wave.[2] The magnitude of the splitting of excited states in the field of a wave of $\sim 10^4$ V/cm turns out to be of the order of 10^7-10^8 sec^{-1}, and this can be recorded by modern methods of laser spectroscopy (cf., for example, Ref. 10).

Thus, the discussion given above indicates completely realistic (particularly in the case of μ^--mesic atoms) experimental possibilities of observing the rotation and relaxation of spin of $\mu^\pm$ mesons due to a quadrupole moment under very varied conditions, and this can be utilized for a further extension of the possibilities of the μ-meson method for investigation of matter. The mechanism for the formation of a quadrupole moment noted above should also be taken into account in investigating the quadrupole and nuclear γ resonances in the case of ions which have common electron-nucleus levels.

The authors express their deep gratitude to I. I. Gurevich, V. L. Lyuboshitz, B. A. Nikol'skiĭ and M. I. Podgoretskiĭ for useful discussions of the questions touched upon in this paper. The authors are also exceedingly grateful to V. N. Gorelkin, V. P. Smilga and V. I. Selivanov for discussing the experimental possibilities of observing the phenomena indicated above and for useful remarks.

[1]I. I. Gurevich and B. A. Nikol'skiĭ, Usp. Fiz. Nauk. **119**, 169 (1976) [Sov. Phys. Usp. **19**, 440 (1976)].
[2]V. G. Baryshevskiĭ, Yadernaya optika polyarizovannykh sred (Nuclear Optics of Polarized Media), Minsk, Belorussian State University, 1976.
[3]H. Bethe and E. Salpeter, Quantum Mechanics of Atoms with One and Two Electrons, Springer, 1957 (Russ. Transl., Fizmatgiz, 1960).
[4]A. G. Sitenko and V. K. Tartakovskiĭ, Lektsii po teorii yadra (Lectures on Nuclear Theory), Atomizdat, 1972.
[5]I. I. Sobel'man, Vvedenie v teoriyu atomnykh spektrov (Introduction to the Theory of Atomic Spectra), Fizmatgiz, 1963.
[6]V. S. Grechishkin, Yadernye kvadrupol'nye vzaimodeĭstviya v tverdykh telakh (Nuclear Quadrupole Interactions in Solids), Nauka, 1973.
[7]A. S. Ivanov, Zh. Eksp. Teor. Fiz. **57**, 1601 (1969) [Sov. Phys. JETP **30**, 866 (1970)].
[8]V. B. Berestetskiĭ, Zh. Eksp. Teor. Fiz. **19**, 1130 (1949).
[9]Y. N. Kim, Mesic Atoms and Nuclear Structure, Am. Elsevier, 1971 (Russ. transl. Atomizdat, 1975).
[10]V. S. Letokhov and V. P. Chebotaev, Printsipy nelineinoĭ lazernoĭ spektroskopii (Principles of Nonlinear Laser Spectroscopy), Nauka, 1975.

Translated by G. Volkoff

Study of the temperature dependence of the probabilities of emission and absorption of resonance γ rays by ^{182}W without loss of energy to recoil

D. K. Kaipov, U. M. Makhanov, A. V. Kuz'minov, Zh. I. Adymov, and A. T. Aspandiyarov

Nuclear Physics Institute, Kazakh Academy of Sciences
(Submitted May 18, 1977)
Zh. Eksp. Teor. Fiz. **73**, 2036–2040 (December 1977)

The current method of γ-ray detection has been used to measure the Mössbauer effect in the 100.1-keV level of ^{182}W in the absorber temperature range 109–255 K at a constant source temperature of 89 K and in the range of source temperatures 93.5–160 K at a constant absorber temperature of 101 K. We have determined the temperature dependence of the probability of absorption and emission of resonance γ rays by ^{182}W without loss of energy to recoil, and the Debye temperatures of metallic tungsten and tantalum.

PACS numbers: 76.80.+y, 75.40.−s

The further extension of the region of nuclei in which it is possible to observe and study the Mössbauer effect depends, on the one hand, on the possibility of selecting sources and absorbers with a large ratio Θ/T, where Θ is the Debye temperature and T is the absolute temperature, and on the other hand—on an increase in the accuracy of the measurements, which is achieved by detection of a very large number of events in relatively short time interval which depends on the stability of the apparatus. However, in the latter case experimenters encounter the problem of dead time in the measuring system.

As a result there has recently been a tendency to use not the pulse method of γ-ray detection, but the current method.[1–3] This method provides the possibility of investigating nuclei with small expected Mössbauer effect, whose study by the usual pulse method of γ-ray spectrometry is extremely difficult. In order to use the current method for Mössbauer spectroscopy, we have developed an apparatus based on an LP-4050 512-channel analyzer and a scintillation detector.

The temperature dependence of the Mössbauer effect in the 100.1-keV level of ^{182}W in the temperature range roughly from 20 to 160 K has been studied only once,[4] by detection of conversion electrons by a β spectrometer of the Kofoed-Hansen type. However, in that work as a

 0038-5646/77/4606-1066$02.40

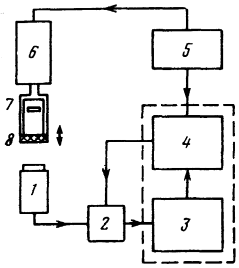

FIG. 1. Block diagram of current spectrometer: 1—NaI(Tl) crystal with FÉU-13 photomultiplier, 2—integrator, 3—amplitude to digital converter (ADC), 4—time block of LP-4050 analyzer, 5—NGPK-3 generator, 6—vibrator, 7—source, 8—absorber.

result of the fact that changes in the temperatures of both the source and the absorber were carried out simultaneously, an independent determination of their Debye temperatures was impossible.

In the present work we report a study of the temperature dependence of the probabilities of emission and absorption of resonance γ rays of ^{182}W over a wide range of temperatures and an independent determination of the Debye temperatures of the source and the absorber.

A block diagram of the current spectrometer working in the constant-acceleration mode is shown in Fig. 1. Gamma rays which have passed through the moving resonance absorber are detected by a scintillator probe. The current from the photomultiplier anode is fed to an integrator, in which, during a certain length of time determined by the width of the time channel, charge is accumulated in a capacitance and then converted to a pulse. The train of pulses of the ADC, whose number is proportional to the amplitude of the signal from the integrator, is fed to an arithmetic unit for summation.

The system for cooling the source and absorber is shown schematically in Fig. 2. The γ-ray source is cooled as the result of the thermal conduction of the holder, which is immersed in liquid nitrogen. The absorber, which moves inside a vessel surrounded by liquid nitrogen, is cooled by nitrogen vapor. This cooling-system design was chosen in order to remove the effect of liquid-nitrogen boiling on the Mössbauer velocity spectrum. Change of the source and absorber temperature was accomplished by heating them. The sample temperatures were measured by copper-constantan thermocouples.

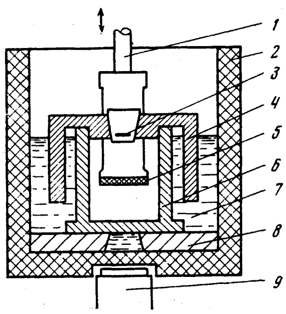

FIG. 2. Cooling system for source and absorber: 1—vibrator rod, 2—foam plastic, 3—source, 4—source holder, 5—absorber, 6—vessel, 7—liquid nitrogen, 8—collimator, 9—detector.

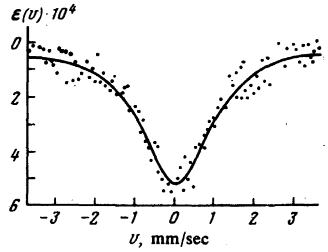

FIG. 3. Absorption spectrum of ^{182}W resonance γ rays without loss of energy to recoil for an absorber of 47.5 mg/cm^2.

The γ-ray source was metallic ^{182}Ta in the form of a disk 10 mm in diameter and 0.1 mm thick, which had been bombarded in the thermal-neutron flux of the VVR-K reactor. The source activity after an appropriate delay for decay of ^{183}Ta ($T_{1/2}=5.2$ days) was several hundred millicuries. The absorber was metallic tungsten powder compressed into paraffin tablets 28 mm in diameter.

The Mössbauer effect in the 100.1-keV level of ^{182}W was measured in the absorber temperature range from 109 to 255 K. Here the source temperature was maintained constant at 89 K.

We have shown as illustration in Fig. 3 one of the velocity spectra of γ rays with energy 100.1 keV which have passed through metallic tungsten of thickness 47.5 mg/cm^2 and temperature 110 K. The magnitude of the effect is $\varepsilon(0)=(5.1\pm0.4)\times10^{-4}$, and the experimental width of the spectrum is $\Gamma_e=2.1\pm0.3$ mm/sec, which with inclusion of correction for the absorber thickness gives a value of $(3.2\pm0.4)\times10^{-7}$ eV for the width of the 100.1-keV level of ^{182}W.

For an absorber of thickness 115 mg/cm^2 we recorded the shapes of the absorption line in the temperature range indicated above. The spectra obtained were analyzed in a BÉSM-4 computer by the method of least squares, assuming that the spectrum shape is described by a Lorentz curve.

To calculate the probability of absorption of 100.1-keV γ rays without energy loss to recoil (f') from the experimental value of the Mössbauer effect $\varepsilon(0)$, we used the well known relation of Mössbauer and Wiedemann.[5] Here the unknown parameters—the relative contribution of γ rays with energy 100 keV to the photomultiplier current (α) and the probability of emission of resonance γ rays without energy loss to recoil (f)—were excluded by use of values of $\varepsilon(0)$ measured for two absorber thicknesses at the same temperature. The calculated values of f' are given in Fig. 4 (the middle curve).

Comparison of the variation of f' as a function of T expected from the Debye solid-state model[6] with its experimental temperature dependence (see Fig. 4) gives the Debye temperature for metallic tungsten, which turned out to be $\Theta_W=330\pm10$ K.

Mahesh and Dayal[8] used values of the Mössbauer effect $\varepsilon(0)$ measured for two thicknesses of tungsten at the same temperature and found that

$$\Theta_W=\left(320\begin{smallmatrix}+70\\-40\end{smallmatrix}\right)\text{K}.$$

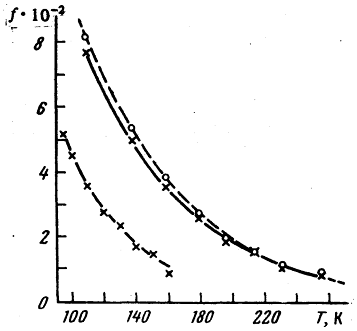

FIG. 4. Temperature dependence of f and f'. The crosses correspond to f and f' values calculated from the experimental data; the solid curves show the dependence of f and f' obtained from the Debye solid-state model for $\theta_W = 330$ K and $\theta_{Ta} = 283$ K. The dashed curve was drawn from the data of Ref. 9 and the hollow points are our normalized data. The normalization point is the value corresponding to $T = 158$ K.

As noted above, as a result of the impossibility of simultaneous determination of the Debye temperatures of the source and absorber,[4] assuming the Debye temperature of tungsten to be 384 K, on the basis of the elastic constants they determined the Debye temperature of tantalum as $\Theta_{Ta} = 280 \pm 10$ K. Mahesh and Dayal[8] give a plot of the temperature dependence of the Debye temperature of tungsten, determined from data on the specific heat in the temperature range from 20 to 200 K. It can be seen from this plot that for the region $T \geqslant 100$ K the Debye temperature of tungsten lies in the range 305–330 K. Thus, the Debye temperature obtained by us for metallic tungsten is in good agreement with the data of Refs. 7 and 8.

For a monatomic cubic lattice the probability of absorption of resonance γ rays without loss of energy to recoil is given[9] as:

$$f' = \exp\left[-\frac{R}{\hbar}\frac{1}{3N}\int_0^{\omega_{max}} \frac{\rho(\omega)}{\omega} \operatorname{cth}\left(\frac{\hbar\omega}{2kT}\right) d\omega\right].$$

Here $3N$ is a normalization factor, $\rho(\omega)$ is the density of phonon states, ω is the phonon frequency, $R = E_0^2/2Mc^2$ is the recoil energy of a nucleus with mass M received in absorption of a γ ray with energy E_0, c is the velocity of light, $\hbar = h/2\pi$, where h is Planck's constant, and k is Boltzmann's constant. In the present work, using the phonon spectrum determined from experiments on inelastic scattering of slow neutrons, we have calculated values of f' for 100.1-keV γ rays of ^{182}W in the temperature range from 4 to 300 K. In Fig. 4 (upper curve) we have given a comparison of the dependence of f' on T obtained in our work and the temperature dependence calculated by Raj and Puri.[9] As can be seen from the figure, our data agree satisfactorily with the temperature dependence of f' calculated on the basis of the experimentally determined phonon spectrum.

The probability of emission of 100.1-keV γ rays without loss of energy to recoil

$$f = 0.04^{+0.02}_{-0.004}$$

was determined by Sumbaev *et al.*[7] only at a temperature 111 K. Kankeleit[4] gives a plot of the dependence of the product ff' on T. It was therefore decided to measure the dependence of f on T. In our experiment the minimum source temperature was 93.5 K and it was varied up to 160 K. Here the absorber temperature remained constant at 101 K.

Here also we used the Mössbauer-Wiedemann relation[5] for calculation of f from the experimental value of $\varepsilon(0)$. From this relation, knowing the value of the product of the exponential and Bessel functions corresponding to the value of f' at a temperature 101 K obtained from our previous data by extrapolation, and the value of f from Ref. 7, we first determined the value of α. Now the temperature dependence of f is easily determined from the measured $\varepsilon(0)$. These values are also given in Fig. 4 (the lower curve).

Comparison of the dependence obtained for f as a function of T with that obtained from the Debye solid-state model[6] gives a Debye temperature for metallic tantalum equal to 283 ± 8 K. The obtained value of Θ_{Ta} is in good agreement with the data of Refs. 4 and 7.

[1]V. M. Lobashov, V. A. Nazarenko, L. F. Saenko, and L. M. Smotritskiĭ, Pis'ma Zh. Eksp. Teor. Fiz. **3**, 76 (1966) [JETP Lett. **3**, 47 (1966)].

[2]A. I. Beskrovnyĭ and Yu. M. Ostanevich, Prib. Tekh. Eksp. No. 5, 54 (1971) [Instrum. Exper. Tech.].

[3]M. P. Viegers and I. M. Trooster, Nuclear Instruments and Methods **118**, 257 (1974).

[4]E. Kankeleit, Z. Phys. **164**, 442 (1961).

[5]R. L. Mössbauer and W. H. Wiedemann, Z. Phys. **159**, 33 (1958).

[6]V. S. Shpinel', Resonans gamma-lucheĭ v kristallakh (Resonance of Gamma Rays in Crystals), Nauka, 1969, p. 44.

[7]O. I. Sumbaev, A. I. Smirnov, and V. S. Zykov, Zh. Eksp. Teor. Fiz. **42**, 115 (1961) [Sov. Phys. JETP **15**, 82 (1961)].

[8]P. S. Mahesh and B. Dayal, Phys. Rev. **143**, 443 (1966).

[9]D. Raj and P. Puri, Phys. Lett. **29A**, 510 (1969).

Translated by Clark S. Robinson