$|4^2S_{1/2}m=-\frac{1}{2}\rangle$, $|4^2P_{1/2}m'=-\frac{1}{2}\rangle$ level crossing at the higher-field crossing point. In this case, the broadening was due to the electric field penetration into the screen-anode region from the control grid, as the electron gun was intentionally constructed with somewhat coarse screens to test our prediction of Eq. (3) when $f \gg \Gamma$ (order of 2-3 GHz), which requires a higher value of the electric field. This phenomenon will be reported elsewhere. Since our experimental observation is based upon Eq. (2), which also explains Bashkin's results, we believe that our experimental observations give additional support for Professor Wangsness' explanation of Professor Bashkin's experiment. Also we believe that this new method is one of the simplest ways to measure the Lamb shift in short-lived excited states.

I express my appreciation to Professor Series for teaching me about the light-beat theory, through private communications and conversations in the past. I am also grateful to Professor Bashkin for his hospitality during my visit to the University of Arizona, for showing me his experimental arrangements, and for discussions which inspired this experiment. The electron gun was constructed by Wilton Berlund of Lawrence Radiation Laboratory glass shop, and his patience in so closely following my electron gun design is greatly appreciated.

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[1]G. W. Series, Phys. Rev. 136, A684 (1964).

[2]S. Bashkin, W. S. Bickel, D. Fink, and R. W. Wangsness, Phys. Rev. 162, 12 (1962).

[3]R. K. Wangsness, Phys. Rev. 149, 60 (1966).

[4]E. B. Aleksandrou, Opt. i Spektroskopiya 16, 377 (1964) [translation: Opt. Spectry. (USSR) 16, 209 (1964)]; O. Nedelec and J. C. Pebay-Peyroula, Compt. Rend. 254, 1951 (1962); T. Hadeishi and C.-H. Liu, Phys. Rev. Letters 16, 1035 (1966), an experiment that refers to the case in which the initial states are members of Zeeman magnetic sublevels.

[5]T. Hadeishi and W. A. Nierenberg, Phys. Rev. Letters 14, 891 (1965); A. Dalgarno and M. R. C. McDowell, in The Airglow and Aurorae, edited by E. B. Armstrong and A. Dalgarno (Pergamon Press, Inc., New York, 1956), p. 340.

[6]K. R. Lea, M. Leventhal, and W. E. Lamb, Jr., Phys. Rev. Letters 16, 163 (1965); H. J. Beyer and H. Kleinpoppen, Z. Physik 206, 117 (1967).

[7]See, for example, T. Hadeishi, Phys. Rev. 162, 16 (1967) for a very simple theoretical derivation.

RECOILLESS RESONANCE ABSORPTION AND HYPERFINE STRUCTURE OF THE 6.2-keV STATE IN ^{181}Ta

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A strong recoilless resonance absorption was observed for the 6.2-keV level ($T_{1/2}$ = 6.8 μsec) of ^{181}Ta. Using sources of ^{181}W in W-metal and Ta-metal absorbers, a linewidth of 11 times the natural width was obtained, with isomer shifts in the range between 0.83 and 0.94 mm/sec, depending on the quality of the sources. From the hyperfine splitting in a longitudinal magnetic field the magnetic moment of the 6.2-keV level was determined to be $\mu_1 = +(5.14 \pm 0.15)\mu_N$.

Ever since the discovery of the recoilless resonance, a considerable effort was devoted to improve the resolution of the method. The 6.2-keV transition in ^{181}Ta is one favorite candidate for this purpose, since the 6.8-μsec half-life of this level implies an extremely narrow relative linewidth,[1] $\Gamma_0/E = 1.1 \times 10^{-14}$, and the recoil-free fraction is approximately 1 at room temperature. On the other hand, the narrow linewidth and the high spin of the transition renders the resonance extremely vulnerable even to minor interactions. Only strongly broadened resonance lines have indeed been found by earlier investigators.[2-4] The difficulties encountered are presumably due to the high sensitivity of the 6.2-keV transition against quadrupole interactions: The ^{181}Ta nucleus exhibits sizable quadrupole moments in both nuclear states, and it is difficult to produce Ta metal with a uniform cubic symmetry throughout the crystal.

We report here on a major improvement in the measurement of the 6.2-keV resonance in Ta^{181}. With the best source-absorber combinations absorption lines of about 11 times the natural width have been achieved; see Fig. 1(a). Such a narrow width allowed us to determine the magnetic mo-

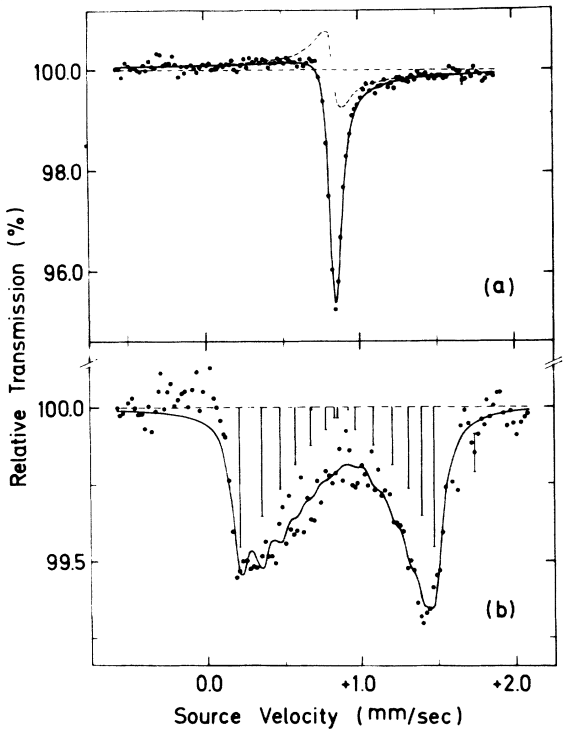

FIG. 1. Velocity spectrum of ^{181}W in W metal versus Ta metal absorber. The solid lines represent the best fit to the data. (a) Field-free case. The dashed line represents the dispersion contribution. 100% corresponds to 1.31×10^{6} counts per channel. (b) Source exposed to a longitudinal field of 1445 Oe; 100% corresponds to 2.56×10^{6} counts per channel.

ment of the 6.2-keV level.

Velocity spectra were measured by using a conventional electromagnetic drive.[5] An Ar-filled proportional counter was used to detect the 6.2-keV γ rays on the slope of the 8.15-keV $L\alpha$ x-ray peak. The ^{181}W activity was obtained by irradiating 93.1% enriched ^{180}W metal with a flux of 5×10^{14} neutrons/cm^2 sec. The activity was dissolved in concentrated HF-HNO_3, dried on high-purity tungsten (99.999%) or tantalum (99.997%) carrier foils, and diffused for some hours at about 2200°C in high vacuum (8×10^{-7} Torr). Ta absorber foils were rolled to a thickness of about 4-5 mg/cm^2 and thereafter annealed for about 5 h at 2000-2200°C in ultrahigh vacuum (3×10^{-10} Torr). Details of source and absorber preparation will be described elsewhere.[6]

The results of our measurements are listed in Table I together with data reported earlier by other groups. The line in Fig. 1(a) shows a distinct asymmetry which is characteristic of all our spectra. The analysis of the data required the introduction of two contributions: a dispersionlike component and an asymmetric component. The latter one is due to a weak quadrupole interaction caused by deviations from cubic symmetry at the source or absorber atom. The physical significance of a dispersion component is less well understood. It is most likely due to an interference between Rayleigh and Mössbauer forward scattering which here appears in an absorption spectrum. Such an interference has previously been observed only in scattering experiments[7,8]; however, since ^{181}Ta has a large Z, a high Debye temperature, low-energy γ rays, and 100% abundancy, the observation of the interference term may become feasible for sin-

Table I. Summary of γ-resonance results for the 6.2-keV transition in ^{181}Ta.

Source	Absorber	Effect (uncorr.)	Linewidth (mm/sec)	Isomer shift (mm/sec)	Ref.
^{181}W in W	$KTaO_3$	no effect			(2)
^{181}W in W	TaC	0.6 %	0.056	0.0	(2)
^{181}W in Ba_2CaWO_6	TaC	no effect			(2)
^{181}W in Pd	Ta	possible eff.			(3)
^{181}Hf in HfC	TaC	no effect			(3)
^{181}W in W	TaC	no effect			(3)
^{181}W in W	Ta	4.5 %	0.26	+0.9	(3)
^{181}W in W	Ta	1.1 %	not defined	+2.7 (c.g.)[a]	(3)
^{181}W in Ta	Ta	2.0 %	1.0	+0.9 (c.g.)	(3)
^{181}W in Ta	Ta	0.8-4.0 %	0.6-1.1	+(0.2-0.6)	(4)
^{181}W in Ta	Ta	1.0 %	0.4	+0.04	pres.work
^{181}W in W	Ta	4.7 %	0.091	+0.86	pres.work[b]

[a]Center of gravity spectrum.

[b]Results of spectrum in Fig. 1(a).

gle-crystal absorbers even in transmission. X-ray studies revealed indeed a preferential orientation of (110) planes parallel to the extension of the foil. Further investigations to check the source of this dispersion-type component are in progress.

Fitting the experimental data in Fig. 1(a) with a single Lorentzian split by a quadrupole interaction and allowing for a dispersion contribution yields a total linewidth of

$$\Delta_{exp} = 0.091 \pm 0.003 \text{ mm/sec}.$$

This has to be compared with twice the natural width of $2\Gamma_0 = 0.0066$ mm/sec. A broadening by a factor of 1.27 is expected due to absorber thickness. Thus the intrinsic broadening of our source and absorber is about $11 \times 2\Gamma_0$. Judging from the asymmetry of the line, this broadening presumably is due to quadrupole interactions. Typical values of the resonance effect for several source and absorber combinations were 4-6%, uncorrected by a factor of 2 to 3 for background.

Although the velocity range shown in Fig. 1(a) is fairly narrow, we did scan up to 10 mm/sec. In contrast to the results of Steyert, Taylor, and Storms[3] we only observed the one line at 0.9 mm/sec. Various combinations of W sources and Ta absorbers show positive isomer shifts between 0.83 and 0.94 mm/sec. Such large shifts are unusual for metals and suggest a considerable change ΔR in the nuclear charge radii associated with the γ transition. Both the ground state and the 6.2-keV level are intrinsic proton states of the strongly deformed ^{181}Ta nucleus with Nilsson assignment [404] and [514], respectively. From the Nilsson model[9] one expects for these levels a sizable change of $\Delta\langle R^2\rangle = 0.079$ fm^2. Using wave functions of a deformed Saxon-Wood potential[10] one obtains instead $\Delta\langle R^2\rangle = 0.109$ fm^2. Relying on the latter value and on the measured isomer shift one derives for the difference in electron density

$$[\psi_{Ta}{}^2(0) - \psi_W{}^2(0)] = 0.78 \times 10^{24} \text{ cm}^{-3}.$$

Sources of ^{181}W dissolved in Ta metal gave poor resonances of about 1% strength and linewidths between 0.4 and 0.8 mm/sec. Again, the lines were asymmetric and showed small positive isomer shifts of 0.04 (narrower width) to 0.15 mm/sec (broader width). This indicates a connection between linewidth and isomer shift; i.e., isomer shifts vary with impurity content and should vanish for very pure samples.

To determine the magnetic moment of the 6.2-keV state the splitting of the resonance in a longitudinal magnetic field was measured. As the 6.2-keV transition is of pure $E1$ character and has a spin sequence of $\frac{9}{2} \rightarrow \frac{7}{2}$, the resulting spectrum in a longitudinal field consists of 16 hyperfine components with intensity ratios 36:28:21:15:10:6:3:1:1:3:6:10:15:21:28:36. The source was fastened onto the surface of a cubic-shape ferrite which produced the magnetic field. This assembly was mounted upon the drive. The field strength was 1445 ± 40 Oe, where the inhomogeneity of the field across the source is included in the error. The stray field at the absorber was less than 10 Oe. Fig. 1(b) shows the split spectrum measured with the same source and absorber as in Fig. 1(a). The spectrum is poorly resolved and not quite symmetric, again indicating a weak quadrupole interaction. A least-squares fit of the data gave $g_1/g_0 = +1.72 \pm 0.05$ and $Q_1/Q_0 = +0.74 \pm 0.30$ for the ratios of the g factors and quadrupole moments, respectively. With ground state moments of $\mu_0 = (2.35 \pm 0.01) \times \mu_N$[11] and $Q_0 = 3.9 \pm 0.4$ b[12] the corresponding experimental values for the 6.2-keV level are $\mu_1 = (+5.20 \pm 0.15)\mu_N$ and $Q_1 = +2.9 \pm 1.2$ b. The errors contain the statistical uncertainty and systematic errors in velocity calibration, magnetic-field calibration, and inhomogeneity. Q_1 is not very reliable due to the poor resolution.

The large isomer shift and the large magnetic moments make a "Zeeman drive" experiment feasible in which one observes the hyperfine components at zero relative velocity as a function of the applied magnetic field. Such an experiment is of interest since it provides a check of the quality of the drive at these low velocities and is not dependent on any velocity calibration. We did measure in a longitudinal magnetic field since the outermost components are most intense. The field ranging up to 2.5 kOe was generated by an electromagnet with an inhomogeneity of about 1.5% across the source. Figure 2 shows the results. The $\frac{9}{2} \rightarrow \frac{7}{2}$ and $\frac{7}{2} \rightarrow \frac{5}{2}$ components are clearly resolved and the beginning of the $\frac{5}{2} \rightarrow \frac{3}{2}$ transition is indicated. By fitting the spectrum with three Lorentzians we obtained a linewidth of 222 Oe or 0.086 ± 0.010 mm/sec, in agreement with the value of 0.091 mm/sec measured with the single line for the same source and absorber combination. The data in Fig. 2 yield a ratio $g_1/g_0 = 1.62 \pm 0.09$, corresponding to a moment of $\mu_1 = (4.9 \pm 0.3)\mu_N$, and an isomer shift of 0.74 ± 0.08 mm/sec, which is consistent

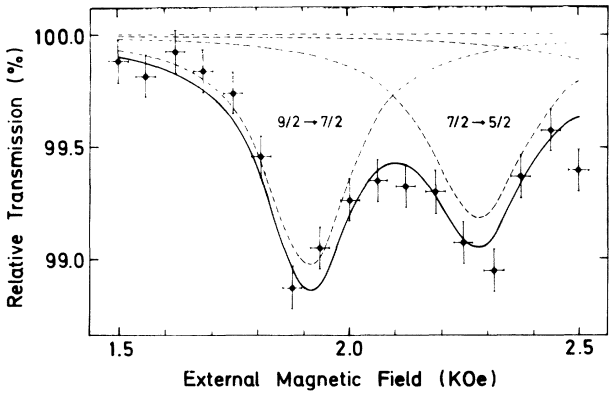

FIG. 2. Outer two components of the magnetic hyperfine spectrum of W source versus a Ta absorber, measured at zero relative velocity as a function of a longitudinal magnetic field. 100% corresponds to 0.996 $\times 10^6$ counts per channel.

with the result obtained in Fig. 1. The slight difference has to be attributed to the fact that two absolute calibrations are involved. A weakness of the Zeeman-drive method is that the magnetic splitting can be falsified by small quadrupole interactions. In our case the correction would amount to about 1.5%, which does not change the magnetic moment within the limits of error.

As a final result for the magnetic moment we give the weighted average obtained in the two measurements. Applying a paramagnetic correction of 1.1%, which is known from Knight-shift measurements,[13] together with a diamagnetic shielding correction of −0.85%,[14] we obtain the following values:

$$g_1/g_0 = +1.70 \pm 0.05$$

and

$$\mu_1 = +(5.14 \pm 0.15)\mu_N.$$

The 6.2-keV state of ^{181}Ta has been classified[15] as the same Nilsson state as the 206-keV state in ^{187}Re, for which the magnetic moment has been measured twice: $(5.02 \pm 0.06)\mu_N$[16] and $(4.71 \pm 0.14) \times \mu_N$.[17] The first value agrees well with our result. It is also consistent with the theoretical prediction of the Nilsson model[9] which is, for a deformation parameter $\delta = 0.23$, $\mu_1 = 5.08\,\mu_N$.

For this calculation we have used a rotational g factor[18] of $g_R = 0.31$ and an effective proton g factor of $g_p^{\text{eff}} = 0.73 g_p^{\text{free}}$.[19]

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[1]Mössbauer Effect Data Index, compiled by A. H. Muir, Jr., K. J. Ando, and H. M. Coogan (Interscience Publishers, Inc., New York, 1967).

[2]S. G. Cohen, A. Marinov, and J. I. Budnick, Phys. Letters 12, 38 (1964).

[3]W. A. Steyert, R. D. Taylor, and E. K. Storms, Phys. Rev. Letters 14, 739 (1965).

[4]A. H. Muir, Jr., and H. Nadler, Bull. Am. Phys. Soc. 12, 202 (1967).

[5]R. L. Cohen, Rev. Sci. Instr. 37, 957 (1966).

[6]C. Sauer and R. L. Mössbauer (to be published).

[7]P. J. Black, G. Longworth, and D. A. O'Connor, Proc. Phys. Soc. (London) 83, 925 (1964).

[8]W. Renz and H. Appel, in Hyperfine Structure and Nuclear Radiations, edited by E. Matthias and D. A. Shirley (North-Holland Publishing Company, Amsterdam, The Netherlands, 1968), p. 370.

[9]S. G. Nilsson, Kgl. Danske Videnskab. Selskab, Mat.-Fys. Medd. 29, No. 16 (1955).

[10]A. Faessler and R. K. Sheline, Phys. Rev. 148, 1003 (1966).

[11]L. H. Bennett and J. I. Budnick, Phys. Rev. 120, 1812 (1960).

[12]L. Lindgren, Arkiv Fysik 29, 553 (1965).

[13]J. I. Budnick and L. H. Bennett, J. Phys. Chem. Solids 16, 37 (1960).

[14]H. Kopfermann, Nuclear Moments (Academic Press, Inc., New York, 1958).

[15]U. Hauser, Nucl. Phys. 24, 488 (1961).

[16]H. K. Walter, A. Weitsch, and P. Kienle, Z. Physik 175, 520 (1963).

[17]S. Koicki, A. Koicki, and G. T. Wood, Nucl. Phys. 49, 161 (1963).

[18]O. Prior, F. Boehm, and S. G. Nilsson, Nucl, Phys. A110, 257 (1968).

[19]Z. Bochnacki and S. Ogaza, in Hyperfine Structure and Nuclear Radiations, edited by E. Matthias and D. A. Shirley (North-Holland Publishing Company, Amsterdam, The Netherlands, 1968), p. 106.