Hyperfine Structure and Isotope Shift in the Spectrum of Tellurium*

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Using separated isotopes of tellurium, the hyperfine structure of the Te I and Te II spectra was studied. The magnetic moments of the two odd isotopes were calculated to be $\mu(Te^{125}) = -0.6 \pm 0.2$ nm, $\mu(Te^{123}) = -0.5 \pm 0.2$ nm. The ratio of the magnetic moments was determined to be $\mu^{125}/\mu^{123} = 1.186 \pm 0.007$. Anomalous shift of the even isotopes was detected in the lines λ4006 ($5s5p^4\ ^4P_{5/2} - 5p^2(^3P_0)6p_{3/2}$) and λ4049 ($5s5p^4\ ^4P_{3/2} - [5p^2(^3P_1)6p]_{3/2}$). The spacings between consecutive even isotopes in the line λ4006 were as follows: $\Delta(130-128) = 0.014$, $\Delta(128-126) = 0.011$, $\Delta(126-124) = 0.026$, $\Delta(124-122) = 0.017$, $\Delta(122-120) = 0.017$ cm^{-1}, the component due to the heaviest isotope lying on the largest frequency side. The centers of gravity of the odd isotopes in the line λ4006 were: $\Delta(124-125) = 0.002$, $\Delta(123-122) = 0.000$ cm^{-1}. λ4049 showed nearly the same isotope effect as λ4006. Regarding the μ-values, see the note §.

INTRODUCTION

THE hyperfine structure (hfs) in the spectrum of tellurium is worthy of study, since the magnetic moments of the odd isotopes have not yet been determined by the nuclear induction method and because tellurium has a large number of even isotopes (120, 122, 124, 126, 128, and 130) in addition to the two odd isotopes (123 and 125). The nuclear spins of Te^{123} and Te^{125} were determined previously[1,2] to be 1/2, and the existence of an isotope shift was also detected by Mack and Arroe.[2] A complete interpretation of the hfs and isotope shift had to wait until the spectrum of Te II was analyzed.[3]

EXPERIMENTAL DETAILS

A liquid-air cooled aluminum hollow-cathode source[4] was used. Helium or neon was used as the carrier gas. Neon enabled us to investigate the regions which were masked by the strong helium lines, and in addition several lines appeared, which were not strongly excited by helium.

In the ultraviolet region, for the study of Te I, a Bausch and Lomb medium quartz spectrograph was used. In the visible region, for the study of Te II, two different Hilger constant deviation spectrographs (flint-glass and crown-glass prisms) were used.

A Fabry-Pérot interferometer, of Invar construction, was used with quartz plates 60 mm in diameter. Invar spacers up to 40 mm were used. For use in the ultraviolet region the plates were coated with an alloy of 20 percent silver and 80 percent aluminum, and the Fabry-Pérot was mounted in front of the spectrograph, the fringes being focused on the slit with a quartz-fluorite achromat. For use in the visible region the plates were coated with silver and the interferometer was used in the usual way between the collimator and the prism of the spectrograph.

Figure 1 shows some reproductions of the interference patterns of tellurium lines.

In the study of the isotope shift, it was necessary to take spectrograms of the two isotopes on the same plate. This had to be done within a relatively short time to insure that there was no change in the interferometer. To do this, two discharge sources, each containing a different isotope, were mounted on a metal frame which could be rotated about a vertical axis.[4] It was thus possible to change from one isotope to another in a matter of a minute or so, by merely rotating the source to a predetermined position. Since the exposure times were of the order of 5 to 15 minutes, it was not necessary to maintain any pressure or temperature control over the interferometer. However, in order to be sure that there was no change, three exposures were taken on each plate: first one isotope

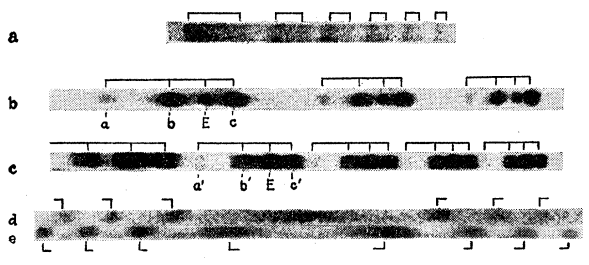

FIG. 1. (a) Te I λ2531. Isotope 125. 20-mm etalon. (b) Te II λ5449. Isotope 125. (Component E is due to even isotopes.) 6-mm etalon. (c) Te II λ5449. Isotope 123. (Component E is due to even isotopes.) 10-mm etalon. {(d) Te II λ4049. Isotope 122. (e) Te II λ4049. Isotope 130.} Taken on the same plate. 30-mm etalon.

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[1] G. R. Fowles, Phys. Rev. **76**, 571 (1949); **78**, 744 (1950). Fowles published a reproduction of the hfs of some Te II lines, together with the result of his measurements, but he made no mention about which component was the stronger. Since the light did not travel normally through his etalon, it is not certain whether he obtained an adequate formula for deriving the hfs. His published separations are considerably smaller than those of the present writers, who used the Fabry-Pérot etalon in the usual manner.
[2] J. E. Mack and O. H. Arroe, Phys. Rev. **76**, 1002 (1949).
[3] Mack, Murakawa, Ross, Pick, and van den Bosch, Phys. Rev. **83**, 654 (1951). In Table I of this letter, the hfs splitting[125] of the term $74_{3/2}$ was tentatively given as 0.00 cm^{-1}. This should read -0.463 cm^{-1}. This error occurred through a misinterpretation of the interference fringes of λ4049, which were largely disturbed by the presence of close lying lines Te II λ4047.2 and Hg I λ4046.6.
[4] O. H. Arroe and J. E. Mack, J. Opt. Soc. Am. **40**, 386 (1950).

TABLE I. Isotopic constitution (percent) of the samples of tellurium.

Sample label	Isotope 120	122	123	124	125	126	128	130
120	22.3	18.8	1.5	5.1	5.5	12.5	17.4	16.9
122	0.7	86.2	1.1	1.7	1.5	2.7	3.4	2.6
123		8.5	45.8	12.3	7.0	10.7	9.0	6.8
124		1.5	0.7	83.9	4.7	4.5	3.0	1.9
125		0.1	0.3	1.4	87.9	6.8	2.4	1.1
126		0.1		0.6	0.7	95.4	2.6	0.6
128					0.2	1.5	94.4	3.9
130						0.4	2.3	97.4
Natural	0.1	2.3	0.9	4.6	6.9	18.7	31.9	34.5

was photographed, then the second isotope, and then the first one again. If the first and third patterns were the same (determined by measuring the fringes), then there will have been no change in the interferometer, and the two different isotopes will have been compared under the same conditions.

Figures 1(d) and 1(e) show an example of interference patterns that were used to measure the isotope shift of 122 against 130.

Table I lists the concentration of the different samples[5] which were used.

RESULTS OF MEASUREMENTS

(A) Hfs of the Te I Spectrum

Using the enriched sample 125, two arc lines λ2530.7 ($5p^4\,{}^3P_1-5p^3 6s\,{}^5S_2$) and λ2385.7 ($5p^4\,{}^3P_1-5p^3 6s\,{}^3S_1$) were studied. The former line was found to consist of two components 0.113 cm^{-1} apart, the lower frequency component being the stronger. According to the theory of hyperfine structure splitting, the splitting factors of $5p^3 6s\,{}^5S_2$ and $5p^4\,{}^3P_1$ should have the same and the opposite sign as the nuclear magnetic moment, respectively, so μ^{125} must be negative. The hfs pattern of λ2530.7 taken with a 20-mm etalon is reproduced in Fig. 1. The line λ2385.7 was found to be single to an accuracy of 0.03 cm^{-1}.

The aforementioned findings can be expressed by the equations:

$$\tfrac{3}{2}A({}^3P_1)-(5/2)A({}^5S_2)=0.113\ \text{cm}^{-1}.$$
$$\tfrac{3}{2}A({}^3P_1)-\tfrac{3}{2}A({}^3S_1)=0\qquad \text{cm}^{-1}.$$

Eliminating $A({}^3P_1)$, we get

$$(5/2)A({}^5S_2)-\tfrac{3}{2}A({}^3S_1)=-0.113\ \text{cm}^{-1}.$$

Using the hyperfine structure formulas for the configuration p^3s derived by Crawford and Wills,[6] we can easily show that

$$(5/2)A({}^5S_2)-\tfrac{3}{2}A({}^3S_1)=a(6s)$$

for both jj- and LS-coupling cases. Calculation in the intermediate coupling case is not possible, since no terms (except ${}^5S_2$ and ${}^3S_1$) of the configuration $5p^3 6s$ are known. However, we have assumed that the foregoing formula is a good approximation for an intermediate coupling cases, since it holds in the two extreme cases. Hence we obtain

$$a(6s)=-0.113\pm0.030\ \text{cm}^{-1}.$$

Using the Fermi-Segrè-Goudsmit formula

$$\mu=\frac{a(s)In^{*3}\cdot\frac{3}{8}\cdot 1836}{R\alpha^2 Z Z_0^2 F(dn^*/dn)}$$

and substituting in the above value for $a(6s)$, $Z=52$, $Z_0=1$, F(relativity correction factor)$=1.34$, together with[7] n^*(effective quantum number)$=1.997$ and $dn^*/dn=1.04$, gives

$$\mu^{125}=-0.73\pm0.20\ \text{nm}.$$

(B) Hfs of the Te II Spectrum

The hfs of the isotope 125 of the Te II spectrum was examined in the visible region, and the result is summarized in Table II. The 125 sample contained 11.8 percent of even isotopes (see Table I). In no lines, except λ4049 and λ4006 (and possibly in λ5038) could any shift of the even isotopes be detected. The position of even isotopes is given in the column Te^{even}, the strongest component of Te^{125} being taken as the origin. A number in square brackets [ ] represents a relative calculated intensity, while a number in parentheses ( ) represents the calculated position of a component too weak or too near to a strong component to be measured.

Table III summarizes the hfs splitting of Te II terms for the isotope 125, which can be derived from Table II.

In the Te II spectrum, many terms of the same parity perturb each other, and it is rather difficult to find terms suitable for calculating the magnetic moment. However, the terms $5p^2({}^3P_0)6p_{1/2}$ and $5p^2({}^3P_0)6p_{3/2}$ are somewhat apart from the terms $5p^2({}^3P_1)6p$ and $5p^2({}^3P_2)6p$, so it appears reasonable to use them in the calculation of μ. From Table III, we get

$$a(6p_{1/2})=-0.053\ \text{cm}^{-1},\quad a(6p_{3/2})=-0.010\ \text{cm}^{-1}.$$
$$\delta(\text{doublet splitting of } 6p)=2166\ \text{cm}^{-1}.$$

Using the formula,

$$\mu=[a(p)Ij(j+1)(l+\tfrac{1}{2})Z_i H 1836]/[\delta l(l+1)F'],$$

and putting $a(6p_{1/2})=-0.053$ cm^{-1}, $j=1$, $Z_i=52-3=49$, H(relativity correction factor)$=1.06$, F'(relativity correction factor)$=1.29$, we obtain

$$\mu^{125}=-0.51\pm0.20\ \text{nm}.$$

The error of the calculation is rather difficult to estimate owing to the difficulty in estimating the effect of the term $101_{1/2}{}^\circ$ on the term $93_{1/2}{}^\circ$ and in estimating the error of δ.

[5] The enriched isotopes were produced by the Y-12 plant, Carbide and Chemicals Division, Oak Ridge, and were obtained by allocation from the AEC.

[6] M. F. Crawford and L. A. Wills, Phys. Rev. 48, 69 (1935).

[7] J. E. Ruedy, Phys. Rev. 41, 588 (1932).

TABLE II. Hyperfine structure of the Te II spectrum (sample 125).

Wavelength	Combination	Hfs of Te^{125} (cm^{-1})	Te^{even}	Separation[125] (Fowles)
6437.1	$78_{1/2}-93_{1/2}°$	−0.227, 0, 0.053 [1] [2] [1]	−0.045	
5974.7	$85_{5/2}'-102_{5/2}°$	(−0.429), −0.173, 0, (0.258) [0.25] [3.5] [5] [0.25]	−0.073	0.169
5755.9	$82_{3/2}-100_{5/2}°$	−0.083, 0 [3] [5]		0.079
5708.1	$85_{5/2}'-103_{7/2}°$	−0.185, 0, (0.246) [7.4] [10] [0.4]	−0.075	0.176
5666.2	$83_{1/2}-101_{3/2}°$	0, 0.061, 0.140 [5] [1] [2]	0.039	0.115
5649.3	$78_{1/2}-96_{3/2}°$	−0.208, 0, (0.020) [2] [5] [1]	−0.049	0.205
5630.6	$99_{3/2}°-117_{3/2}$	(−0.064), −0.054, 0, (0.010) [1] [5] [9] [1]		
5618.5	$83_{1/2}-101_{1/2}°$	−0.078, 0, 0.082 [1] [2] [1]		
5576.4		−0.1338, 0	−0.054	0.121
5536.7	$85_{5/2}-103_{7/2}°$	0, 0.153, (0.246) [10] [7.4] [0.4]		
5487.9	$81_{3/2}-100_{5/2}°$	−0.057, 0 [3] [5]		
5479.1	$86_{3/2}-105_{3/2}°$	0, 0.031, 0.111, 0.141 [9] [1] [1] [5]	0.060	
5449.8	$85_{5/2}'-103_{3/2}°$	−0.431, −0.238, 0 [1] [9] [14]	−0.108	0.226
5366.9	$82_{3/2}-101_{1/2}°$	−0.161, −0.081, 0 [2] [1] [5]	−0.051	
5311.1	$86_{3/2}-105_{5/2}°$	0, (0.219), 0.249 [14] [1] [9]	0.115	
5300.7		0, 0.136		
5244.2	$105_{5/2}°-124_{5/2}$	(−0.222), −0.086, 0, (0.137) [0.5] [7] [10] [0.5]		
5037.9	$76_{1/2}-96_{3/2}°$	∼−0.53, 0, (0.020) [2] [5] [1]		
5000.8	$85_{5/2}'-105_{5/2}°$	(−0.429), −0.208, 0, (0.223) [0.25] [3.5] [5] [0.25]	−0.081	
4961.9	$101_{1/2}°-121_{3/2}'$	0, (0.044), 0.122 [5] [1] [2]		
4910.6	$83_{1/2}-103_{3/2}°$	0, 0.193, 0.275 [5] [1] [2]	0.088	
4895.0	$85_{3/2}-105_{5/2}°$	0, 0.221 [7] [5]	0.090	
4893.6	$81_{3/2}-102_{5/2}°$	0, 0.194, (0.256) [14] [9] [1]	0.078	
4842.9		−0.203, 0	−0.072	
4827.1	$103_{3/2}°-124_{5/2}$	−0.057, 0, 0.136 [9] [14] [1]		
4729.9	$78_{1/2}-99_{3/2}°$	−0.164, 0, 0.064 [2] [5] [1]	−0.040	
4665.4	$83_{1/2}-105_{3/2}°$	0, 0.110, 0.190 [5] [1] [2]	0.066	
4478.6	$102_{5/2}°-124_{5/2}$	(−0.256), −0.124, 0, (0.136) [0.25] [3.5] [5] [0.25]		
4364.0	$85_{5/2}-107_{5/2}°$	−0.139, (−0.093), (−0.046), 0 [5] [1] [1] [9]		
4048.9	$5s5p^4\ {}^4P_{3/2}-99_{3/2}°$	(−0.463), −0.399, 0, (0.064) [1] [5] [9] [1]	Fig. 2	
4006.5	$5s5p^4\ {}^4P_{5/2}-96_{3/2}°$	(−0.824), −0.804, 0 [1] [9] [14]	Fig. 2	

λ5410.4 ($82_{3/2}-101_{3/2}°$) has a slight broadening (observed with a 20-mm etalon), but the measurement is difficult, owing to stray light with a continuous background.
λ5709.0 ($103_{7/2}°-120_{5/2}$), λ4865.1 ($103_{7/2}°-123_{7/2}$), λ4766.0 ($101_{3/2}°-122$) and λ4686.9 ($102_{5/2}°-123_{7/2}$) were examined by a 10-mm etalon, but the hfs could not be resolved.

From $a(6p_{3/2})$ we get $\mu^{125}=-0.6$ nm, but it is generally known that the hfs of a $p_{3/2}$ term does not give a reliable value of the magnetic moment, so we can consider the aforementioned value only as confirming the order of magnitude.

Using an approximate formula,[8] the value of $a(5s)$ was calculated from the splittings of the terms $5s5p^4\ {}^4P_{5/2}$ and $5s5p^4\ {}^4P_{3/2}$, and $a(5s)=-0.36$ cm^{-1} was obtained, from which it was calculated that

$$\mu^{125}=-0.5\pm0.2 \text{ nm}.$$

Taking a weighted mean of the four values of μ^{125} obtained from the hfs of the Te I and Te II spectra

[8] P. Güttinger and W. Pauli, Z. Physik **67**, 743 (1931).

TABLE III. Hfs splitting of Te II terms (isotope 125).

Configuration	Term symbol	Term value (cm^{-1})[a]	Hfs splitting (cm^{-1})[b]
$5s5p^4\,{}^4P_{5/2}$	$71_{5/2}$	71191.66	−0.824
$5s5p^4\,{}^4P_{3/2}$	$74_{3/2}$	74892.51	−0.463
$5s5p^4\,{}^4P_{1/2}$	$76_{1/2}$	76299.96	∼−0.55
$5p^26s$ and $5p^25d$	$78_{1/2}$	78447.25	−0.228
	$81_{3/2}$	81894.55	−0.057
	$82_{3/2}$	82742.49	−0.083
	$83_{1/2}$	83576.56	+0.082
	$85_{5/2}$	85048.45	−0.093
	$85_{3/2}$	85158.81	0.000
	$85_{5/2}'$	85591.02	−0.431
	$86_{3/2}$	86758.94	+0.030
$5p^27s$ and $5p^26d$	$117_{3/2}$	117338.75	−0.010
	$120_{5/2}$	120616.23	−0.25
	$121_{3/2}'$	121518.02	−0.044
	$124_{5/2}$	124645.47	−0.136
$5p^2(^3P_0)6p$	$93_{1/2}°$	93978.00	−0.053
	$96_{3/2}°$	96143.84	−0.020
	$99_{3/2}°$	99583.68	−0.064
$5p^2(^3P_1)6p$	$100_{5/2}°$	100111.18	0.000
	$101_{3/2}°$	101220.10	−0.061
	$101_{1/2}°$	101370.01	+0.078
	$102_{5/2}°$	102323.61	−0.256
$5p^2(^3P_2)6p$	$103_{7/2}°$	103104.98	−0.246
	$103_{3/2}°$	103935.04	−0.193
	$105_{3/2}°$	105005.21	−0.109
	$105_{5/2}°$	105582.14	−0.221
$5p^26p$ (or $5p^24f$)	$107_{5/2}°$	107956.82	+0.046

[a] The deepest term of Te II is taken as the origin.
[b] + and − mean that the hfs terms are normal and inverted respectively.

and assigning conservative limits of error, we obtain as our final value:

$$\mu(\mathrm{Te}^{125}) = -0.6 \pm 0.2 \text{ nm.}§$$

If we use the value of $\mu^{125}/\mu^{123} = 1.186 \pm 0.007$ to be described, we get

$$\mu(\mathrm{Te}^{123}) = -0.5 \pm 0.2 \text{ nm.}§$$

Besides the sample 125, the sample 123 was examined in the case of the Te II spectrum. The distances between the two strongest components in λλ5449, 5311, and 4049 were measured and the positions of the 123 components were corrected by taking the presence of the 125 components into account. The results of these measurements are given in Table IV.§

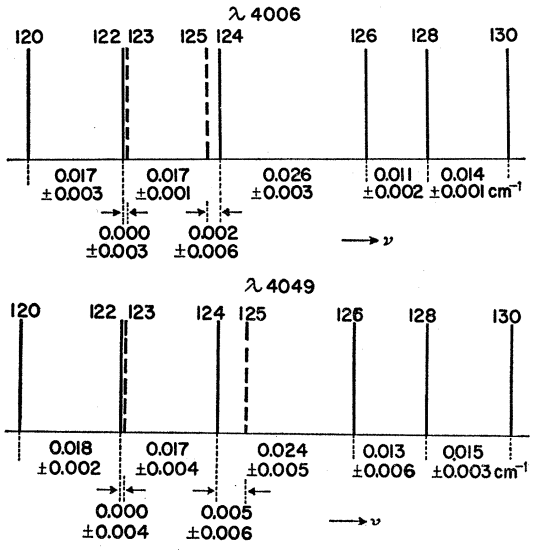

FIG. 2. Isotope shift in the Te II lines λ4006 ($5s5p^4\,{}^4P_{5/2} - 5p^2(^3P_0)6p_{3/2}$) and λ4049 ($5s5p^4\,{}^4P_{3/2} - [5p^2(^3P_1)6p]_{3/2}$). The dashed lines above the horizontal lines are centers of gravity of the odd isotopes 123 and 125.

(C) Isotope Shift in the Te II Spectrum

In two lines λ4049 ($5s5p^4\,{}^4P_{3/2} - [5p^2(^3P_1)6p]_{3/2}$) and λ4006 ($5s5p^4\,{}^4P_{5/2} - 5p^2(^3P_0)6p_{3/2}$), isotope shift of considerable magnitude was detected. This is to be expected, because the final terms of these lines contain an unpaired 5s electron, whereas the initial terms do not.

Since the line λ4049 was often disturbed by close lying lines Te II λ4047.2 and Hg I λ4046.6, isotope shift in the line λ4006 could be measured more accurately than in λ4049. The following seven distances were measured in λ4006.

$$\Delta(130-122) = 0.069 \pm 0.003 \text{ cm}^{-1}.$$
$$\Delta(126-122) = 0.042 \pm 0.003 \text{ cm}^{-1}.$$
$$\Delta(122-120) = 0.017 \pm 0.003 \text{ cm}^{-1}.$$
$$\Delta(128-124) = 0.039 \pm 0.002 \text{ cm}^{-1}.$$
$$\Delta(128-122) = 0.053 \pm 0.002 \text{ cm}^{-1}.$$
$$\Delta(124-122) = 0.017 \pm 0.001 \text{ cm}^{-1}.$$
$$\Delta(130-128) = 0.014 \pm 0.001 \text{ cm}^{-1}.$$

TABLE IV. Hfs of Te II of the isotopes 125 and 123.

	Hfs 125 (cm^{-1})	Hfs 123 (cm^{-1})	μ^{125}/μ^{123}
λ5449	0.2386	0.2011	1.186±0.010
λ5311	0.2486	0.2103	1.184±0.010
λ4049	0.3993	0.3367	1.186±0.007
		Mean:	1.186±0.007

The numbers following the symbol ± are approximate probable errors. From these measurements the consecutive distances of the components due to even isotopes were deduced. They are shown in Fig. 2. In Fig. 2, the centers of gravity of the 125 components and 123

§ *Note added in proof, February 8, 1952.*—Since submitting this paper we have found that, contrary to our original belief, $A(^4P_{3/2})$ is very sensitive to the coupling and introduces a large uncertainty into the calculation of μ based upon $5s5p^4\,{}^4P$. We have been able to calculate μ from $^4P_{5/2}$ alone, assuming that in Te III the distance $p^4\,{}^1D_2 - p^4\,{}^3P_2$ is sufficiently large, as it is in neighboring elements, which yields $\mu^{125} = -0.94 \pm 0.14$ nm. Substituting this for the −0.5 from $5s5p^4(^4P_{5/2}$ and $^4P_{3/2})$ which was used as one of the four data originally contributing to the final -0.6 ± 0.2 nm for μ^{125}, we now obtain as our final values

$$\mathbf{u(Te^{125}) = -0.7 \pm 0.2 \text{ nm}}$$

and from the ratio shown in Table IV

$$\mathbf{u(Te^{123}) = -0.6 \pm 0.2 \text{ nm},}$$

and whereas our values calculated before discarding $A(^4P_{3/2})$ lay just outside the much more accurate values, more recently obtained by Dharmatti and Weaver [S. S. Dharmatti and H. E. Weaver, Jr., Phys. Rev. **84**, 843 (1951)]

$$\mu(\mathrm{Te})^{125} = -0.88235 \pm 0.00004 \text{ nm}$$
$$\mu(\mathrm{Te}^{123}) = -0.73188 \pm 0.00004 \text{ nm}$$
$$\mu(\mathrm{Te}^{125})/\mu(\mathrm{Te}^{123}) = 1.20560 \pm 0.00007,$$

the final values given here leave no essential disagreement.

components are also shown. When the isotope shift investigation was begun, all the 125 sample had been sputtered in the investigation of the hyperfine structure of 125, and natural tellurium had to be used instead of 125. This explains why the center of gravity of 125 components is located with inferior accuracy in Fig. 2. In the same figure the isotope shift in λ4049 is also shown. Within experimental error, the isotope shifts in λ4006 and λ4049 are quite the same. In heavy elements, isotope shifts in the terms arising from the configuration $5s5p^4$ should be nearly the same and insensitive to the J values in one and the same element. This expectation is in agreement with the observation.

The anomalously large shift at $A=124-126$ namely at $N=72-74$ (A is the atomic weight integer and N the neutron number) is quite conspicuous, and must be connected with the structure of nuclei with $N=72$ or $N=74$.

The classification of the Te II spectrum, which is important in interpreting the hfs, was put at our disposal before publication, by Professor J. E. Mack and Dr. J. C. van den Bosch. We appreciate the deep interest of Professor Mack in our work. One of us (K.M.) would like to express his appreciation to Professor Mack for making it possible to spend this past year at the University of Wisconsin.

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Proton Bremsstrahlung at 140 Mev*

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The high energy gamma-rays arising from 140-Mev proton bombardment of several elements has been studied using a scintillation counter telescope to detect secondary electrons. The angular distribution is consistent with an approximately isotropic distribution in the center-of-mass system if we assume the bremsstrahlung to come from p-n collisions inside the nucleus. This is in disagreement with a phenomenological potential treatment of the p-n force or the scalar-meson theory.

The form of the spectrum is found to be consistent with the $d\nu/\nu$ shape and the dependence on Z much as would be expected from an opaque nucleus with only the neutron contributing to the bremsstrahlung.

INTRODUCTION

HIGH energy radiation has been detected from cyclotron targets bombarded with protons and deuterons.[1] The energy of the bombarding particle was, in most cases, high enough so that most of the radiation can be attributed to the decay of neutral mesons; only in the case of bombardment by 180-Mev deuterons is this explanation implausible.

It is of interest to investigate the γ-radiation directly accompanying nuclear events in the target; this will result from the deceleration of the proton in a field of force, in a similar manner to the well-known electron bremsstrahlung; but in the present case, the force is the nuclear force between the neutron and the proton rather than the Coulomb force. Thus a study of the γ-radiation should throw light on the charcater of the p-n force. The radiation is expected to arise only from p-n collisions and not from p-p collisions: calculations have neen made for p-n collisions by Ashkin and Marshak[2] and by Simon.[3] Variations might be expected in the angular distribution and spectral shape of the γ-rays according to the form of nuclear interaction.

EXPERIMENTAL

A target was set up at 43-in. radius in the Rochester cyclotron, corresponding to a maximum energy of 145 Mev, in order to be below the threshold for neutral and charged π-meson production.[4] The energy is 5 Mev above the threshold for neutral meson production in a heavy element, such as uranium, but the contribution of the γ-rays from decay of the neutral particles is expected to be less than 1 percent in this case, and for the lighter elements even a big impurity of the heavy elements could not be a cause of the radiation.

Figure 1 is a plan view of the apparatus; a collimator in the fringing field removes all charged particles, leaving only γ-rays and neutrons, to enter the counters. The γ-rays are converted on a 1.0-mm Pb sheet placed in front of 4 scintillation crystals (anthracene or stilbene) in coincidence. Absorbers may be placed in front of the collimator to analyze the primary radiation, and absorbers between counters 3 and 4 analyze the range of the secondary particles from the radiator.

The four counters are connected in pairs to two fast (10^{-8} sec) coincidence circuits, modified from a design of Garwin.[5] The outputs of the two coincidence circuits are taken to a slow (2×10^{-7} sec) coincidence circuit.

The crystals are of different sizes, as shown in Fig. 2.

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[1] Bjorkland, Crandall, Moyer, and York, Phys. Rev. **77**, 213 (1950).
[2] J. Ashkin and R. E. Marshak, Phys. Rev. **76**, 58 (1949).
[3] A. Simon, Phys. Rev. **79**, 573 (1950).
[4] W. H. Barkas, Phys. Rev. **75**, 1109 (1949).
[5] R. L. Garwin, Rev. Sci. Instr. (1950).

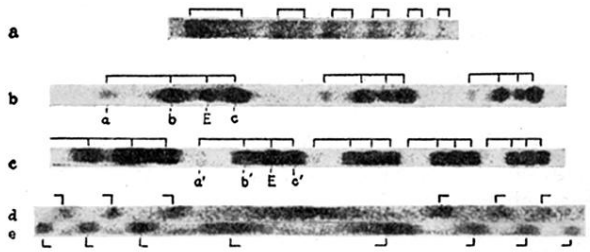

FIG. 1. (a) Te I λ2531. Isotope 125. 20-mm etalon. (b) Te II λ5449. Isotope 125. (Component *E* is due to even isotopes.) 6-mm etalon. (c) Te II λ5449. Isotope 123. (Component *E* is due to even isotopes.) 10-mm etalon. {(d) Te II λ4049. Isotope 122. (e) Te II λ4049. Isotope 130.} Taken on the same plate. 30-mm etalon.