Taking $\delta_1=\delta_2=0$, we have for the angular distribution

$$d\sigma/d\Omega=(8\pi/3)\sin^2\theta[3\sigma_d+6(5\sigma_d\sigma_q)^{\frac{1}{2}}\cos\theta+15\sigma_q\cos^2\theta]+(3/4\pi)\sigma_{mq}\cos^2\theta. \quad (42)$$

The expressions for the cross sections in the case of the square well are quite a bit more complicated than those for the Hulthén and exponential potentials, and are most simply computed by substitution in recursion formulas.

2. *Effect of Mixture*

Dipole cross sections for several exchange mixtures are plotted in Fig. 5 for a square well of intrinsic range, 2.8×10^{-13} cm. From these curves one can obtain a qualitative idea of how the mixture will affect both total cross sections and angular distributions.

The cross section for $x=0$ (a simple derivation is given in the Appendix) is found to fall off much more rapidly than that for $x=0.5$, and actually goes to zero at 90 Mev. Furthermore, since the quadrupole cross section is unaffected by mixture the angular distributions will be radically different for the two cases. Consequently, it should be very easy to determine experimentally whether the interaction potential has a large percentage of ordinary forces.

The dipole cross section for $x=0.4$, however, is seen to be very nearly equal to that for $x=0.5$ and a rough estimate indicates that all values of x greater than 0.4 yield very nearly the same value of the cross section. Consequently, very careful experiments would have to be made in order to assign an exact value to x.

APPENDIX. DERIVATION OF σ_d FOR ORDINARY FORCES

The matrix element for the dipole transition is proportional to the absolute square of the integral (matrix)

$$x_{01}=\int_0^\infty \psi_i z\psi_1 d\tau. \quad (43)$$

We can transform this integral and evaluate it at once by using the equation of motion

$$M\ddot{x}_{01}=-\left(\frac{\partial V}{\partial x}\right)_{01}, \quad \ddot{x}_{01}=-\frac{(E_1-E_0)^2}{M\hbar^2}x_{01}. \quad (44)$$

inserting (44) in (43) we obtain

$$x_{01}=\frac{M\hbar^2}{(E_1-E_0)^2}\int \psi_i\frac{\partial V}{\partial r}\cos\theta\psi_1 d\tau. \quad (45)$$

But for a square well $\partial V/\partial r=\delta(r-b_l)$, therefore

$$\int_0^\infty \psi_i(\partial V/\partial r)\psi_1 r^2dr=\psi_i(b_l)\psi_1(b_l)b_l^2 \quad (46)$$

giving σ_d in a rather compact form.

This result agrees with that of Breit and Condon[22] which was obtained on the basis of a more involved computation.

[22] G. Breit and E. U. Condon, Phys. Rev. **49**, 904 (1936).

PHYSICAL REVIEW VOLUME 78, NUMBER 6 JUNE 15, 1950

Hyperfine Structure and Nuclear Spins of Tungsten and Tellurium

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(Received March 3, 1950)

By the use of enriched isotopes, hyperfine structure in the optical spectra of Te^{123}, Te^{125}, and W^{183} has been observed. Milligram amounts of the isotopes were used in a modified Schüler hollow-cathode discharge tube. In the visible region, 4000 to 6000A, about a dozen lines of singly ionized tellurium showed hyperfine structure, all of them giving just two components for the odd isotope. Te^{123} and Te^{125} gave identical structures except for a scale factor, the total splitting of the lines of Te^{123} being about 88 percent of that of Te^{125}. In the spectrum of neutral tungsten, all of the lines which show the isotope shift for natural tungsten gave just two components with highly enriched W^{183}. The number of hyperfine-structure components, namely two, gives for Te^{123}, Te^{125}, and W^{183} a nuclear spin of $\frac{1}{2}$. This was also verified by intensity measurements.

I. INTRODUCTION

THE nuclear spins of all the stable isotopes of odd atomic number are now believed to be known, and even the spins of a number of radioactive nuclei have been measured. On the other hand, the spins of about one-third of the stable nuclei of even atomic number and odd atomic weight remain unknown. The reason for the scarcity of data on the spins of even-odd nuclei is in many cases the low abundance of the odd isotopes in the natural element. Enriched isotopes of many elements separated by mass-spectrographic methods have recently become available in milligram amounts through the Atomic Energy Commission. By the use of these enriched isotopes several nuclear spins heretofore not known or not definitely established have been measured recently. Although the spin of any nucleus is a desirable datum, there are some nuclei which are particularly important or interesting from a theoretical point of view. In this investigation the spins of three interesting nuclei—the two odd isotopes of tellurium, Te^{123} and Te^{125}, and the odd isotope of tungsten, W^{183}—are measured by observations on the hyper-

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fine structure using enriched isotopes. The result on the spin of Te^{125} was reported earlier by the author.[1] After the work was begun, Mack and Arroe[2] reported a successful measurement on Te^{123}, which was in substantial agreement with the result reported here. The importance of the spins of these nuclei will be discussed in Section III.

II. EXPERIMENTAL

In these investigations of hyperfine structure a silvered Fabry-Perot etalon was used as the instrument of high dispersion and resolving power. To provide the auxiliary dispersion, a large glass spectrograph was used. In order to obtain large linear dispersion only a few fringes near the center of the fringe system were used. This was accomplished by tilting the interferometer so that the desired order of the off-center fringes fell into coincidence with the illuminated portion of the slit.

The etalon plates were of quartz and were figured to a flatness of about 1/30 wave-length of yellow light by W. E. Williams, using the method of localized fringes developed by Rasmussen.[3] The reflecting surfaces of the etalon were evaporated silver of such thickness that the light reflection in the visible amounted to nearly 90 percent. The etalon spacers were invar pins of fixed lengths mounted in brass rings, the lengths varying from 4 to 40 mm.

The spectral source was a Schüler hollow-cathode discharge tube of the type designed by Walcher[4] for the excitation of the spectra of very small amounts of material. Walcher's design was here modified to simplify the removal of the hollow cathode and to allow for a maximum of recovery of the material under investigation. A drawing of the discharge tube is given in Fig. 1. The main feature of the tube is the inner glass cylinder which extends to within about 3 mm of the cathode. This inner cylinder holds the anode at the lower extremity. The anode and the cathode cup are both made of commercially pure aluminum, and they are both easily removable. The whole cathode assembly is removed simply by warming the wax seal and sliding it off the outer glass cylinder. This can be done without disturbing the carrier-gas leads to the vacuum and purifying system. The wax seal is kept at room temperature by means of a water jacket soldered to the upper end of the brass cathode-housing. The cathode assembly is surrounded with water or liquid nitrogen to cool the cathode and reduce line width.

Helium from the inlet tube goes down the inner glass cylinder through the circular opening of the anode and then flows back up in the space between the two glass cylinders to the outlet. This provides a "gas window" to prevent diffusion of the sample out of the hollow cathode. The helium is continuously circulated in a purifying circuit consisting of a liquid-air-cooled charcoal trap and a mercury diffusion pump. The diffusion pump is also used to evacuate the system before admitting the helium. The discharge is run at helium pressures of from 1 to 3 mm.

About 20 mg of the material whose spectrum is to be studied is put into the bottom of the hollow cathode. Using a cathode 6 mm in diameter and 25 mm in length, an excitation current of about 150 milliamperes gave good results. The direct current source was a 1000-volt power supply. A variable series resistor was used to limit the current to the proper value. Tellurium in the form of the powdered element was used for the tellurium spectra. The separated tungsten isotope was furnished in the form of the oxide WO_3. It was found that the unreduced oxide itself gave a good spectrum of atomic tungsten from the Schüler tube after about one-half hour of operation. No special procedures for plating of the cathode or clean-up of the tube were found to be necessary except for a thorough initial pumping out of the system with the diffusion pump.

Under the conditions described, fairly bright spectra were obtained, and good spectrograms could be obtained in from three to five minutes on Eastman 103a-F or 103a-J spectroscopic plates. This short exposure time made it unnecessary to use any temperature control mechanism for the Fabry-Perot etalon. The intensity measurements were made by the standard

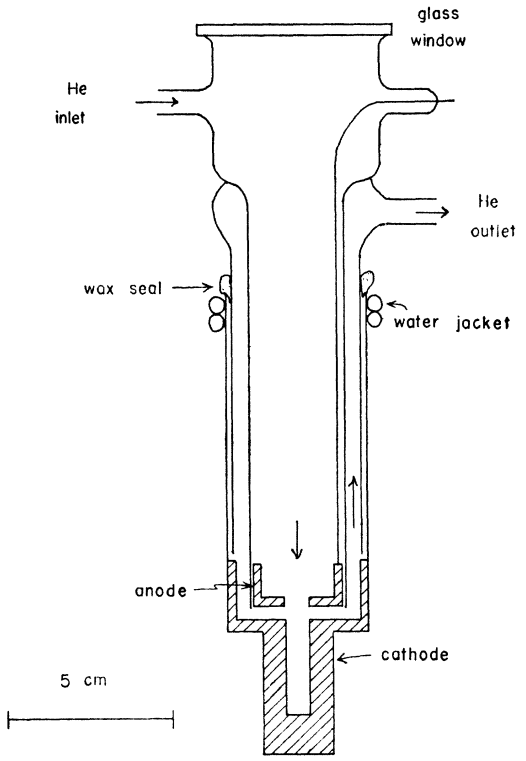


FIG. 1. Modified Schüler tube.

[1] G. R. Fowles, Phys. Rev. **76**, 571 (1949).
[2] J. E. Mack and O. H. Arroe, Phys. Rev. **76**, 1002 (1949).
[3] E. Rasmussen, Physica **12**, 656 (1946).
[4] W. Walcher, Zeits. f. Physik **122**, 62 (1944).

TABLE I. Measurements on the tellurium lines.

Wavelength (A)	Separations in cm^{-1} Te^{125}	Te^{123}	Ratio $\Delta_{123}/\Delta_{125}$	Intensity ratio $I_{j+\frac{1}{2}}/I_{j-\frac{1}{2}}$	Displacement ratio* $\Delta_{j-\frac{1}{2}}/\Delta_{j+\frac{1}{2}}$
5974	0.169	0.145	0.86	1.5	1.59
5755	0.079				1.5
5708	0.176	0.157	0.89	1.6	1.6
5666	0.115	0.103	0.90	~3	~3
5649	0.205			~3	2.9
5576	0.121	0.108	0.89		1.5
5449	0.226	0.192	0.85	1.4	1.3

* Taken with respect to the central unresolved component of the even isotopes.

method in which the plates are calibrated by the use of a step-slit.[5]

III. RESULTS AND DISCUSSION

Tellurium

The two odd isotopes of tellurium, Te^{123} and Te^{125}, have been observed to have long-lived isomeric states.[6,7] A knowledge of the spins of the ground states of these nuclei would permit one to say something about the angular momentum of the nucleus in the excited state, when the lifetime and energy of the isomeric transition are known.[8] Recent theories[9–11] concerning the shell structure of nuclei indicate that in the region of tellurium (neutron numbers 69 to 79) isomerism should occur. The spin changes which occur in these isomeric transitions have an important bearing on the theories. In addition, Te^{123} has a stable isobar, Sb^{123}, whose spin is known to be 7/2. Only a few odd isobaric pairs exist in the natural elements, and the spins of the members of these pairs are important data.[12]

In natural tellurium the isotopes of mass 123 and 125 occur in the amounts 0.85 and 6.97 percent, respectively. Because of this low abundance of the odd isotopes, hyperfine structure in the spectrum of natural tellurium has never been reported. By the use of the enriched isotopes Te^{125} and Te^{123} in this investigation, it was possible to find hyperfine structure in about a dozen lines of singly ionized tellurium in the visible region, 4000 to 6000A. All of the lines gave only two components for the odd isotope. Tellurium enriched to about 80 percent in Te^{125} in the one case,[13] and to about 45 percent in Te^{123} in the other,[14] showed identical

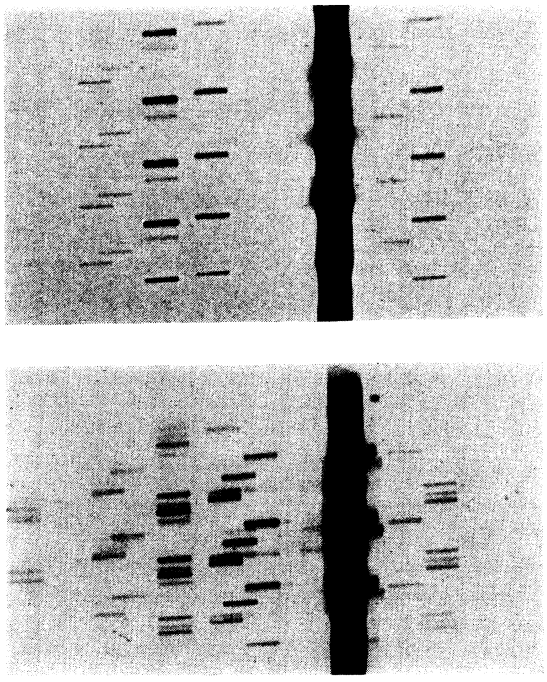


FIG. 2. Fabry-Perot spectrograms of natural tellurium (upper) and Te^{125} (lower). Etalon separation 7 mm.

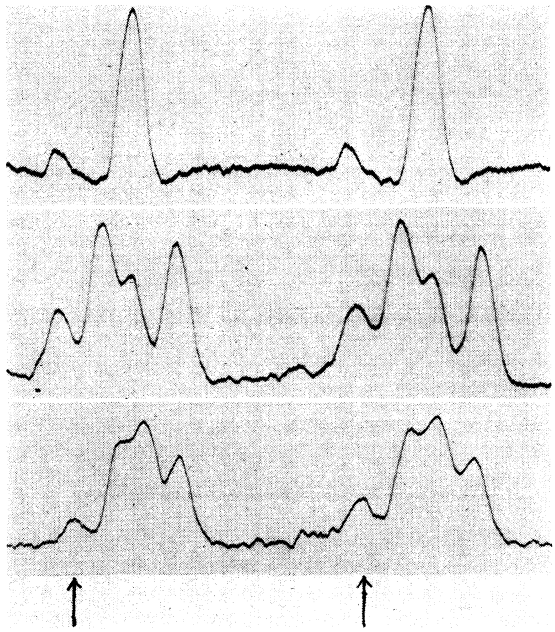


FIG. 3. Microphotometer traces of the line Te II λ5707 taken using natural Te (upper), 80 percent enriched Te^{125} (middle), and 45 percent enriched Te^{123} (lower). The peak indicated by the arrows is not a part of the structure of the line, but is another line appearing in a different order.

[5] See, for example, R. A. Sawyer, *Experimental Spectroscopy* (Prentice Hall, Inc., New York, 1944), p. 259.
[6] R. D. Hill, Phys. Rev. **76**, 333 (1949).
[7] Friedlander, Goldhaber, and Scharff-Goldhaber, Phys. Rev. **74**, 981 (1948).
[8] For an extensive review of this subject, see E. Segrè and A. C. Helmholtz, Rev. Mod. Phys. **21**, 271 (1949).
[9] E. Feenberg and K. C. Hammack, Phys. Rev. **75**, 1877 (1949).
[10] L. Nordheim, Phys. Rev. **75**, 1894 (1949).
[11] M. G. Mayer, Phys. Rev. **75**, 1969 (1949).
[12] H. A. Bethe and R. F. Bacher, Rev. Mod. Phys. **8**, 83 (1936).
[13] Obtained from the Isotopes Division of the Atomic Energy Commission with the assistance of Professors I. Perlman and A. C. Helmholz.
[14] Kindly loaned by Professor J. E. Mack of the University of Wisconsin, as a portion of the material allocated to him by the Isotopes Division of the Atomic Energy Commission.

structures except for magnitude, the splitting of the lines in Te^{123} in each case being about 88 percent that of Te^{125}. Since the splitting is proportional to the magnetic moment of the nucleus, the ratio of magnetic moments in the tellurium isotopes is $\mu_{123}/\mu_{125}=0.88$. A summary of the measurements is given in Table I, and some of the spectrograms are reproduced in Fig. 2. Microphotometer traces of Te II λ5707 are shown in Fig. 3.

In view of the present lack of a term analysis of the Te II spectrum, it is fortunate that the spins of these

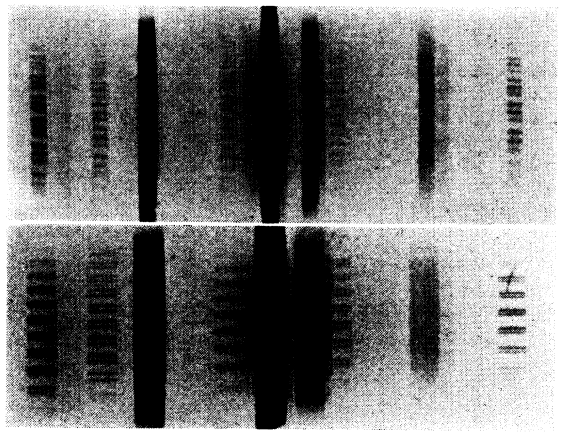


FIG. 4. Fabry-Perot spectrograms taken using natural tungsten (upper) and W^{183} (lower). Etalon separation 19 mm.

isotopes turns out to be $\frac{1}{2}$, since for any higher value it would have been impossible to reach an unambiguous conclusion. As it is, the results are very definite, and should be of considerable interest to the theory of nuclear structure. For example, from Mayer's theory of the shell structure, it would be expected that Te^{123} would have spin $\frac{1}{2}$, but for Te^{125} either $\frac{1}{2}$ or $\frac{3}{2}$ would be possible.

Tungsten

In 1933 Grace, More, and White[15,16] observed isotope structure in the spectrum of neutral tungsten. They found that a number of lines in the visible region consisted of three nearly equidistant components which were attributed to the even isotopes of mass 182, 184, and 186. The abundances of these are 26, 30, and 28 percent, respectively, in natural tungsten. The isotope of mass 180 occurs only in the amount of 0.14 percent, and so its lines did not appear in any of the spectrograms. Tungsten has just one odd isotope, W^{183}, which occurs in the amount 14.4 percent in natural tungsten. Since Grace, More, and White did not observe more than three components in any of the lines, they tentatively suggested that the spin of W^{183} was $\frac{1}{2}$ and that

[15] N. S. Grace and H. E. White, Phys. Rev. **43**, 1039 (1933).
[16] N. S. Grace and K. R. More, Phys. Rev. **45**, 166 (1935).

TABLE II. Measurements on W^{183}.

Wavelength (A)	J value	Separation (cm^{-1})	Intensity ratio Meas.	Intensity ratio Theory	Separation of W^{182} and W^{184} (Kopferman and Meyer)
4844	2	0.046	1.4	1.50	0.055
4887	5	0.068	1.1	1.20	0.061
4983	1	0.045			0.059
5053	1	0.050	1.8	2.00	0.052
5069	3	0.057			0.059
5225	2	0.042	1.45	1.50	0.053

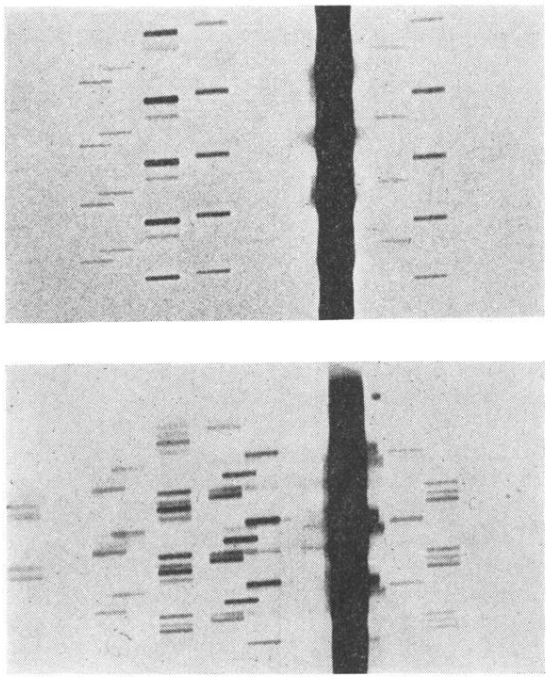
the two components due to this isotope practically coincided with two of the three components of the even isotopes. In 1948 Kopferman and Meyer[17] in Germany made some careful measurements on the intensity distribution among the three components in the tungsten spectrum and concluded that the intensities were consistent with the assumption of a spin of $\frac{1}{2}$ for W^{183} and that the two components due to this isotope coincided almost exactly with the components of W^{182} and W^{184} in those lines which show the isotope effect.

In the present investigation photographs taken using tungsten[18] enriched to about 90 percent in W^{183} gave a satisfactory confirmation of Kopferman's conclusions. All of the lines which show the three isotopic components in natural tungsten yield just two components for the enriched odd isotope. The J-values of these lines are known from the classification of Laporte and Mack.[19] Intensity measurements made on some of the lines also verify the fact that the spin is $\frac{1}{2}$. The numerical results are given in Table II. The isotope shift of the components of W^{182} and W^{184} as given by Kopferman and Meyer are included for comparison. A comparison of spectrograms for ordinary tungsten and tungsten 183 is given in Fig. 4.

In conclusion it may be pointed out that although the results reported here merely serve to confirm a conclusion that has been reached by previous investigators, that conclusion was not previously so well substantiated as could be desired. Results based on intensity measurements are notoriously subject to error, and it could well have been that the presence of weak components had been missed. Use of the enriched isotope has, however, put the results on a firm foundation.

The author wishes to express his deep appreciation to Professor F. A. Jenkins under whose very able direction these researches were done. Thanks are due Professor H. E. White for much valuable help. Professor A. C. Helmholz took a stimulating interest in the work for which the author is greatly appreciative.

[17] H. Kopferman and D. Meyer, Zeits. f. Physik **124**, 685 (1948).
[18] Obtained from the Isotopes Division of The Atomic Energy Commission with the assistance of Professor I. Perlman.
[19] O. Laporte and J. E. Mack, Phys. Rev. **63**, 246 (1943).



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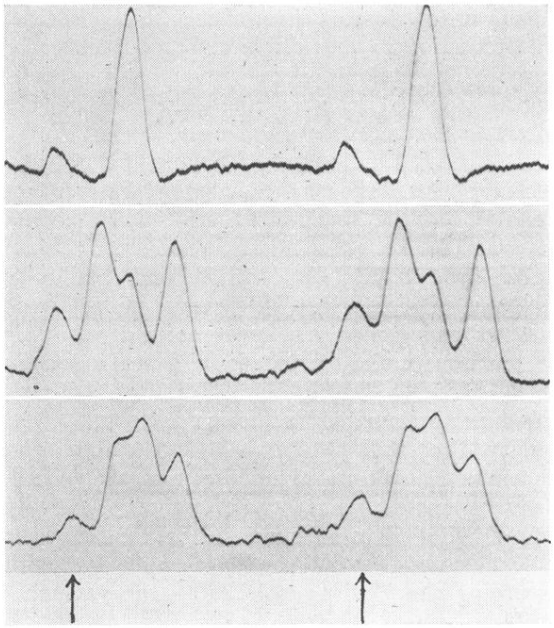

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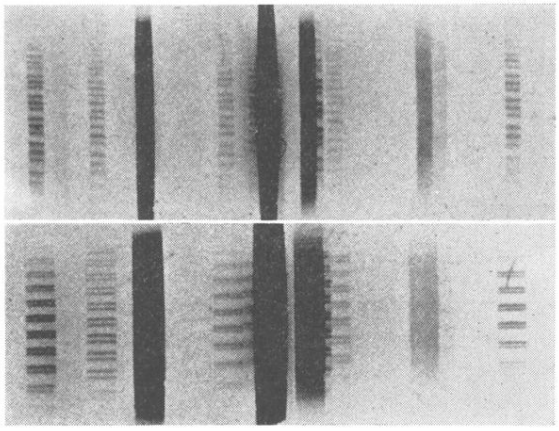

FIG. 4. Fabry-Perot spectrograms taken using natural tungsten (upper) and W^{183} (lower). Etalon separation 19 mm.