Fifty-eight-day  $^{125}\text{Te}^m$  in a  $\text{Mg}_3\text{TeO}_6$  host provides an easily produced, rugged, high recoil-free fraction and narrow-emission-linewidth source for  $^{125}\text{Te}$  Mössbauer spectroscopy. The high  $f$  factor of this source opens the possibility of precision  $T$ -dependent Mössbauer-spectroscopy measurements in Te-bearing compounds with the source kept at room temperature. Using such a source at 300 K, we have measured the  $T$  dependence of the  $f$  factor for both  $\text{Mg}_3\text{TeO}_6$  and cubic ZnTe absorbers and find Debye temperatures  $\Theta_D$  of 390(2) K and 188(2) K, respectively. At 300 K, the  $f$  factor of  $\text{Mg}_3\text{TeO}_6$  (0.46) is found to be an order of magnitude larger than in cubic ZnTe (0.040) thus making feasible room-temperature observation of the Mössbauer effect with the oxide source. Both emission and absorption linewidths of the oxide matrix have been examined and display a 14(3)% line broadening over the natural width ( $\Gamma_n$ ), a result that is thought to be intrinsic to the oxide host. The isomer shift of Te metal (78 K) and cubic ZnTe (78 K) relative to  $\text{Mg}_3\text{TeO}_6$  at 300 K is +1.86(9) and +1.21(3) mm/s, respectively.  $\text{Mg}_3\text{TeO}_6$  is easily prepared in a pure form and yields reproducible crystal structure and Mössbauer-effect parameters.  $\text{Mg}_3\text{TeO}_6$  provides a suitable standard matrix for  $^{125}\text{Te}$  isomer shift and  $f$ -factor measurements.

## I. INTRODUCTION

$^{125}\text{Te}$  Mössbauer spectroscopy offers the prospect of chemically probing a wide variety of chalcogen-based organic<sup>1</sup> and inorganic<sup>2,3</sup> materials. In our laboratory, chalcogen-based semiconducting crystals and glasses have received particular interest over the years.<sup>2,3</sup> Unfortunately, to date these measurements have had to be performed at 78 K or lower, largely because the source matrices used such as  $^{125}\text{Sb}$  in Cu,<sup>4</sup> or  $^{125}\text{Te}^m$  in GeTe (Ref. 3) or ZnTe, possess low Debye-temperatures ( $\Theta_D \lesssim 200$  K). Interest in  $\text{Mg}_3\text{TeO}_6$  was recently stimulated by Pasternak, Van der Heyden, and Langouche<sup>5</sup> who reported observing a room-temperature  $^{129}\text{I}$  Mössbauer effect with the 27.8-keV  $\gamma$  ray using sources of  $^{129}\text{Te}^m$  in  $\text{Mg}_3\text{TeO}_6$ . The Debye temperature of this matrix can be established directly in  $^{125}\text{Te}$  Mössbauer absorption spectroscopy. To evaluate this matrix for  $^{125}\text{Te}$  spectroscopy, we have now measured the  $f$  factor and linewidth of  $\text{Mg}_3\text{TeO}_6$  in the present work. Our results reveal  $\text{Mg}_3\text{TeO}_6$  to possess a rather high Debye temperature,  $\Theta_D = 390(2)$  K, yielding an  $f$  factor of 0.46 at room temperature. Our results on the  $\text{Mg}_3^{125}\text{Te}^m\text{O}_6$  source reveal the emission linewidth to be broadened by 14(3)%

over the natural width ( $\Gamma_n$ ), a broadening which is thought to be intrinsic to the oxide matrix. In spite of this minor limitation, the high  $f$  factor of such sources at room temperature opens for the first time the possibility of precision  $T$ -dependent  $^{125}\text{Te}$  Mössbauer spectroscopy measurements in a wide variety of Te salts.

## II. PROCEDURE, SAMPLE PREPARATION, AND X-RAY CHARACTERIZATION

$\text{Mg}_3\text{TeO}_6$  samples were prepared by two methods, one wet chemical and the other dry chemical. Enriched  $^{124}\text{Te}$  in its elemental form was oxidized in  $\text{NH}_4\text{OH}$  by 30%  $\text{H}_2\text{O}_2$  followed by precipitation with magnesium nitrate. The precipitate was heated to 750 °C causing loss of volatile products and leaving  $\text{Mg}_3\text{TeO}_6$  crystals. This chemical method has been shown<sup>6</sup> by Koudelka and Boolchand to provide rather high yield (> 90%) even when working with mg batches of the starting enriched  $^{124}\text{Te}$ . The dry chemical route consisted of homogeneously mixing powders of  $\text{TeO}_2$  and  $\text{MgO}$  in the molar ratio of 1:3 and forming pellets. The pellets were sintered at 900 °C for 12 h in air. The resulting samples were finely ground, mixed, pelletized, and sintered once again to promote

homogeneity. Samples prepared by the wet and dry chemical route were both subjected to x-ray diffraction (XRD) using a Siemens diffractometer. Both samples yielded quite similar results as illustrated in Fig. 1. The XRD peaks are easily indexed on the hexagonal structure of  $\text{Mg}_3\text{TeO}_6$  reported by Newham, Dorrian, and Meagher.<sup>7</sup> The lattice parameter of our sintered sample ( $a = 8.59 \text{ \AA}$ ,  $c = 10.33 \text{ \AA}$ ) and chemically prepared sample ( $a = 8.60 \text{ \AA}$ ,  $c = 10.34 \text{ \AA}$ ) are in good agreement with the published report of Newham, Dorrian, and Meagher<sup>7</sup> ( $a = 8.58 \text{ \AA}$ ,  $c = 10.30 \text{ \AA}$ ) who prepared their sample by sintering.

Neutron activation of the wet chemically prepared  $\text{Mg}_3\text{TeO}_6$  sample was performed at the University of Missouri Research reactor. A 20-mg quantity of  $\text{Mg}_3^{124}\text{TeO}_6$  was activated for a 2-week period at  $3 \times 10^{14}$  neutron flux to produce a 6.5-mCi quantity of 58 days  $^{125}\text{Te}^m$  by  $(n, \gamma)$  reaction on  $^{124}\text{Te}$ . The activated sample was heated at  $600^\circ\text{C}$  for 12 h to thermally anneal radiation damage, prior to evaluation in the  $^{125}\text{Te}$  Mössbauer-effect experiments. Neutron irradiation of  $\text{Mg}_3\text{TeO}_6$  produces no undesirable radioactive species due to the presence of Mg or O in the target. In the pulse height spectrum of the source taken with a Xe-filled proportional counter (shown in Fig. 2), we can clearly discern the Te  $K_\alpha$  (27.5 keV) and  $K_\beta$  (31.0 keV) x rays and the Mössbauer  $\gamma$  ray at 35.5 keV. The prominent peak at 6 keV is the escape

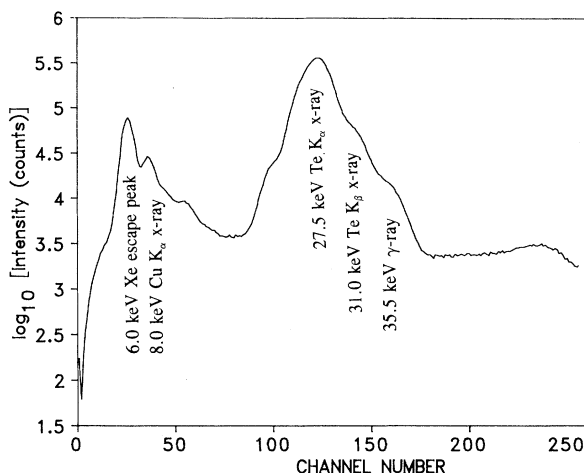


FIG. 2. Pulse height spectrum of the  $\text{Mg}_3^{125}\text{Te}^m\text{O}_6$  source taken with a Xe-filled proportional counter.

peak of the 35.5-keV  $\gamma$  ray.

The Mössbauer spectrometer consisted of an electromechanical drive (K4 motor) from Austin Science Associates. The data were recorded in a 286 personal-computer-based multichannel analyzer using the PCA-2 card from the Nucleus, Inc. The 35.5-keV  $\gamma$  rays from the  $\text{Mg}_3^{125}\text{Te}^m\text{O}_6$  source were detected using the escape peak (6 keV) in a Xe-gas-filled proportional counter (Fig. 2). With our setup, we could retrieve, analyze, and plot a spectrum in the background mode while accumulating a spectrum in the foreground.

Two types of Mössbauer-effect experiments were undertaken. Observed line-widths of the  $\text{Mg}_3^{125}\text{Te}^m\text{O}_6$  source were systematically studied with cubic ZnTe absorbers of varying thickness, with both the source and absorber cooled to 78 K in an exchange-gas liquid-helium Dewar. The observed line shapes were least-squares fit to a Lorentzian profile to extract the centroid, full width at half maximum ( $\Gamma_{\text{obs}}$ ), and the integrated intensity. These measurements permitted us to obtain the emission linewidth ( $\Gamma_s$ ) of the source. A parallel set of linewidth measurements of the source were performed using the chemically prepared  $\text{Mg}_3\text{TeO}_6$  material as an absorber, to establish the absorber thickness dependence of  $\Gamma_{\text{obs}}$ . These measurements permitted us to obtain the absorption linewidth ( $\Gamma_a$ ) in the  $\text{Mg}_3\text{TeO}_6$  absorber.

The second type of Mössbauer-effect experiment included measurements of the integrated intensity (area) under the resonance using the  $\text{Mg}_3^{125}\text{Te}^m\text{O}_6$  source at 300 K, and an absorber (either of cubic ZnTe or of  $\text{Mg}_3\text{TeO}_6$ ) cooled to a temperature  $T$  in the range  $12 < T < 300 \text{ K}$ . We used a He closed-cycle cryostat, Displex model CS202 from APD, Inc. with the DMX-20 shroud to vary the temperature of the absorber. We have developed a special mounting arrangement to completely decouple vibrations of the expander from the absorber. In our system, the vibration decoupling was checked by measuring the linewidth of the inner two lines of  $\alpha\text{-Fe}$ . No line broadening was observed upon switching on the expander. A Lakeshore Cryotronics model DRC 80C temperature controller with Si-diode thermometers were used

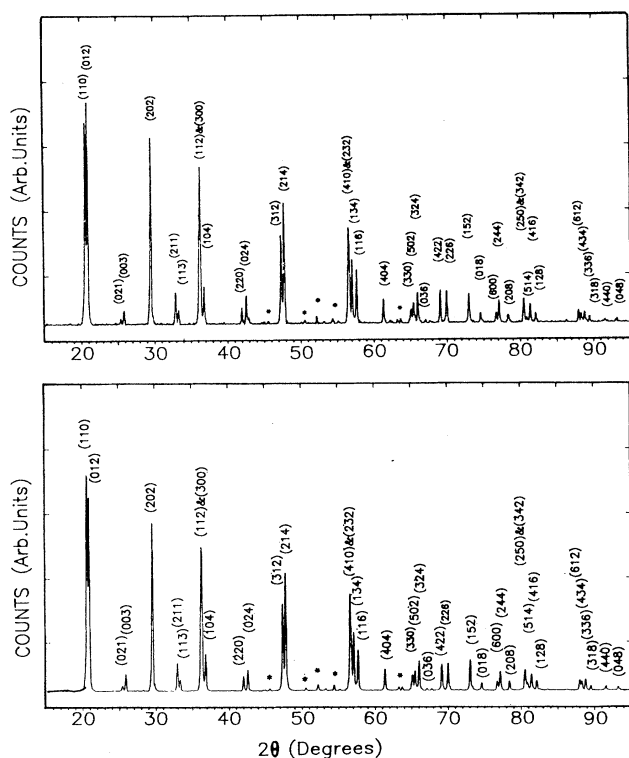


FIG. 1. X-ray-diffraction scans of wet (top) and dry (bottom) chemically processed  $\text{Mg}_3\text{TeO}_6$  samples taken with a Siemens Diffractometer using  $\text{Cu } K_\alpha$  radiation. The peak identification is taken from Ref. 7. The peaks with asterisks are thought to result from impurities.

to measure and control the temperature of the absorber to  $\pm 1^\circ\text{C}$  in the  $12 < T < 300$  K range. The  $T$  dependence of the integrated area  $A(T)$  in these experiments is directly proportional to the  $f$  factor  $f(T)$  of the absorber since the temperature of the source is kept fixed. The observed  $f(T)$  variation was fit to a Debye model to extract an effective Debye temperature ( $\Theta_D$ ). For this purpose, we used a nonlinear least-squares-fitting routine to analyze measured  $f(T)$  results to obtain  $\Theta_D$ . Results of both types of Mössbauer-effect measurements, i.e., those performed at 78 K and those at variable temperatures, are correlated and, as we will show, uniquely permit a reliable evaluation of the  $\text{Mg}_3\text{TeO}_6$  matrix for  $^{125}\text{Te}$  Mössbauer-spectroscopy work.

### III. MÖSSBAUER-SPECTROSCOPY RESULTS

Figure 3 illustrates spectra of several Te-based compounds taken with the  $\text{Mg}_3^{125}\text{Te}^m\text{O}_6$  source at 300 K. The temperature of the absorber is indicated in each case. As can be seen from Fig. 3, the room-temperature Mössbauer effect of the 35.5-keV  $\gamma$  ray is rather easily observed using the source with a thin (28 mg/cm<sup>2</sup> of natural Te)  $\text{Mg}_3\text{TeO}_6$  absorber.

Figure 4 summarizes the observed linewidths as a function of absorber thickness for both cubic ZnTe and  $\text{Mg}_3\text{TeO}_6$ . The cubic ZnTe absorbers used presently were the same ones used by Oberschmidt and Boolchand<sup>8</sup> several years ago to demonstrate that  $^{125}\text{Sb}$  sources in the Cu matrix yield the natural width for the 35.5-keV  $\gamma$  ray. The natural linewidth of the 35.5-keV  $\gamma$  resonance  $\Gamma_n$  equals  $h/\bar{\tau} = 2.6$  mm/s based on  $\bar{\tau} = 2.13$  ns for the 35.5-keV level.<sup>9</sup> The minimum observable linewidth in a Mössbauer experiment equals  $2\Gamma_n = 5.2$  mm/s. From the observed linear variation of  $\Gamma_{\text{obs}}$ , we have obtained the extrapolated linewidth for zero absorber thickness, which represents the sum of the emission and absorption linewidths, i.e.,  $\Gamma_s + \Gamma_a$ . For cubic ZnTe absorbers, since  $\Gamma_a = \Gamma_n$ , as demonstrated in Ref. 8, the extrapolated width of 5.66(8) mm/s, greater than  $2\Gamma_n$ , implies that the  $\text{Mg}_3^{125}\text{Te}^m\text{O}_6$  source does not yield the natural width. From this result, we deduce the source linewidth  $\Gamma_s = 3.06(8)$  mm/s, and it is greater than the natural width  $\Gamma_n = 2.6$  mm/s by 18(4)%. Results obtained with  $\text{Mg}_3\text{TeO}_6$  absorbers of varying thickness yield an extrapolated linewidth of 5.94(8) mm/s from which we deduce an absorption linewidth  $\Gamma_a = 2.88(8)$  mm/s, which is 11(3)% greater than  $\Gamma_n$ . Thus, both the source and absorber matrix of  $\text{Mg}_3\text{TeO}_6$  give about a 14(3)% line broadening over  $\Gamma_n$ . This clearly indicates that the small broadening is largely intrinsic to the oxide matrix, a point we shall return to later. These linewidth results are summarized in Table I.

Results of Mössbauer-effect measurements performed with the  $\text{Mg}_3^{125}\text{Te}^m\text{O}_6$  source held at room temperature and a  $\text{Mg}_3\text{TeO}_6$  absorber mounted in a He closed-cycle cryostat appear in Fig. 5. In this set of experiments, as we alluded earlier, changes in the integrated area  $A(T)$  under the  $\gamma$  resonance profile directly reflect the  $T$  dependence of the  $f$  factor  $f(T)$  of the thin  $\text{Mg}_3\text{TeO}_6$  absorber, since the source temperature and the geometry of the set-

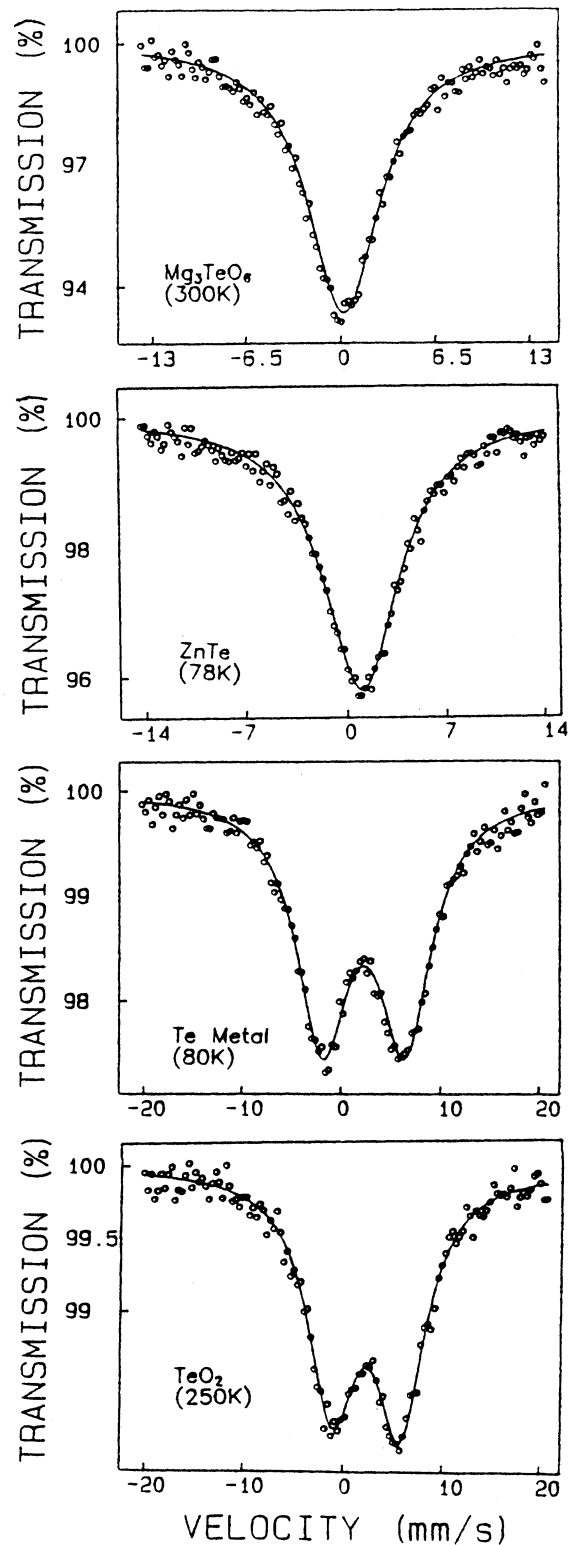


FIG. 3. Mössbauer spectra of Te-based compounds at indicated temperatures taken with a  $\text{Mg}_3^{125}\text{Te}^m\text{O}_6$  source at 300 K. The absorbers made out of natural Te had thicknesses of  $\text{Mg}_3\text{TeO}_6$ , 1.75 mg/cm<sup>2</sup>  $^{125}\text{Te}$ ; ZnTe, 2 mg/cm<sup>2</sup>  $^{125}\text{Te}$ ; Te metal, 3 mg/cm<sup>2</sup>  $^{125}\text{Te}$ ; and  $\text{TeO}_2$ , 3 mg/cm<sup>2</sup>  $^{125}\text{Te}$ .

TABLE I.  $^{125}\text{Te}$  linewidth results deduced from Fig. 4.  $\Gamma_s$  and  $\Gamma_a$  represent the source and absorber linewidths.

Absorber	$T$ (K)	$\Gamma_{\text{obs}}^a$ (mm/s)	$\Gamma_s$ (mm/s)	$\Gamma_a$ (mm/s)
ZnTe <sup>b</sup>	78	5.66(8)	3.06(8)	2.60(8)
Mg <sub>3</sub> TeO <sub>6</sub>	78	5.94(8)	3.06(8)	2.88(8)

<sup>a</sup>Extrapolated width measured using the Mg<sub>3</sub><sup>125</sup>Te<sup>m</sup>O<sub>6</sub> source at 78 K.

<sup>b</sup>In Ref. 8 these absorbers were shown to yield  $\Gamma_a = \Gamma_n = 2.60$  mm/s.

up is kept fixed. We have least-squares fitted the observed  $f(T)$  dependence, to extract the Debye temperature of the Mg<sub>3</sub>TeO<sub>6</sub> absorber and obtain a value of  $\Theta_D = 390(2)$  K.

We cooled a cubic ZnTe absorber in a He closed-cycle cryostat and systematically recorded spectra using the Mg<sub>3</sub><sup>125</sup>Te<sup>m</sup>O<sub>6</sub> source at 300 K. In relation to Mg<sub>3</sub>TeO<sub>6</sub>, the  $f(T)$  variation in cubic ZnTe displays a sharper  $T$  dependence, and this is indicative of a lower  $\Theta_D$  in the II-VI semiconductor. A least-squares fit of the observed variation yields  $\Theta_D = 188(2)$  K for cubic ZnTe, which compares favorably with the x-ray Debye temperature of 180(6) K due to Blattner, Walford, and Baldwin.<sup>10</sup>

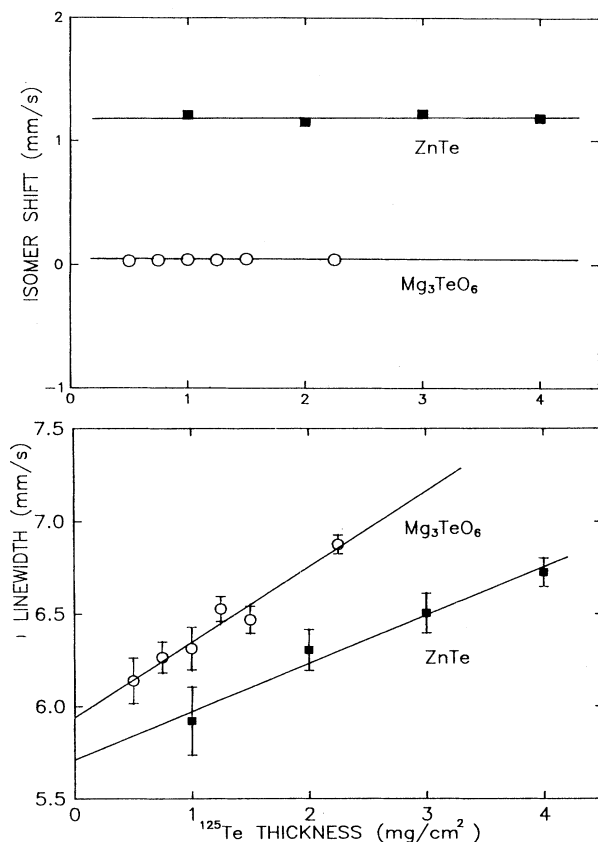


FIG. 4. (Top) Isomer shift ( $\delta$ ) and (bottom) observed linewidths ( $\Gamma_{\text{obs}}$ ) results on cubic ZnTe and Mg<sub>3</sub>TeO<sub>6</sub> absorbers. For these measurements both the Mg<sub>3</sub><sup>125</sup>Te<sup>m</sup>O<sub>6</sub> source and absorbers were at 78 K.

## IV. DISCUSSION

### A. Debye temperature of Mg<sub>3</sub>TeO<sub>6</sub>

The Mg<sub>3</sub>TeO<sub>6</sub> Debye temperature  $\Theta_D = 390(2)$  K deduced from the present  $^{125}\text{Te}$  absorption Mössbauer spectroscopy is significantly higher than  $\Theta_D = 320$  K deduced by Pasternak, Van der Heyden, and Langouche<sup>5</sup> from  $^{129}\text{Te}^m$  labeled Mg<sub>3</sub>TeO<sub>6</sub> sources in  $^{129}\text{I}$  emission Mössbauer spectroscopy. In the latter, one actually measures the local vibrational density of states at an  $^{129}\text{I}$  impurity formed in the  $\beta$  decay of a  $^{129}\text{Te}^m$  parent in the Mg<sub>3</sub>TeO<sub>6</sub> matrix. Since chemical bond rearrangement in solids generally proceed on a time scale ( $10^{-10}$ – $10^{-12}$  s) much faster than the mean life (21.6 ns) of the 27.8-keV state, the difference in  $\Theta_D$ 's between the  $^{129}\text{I}$  and the  $^{125}\text{Te}$  measurements are rather curious. We recognize that the chemical bonding of I daughter in the [IO<sub>6</sub>] unit probably displays a slightly reduced ionicity in relation to Te in the parent [TeO<sub>6</sub>] unit. This is suggested by the Pauling electronegativities of Te, I, and O of 2.1, 2.5, and 3.5, respectively. However, such a small change in ionicity alone is not likely to be the principal reason for the striking change in  $\Theta_D$ . Furthermore, the ionic radii of

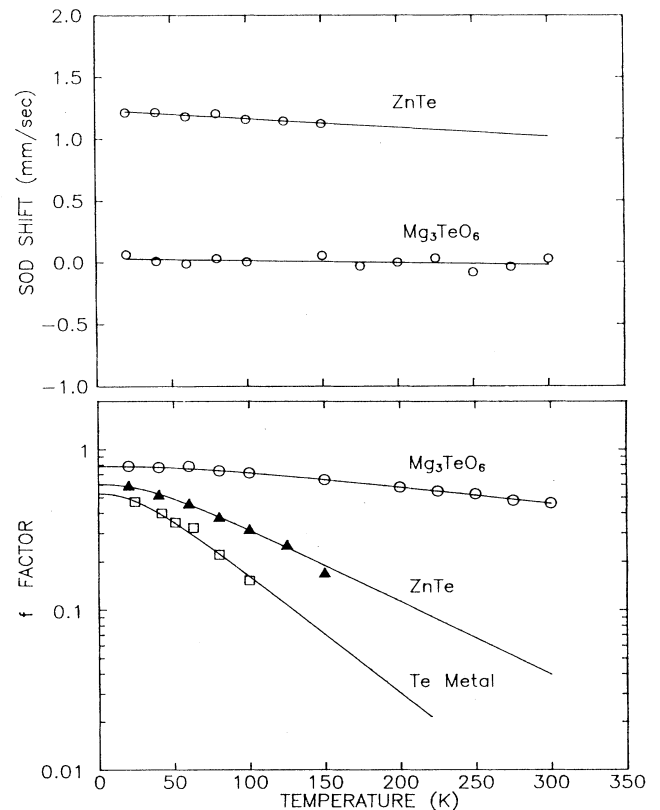


FIG. 5.  $T$  dependence of (top) isomer shift ( $\delta$ ) and (bottom) recoil-free fraction ( $f$ ) of Mg<sub>3</sub>TeO<sub>6</sub>, cubic ZnTe, and Te-metal absorbers. The  $f(T)$  dependence has been least-squares fit (smooth line) yielding Debye temperatures  $\Theta_D$  of 390(2) K, 188(2) K, and 148(2) K, respectively, for Mg<sub>3</sub>TeO<sub>6</sub>, ZnTe, and Te metal.

$\text{I}^{7+}$  (53 pm) and  $\text{Te}^{6+}$  (56 pm) are also nearly the same so that one would be hard pressed invoking a rattling of the  $\text{I}^{7+}$  daughter in the  $\text{TeO}_6$  cage.

It is possible that the local vibrational density of states probed in the source experiments are intrinsically different from those in the absorber experiment. Here we must recognize that we are comparing the local vibrational density of states in  $\text{Mg}_3\text{TeO}_6$  probed by a quiescent  $^{125}\text{Te}$  atom (in the absorber experiment) to those probed by an  $^{129}\text{I}$  atom formed from nuclear transmutation of  $^{129}\text{Te}^m$  parent atom (in the source experiment). In the latter, conceivably, the vibrational temperature of the  $^{129}\text{I}$  probe can be higher than its equilibrium value largely because of precursor events (related to the isomeric transition  $^{129}\text{Te}^m \rightarrow ^{129}\text{Te}$ , and  $\beta$  decay  $^{129}\text{Te} \rightarrow ^{129}\text{I}$ ). Normally such precursor events in metals relax on a timescale of picoseconds and for this reason such states are not observed in Mössbauer spectroscopy. In insulators, on the other hand, the relaxation may be significantly slowed down because of a reduced conduction electron charge density, and the  $^{129}\text{I}$  daughter may not completely attain its quiescent equilibrium vibrational state even in 20 ns before the 27.8-keV Mössbauer  $\gamma$ -ray transition occurs. We believe such a nuclear aftereffect is probably responsible for the reduced effective Debye temperature observed by Pasternak, Van der Heyden, and Langouche.<sup>5</sup> If indeed this is the case, it is likely that a measurement of the Te Debye temperature in a  $\text{Mg}_3^{125}\text{Te}^m\text{O}_6$  source, would yield a  $\Theta_D$  less than 390 K, the value that we have measured in a  $\text{Mg}_3\text{TeO}_6$  absorber. This we are currently examining.

The unusually high  $\Theta_D$  of  $\text{Mg}_3\text{TeO}_6$  makes this matrix most attractive for  $^{125}\text{Te}$  Mössbauer spectroscopy.  $^{125}\text{Te}^m$  labeled  $\text{Mg}_3\text{TeO}_6$  sources yield a high enough recoil-free fraction at room temperature (Fig. 3) that these sources can be used routinely at 300 K to record spectra of Te-bearing compounds at lower temperatures. With  $\text{Mg}_3^{125}\text{Te}^m\text{O}_6$  sources,  $^{125}\text{Te}$  Mössbauer-effect methodology can be practiced like  $^{57}\text{Fe}$  and  $^{119}\text{Sn}$  methodology, where measurements with the source at 300 K are routine. Experimentally, one cannot overemphasize the ease of performing  $T$ -dependent Mössbauer experiments with the source at room temperature. For, in such a case, only absorber cooling is required and a substantial range of temperature variation can be probed.

### B. Linewidth in $\text{Mg}_3\text{TeO}_6$

The present  $^{125}\text{Te}$  results clearly demonstrate that the  $\text{Mg}_3\text{TeO}_6$  host does not display the natural width either in the source or in the absorber. Furthermore, both the emission linewidth of the  $\text{Mg}_3^{125}\text{Te}^m\text{O}_6$  source and absorption linewidth in  $\text{Mg}_3\text{TeO}_6$  reveal about a 14(3)% broadening over the natural width ( $\Gamma_n$ ). This implies that the source linewidth taken with a cubic absorber would result in half of that broadening, i.e., 7(2)% over the minimum observable width of  $2\Gamma_n$ . This may be compared to the result of Pasternak, Van der Heyden, and Langouche,<sup>5</sup> who found their  $\text{Mg}_3^{129}\text{Te}^m\text{O}_6$  sources to yield a 19% broadening over the minimum observable width ( $2\Gamma_n$ ). In their experiment Pasternak used a  $\text{Cu}^{129}\text{I}$  absorber to measure the source linewidth and

corrected for the finite thickness of the absorber. Clearly in both the  $^{125}\text{Te}$  and  $^{129}\text{I}$  Mössbauer experiments some line broadening in the  $\text{Mg}_3\text{TeO}_6$  host is observed.

The origin of this line broadening, we believe, is intrinsic to the structure of  $\text{Mg}_3\text{TeO}_6$ . The crystal structure of  $\text{Mg}_3\text{TeO}_6$  provides for two inequivalent  $[\text{TeO}_6]^{6-}$  units in the crystallographic unit cell, with one of these octahedra characterized by a Te-O bond length of 1.66 Å while the other octahedra characterized by a longer Te-O bond length of 1.84 Å. These crystal structure results suggest that the electric field gradient at the two octahedrally coordinated  $\text{Te}^{6+}$  species probably vanishes, but their isomer shifts may be intrinsically different because of differences in the  $\text{Te}^{6+}$ -O charge-transfer effects. The small line broadening in  $\text{Mg}_3\text{TeO}_6$  could result from the chemical inequivalence of these two sites producing slightly different isomer shifts. Thus, the emission and absorption line shape in the  $\text{Mg}_3\text{TeO}_6$  matrix is best deconvoluted in terms of two singlets with slightly different centroids. From the observed broadening, we can place an upper limit to the difference in isomer shift of the two  $\text{Te}^{6+}$  species in  $\text{Mg}_3\text{TeO}_6$  of 0.15 mm/s. The larger broadening in the  $^{129}\text{I}$  emission experiment<sup>5</sup> could then be understood in terms of the larger (factor of 4) nuclear moment<sup>11</sup>  $\Delta\langle r^2 \rangle$  for the 27.8-keV transition in relation to that of the 35.5-keV transition in  $^{125}\text{Te}$ .

### C. $^{125}\text{Te}$ isomer shift and recoil-free fraction in $\text{Mg}_3\text{TeO}_6$

During the course of this work, we have measured the  $T$  dependence of the isomer shift of  $\text{Mg}_3\text{TeO}_6$  and of cubic  $\text{ZnTe}$  in the range  $12 < T < 300$  K. The results appear in Fig. 4. Because of the high  $\Theta_D$ , in  $\text{Mg}_3\text{TeO}_6$ , the second-order Doppler shift between 300 and 78 K is rather small 0.01(2) mm/s. With this calibration, it will be possible to quote isomer shifts of Te compounds relative to  $\text{Mg}_3\text{TeO}_6$  at 300 K even when measured at lower temperatures. The  $\text{Mg}_3\text{TeO}_6$  isomer shift for both the dry and wet chemically prepared samples are identical, and this shift is characteristic of a  $\text{Te}^{6+}$  species.

The principal drawback of the use of  $\text{ZnTe}$  as a standard for  $^{125}\text{Te}$  isomer shifts or  $f$  factors is that polycrystalline samples can exist in both the cubic and hexagonal forms yielding different chemical shifts and linewidths.<sup>8</sup> Polycrystalline samples bought off the shelf are usually neither cubic nor hexagonal but a mixture of the two phases. This may be the reason for the slight difference in isomer shifts (Table II) given here to those reported by Sakai and Maeda,<sup>12</sup> who used  $\text{ZnTe}$  as a reference. The  $\text{Cu}^{125}\text{I}$  source used by Sakai and Maeda in their work<sup>12</sup> yields a smaller  $f$  factor than the source used presently, as can be seen by their need to record spectra with the source and absorber cooled to 16 K. In the present work the isomer shifts in Table II are quoted relative to  $\text{Mg}_3\text{TeO}_6$  at 300 K, and the shift of  $\text{ZnTe}$  pertains to the cubic  $\text{ZnTe}$  single-crystal chip.<sup>8</sup>

The use of the  $\text{Mg}_3\text{TeO}_6$  host as a standard for the  $^{125}\text{Te}$  isomer shift and  $f$ -factor measurements has several appealing features. First, the high  $\Theta_D$  permits easy observation of the Mössbauer effect at room temperature. For example, a significant (6%) absorption signal is ob-

TABLE II.  $^{125}\text{Te}$  Mössbauer-effect parameters deduced from the spectra of Fig. 3,  $\delta$ -isomer shift,  $\Delta$ -quadrupole splitting,  $\Gamma_{\text{obs}}$ -observed linewidth. The thickness of the absorbers appear in the Fig. 3 caption.

Absorber	$T$ (K)	$\delta^a$ (mm/s)	$\Delta$ (mm/s)	$\Gamma_{\text{obs}}$ (mm/s)
$\text{Mg}_3\text{TeO}_6$	300	0	0	6.33(13)
	78	0.01(2)	0	6.75(12)
ZnTe	78	+1.21(3)	0	6.43(13)
Te metal	78	+1.86(9)	7.83(9)	6.17(21)
	24	+1.87(6)	7.77(6)	6.09(14)
$\alpha\text{-TeO}_2$	250	+2.02(7)	6.81(7)	5.86(15)
	78	+2.03(5)	6.99(5)	6.40(11)
	24	+2.07(4)	7.05(4)	6.44(10)

<sup>a</sup>Relative to  $\text{Mg}_3\text{TeO}_6$  at 300 K.

served using a thin  $\text{Mg}_3\text{TeO}_6$  absorber (28 mg/cm<sup>2</sup> of natural Te). There is no explicit need to use enriched  $^{125}\text{Te}$  absorbers for this purpose. Second, the resonance line shape yields a narrow linewidth with a shift that is the smallest of any Te compound largely because in  $\text{Te}^{6+}$ , formally, the absence of 5s electrons leads to a reduced contact charge density on the nucleus. Thus, all  $^{125}\text{Te}$  isomer shifts will be positive relative to  $\text{Mg}_3\text{TeO}_6$ . This situation is reminiscent of  $^{119}\text{Sn}$  spectroscopy, where the perovskite  $\text{BaSnO}_3$  is used as a standard. The perovskite also possesses a high  $\Theta_D$  and displays the smallest shift because formally,  $\text{Sn}^{4+}$  lacks 5s charge density, and this reduces the contact charge density at  $^{119}\text{Sn}$ . Thirdly,  $\text{Mg}_3\text{TeO}_6$  can be prepared in a pure form rather easily either by a dry or wet chemical method and yields an isomer shift that is rather reproducible. Finally the measurement of the  $T$  dependence of the  $f$  factor in  $\text{Mg}_3\text{TeO}_6$  (see Fig. 5 and Table III) now permits a measurement of the  $f$  factor of any Te compound at any temperature by a direct comparison of the integrated areas. For this purpose one merely needs to record the integrated area under the resonance of a Te absorber of interest and compare it to that of a  $\text{Mg}_3\text{TeO}_6$  absorber of known thickness, run at the same temperature.

## V. CONCLUSIONS

$^{125}\text{Te}$  Mössbauer-spectroscopy experiments reveal  $\text{Mg}_3\text{TeO}_6$  to possess high  $\Theta_D=390(2)$  K, yielding a

TABLE III.  $T$ -dependence of the recoil-free fraction  $f(T)$  of the  $\text{Mg}_3\text{TeO}_6$  absorber for the 35.5-keV  $\gamma$  ray based on  $\Theta_D=390$  K (see Fig. 4).

$T$ (K)	$f$ (T)
0	0.785
20	0.782
40	0.772
60	0.756
80	0.736
100	0.711
120	0.686
140	0.659
160	0.632
180	0.605
200	0.578
220	0.553
240	0.528
260	0.504
280	0.481
300	0.459

room-temperature recoil-free fraction of 0.46(1).  $\text{Mg}_3\text{TeO}_6$  displays a narrow absorption and emission profile, possessing a linewidth which is only 14(3)% broader than the natural width  $\Gamma_n=2.6$  mm/s. Fifty-eight-day  $\text{Mg}^{125}\text{Te}^m\text{O}_6$  sources can be easily prepared by neutron irradiation of  $^{124}\text{Te}$  enriched  $\text{Mg}_3\text{TeO}_6$  samples with no interfering radioactivity produced by Mg and O. Such sources can be used repeatedly with no detrimental effect due to neutron irradiation provided the source matrix is suitably annealed. Such sources display high  $f$  factor and narrow linewidths and open the possibility of precision  $T$ -dependent measurements in Te-bearing compounds with the source kept at room temperature.

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