Decay of Te^{125m} *

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The two-step isomeric transition in Te^{125m} has been studied with proportional counters in coincidence, a NaI crystal scintillation spectrometer and a thin lens beta-ray spectrometer. The following branching fractions were determined: 110-kev transition: K conversion $=0.54\pm0.01$, other conversion $=0.46$, unconverted gamma-ray $=0.0034\pm0.0005$; 35.5-kev transition: K conversion $=0.80\pm0.05$, L conversion $=0.11\pm0.02$, M conversion $=0.02\pm0.004$, unconverted gamma-ray $=0.07\pm0.02$.

These data are shown to confirm completely the level assignments in Te^{125} as $s_{1/2}$, $d_{3/2}$, and $h_{11/2}$. In addition, comparison with theoretical conversion coefficients show an agreement between experiment and extrapolated theoretical values. The second transition (35.5 kev) is almost entirely magnetic dipole; an upper limit of about 1 percent can be placed on the electric quadrupole admixture.

INTRODUCTION

THE 58-day isomer,[1] Te^{125m}, decays by two successive transitions. The first radiation emitted is a highly converted 109.7-kev gamma-ray.[2] The second transition has an energy of 35.5 kev[3] and follows the 110-kev transition with a delay of less than 4×10^{-9} sec.[4]

This paper reports the relative amounts of conversion electrons and unconverted gamma-rays for each of these transitions. The quantitative results are included in the decay scheme shown in Fig. 1. The different experimental techniques which were used to determine the branching ratios, are summarized in the following two paragraphs.

Two measurements were made to study the 110-kev gamma-rays: (1) A NaI crystal scintillation spectrometer was used to find the ratio of the number of unconverted 110-kev gamma-rays to the total number of K x-rays. (2) The fraction of 110-kev transitions which emits K conversion electrons was found by observing the electron spectrum both in a proportional counter and in a thin lens beta-ray spectrometer.

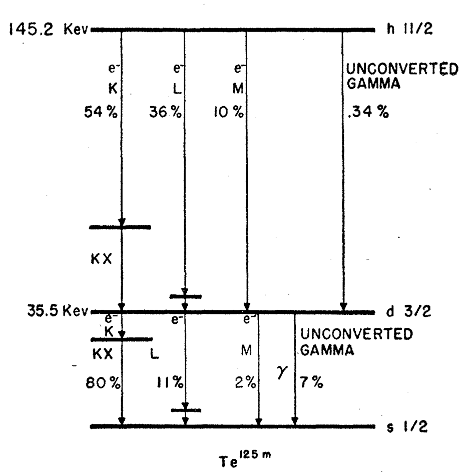

FIG. 1. Decay scheme of Te^{125m}.

Three measurements were used to establish the branching of the 35.5-kev transition: (1) The fraction of these transitions that are K converted was determined from x-x and x-35.5-kev gamma-coincidence data. The coincidences were measured by using two proportional counters as detectors. (2) The numbers of L and M conversion electrons were found from the electron spectrum taken with the lens spectrometer. (3) The number of unconverted 35.5-kev gamma-rays was derived from the photon spectrum taken with a proportional counter.

SOURCE AND EQUIPMENT

The Te^{125m} was provided by the Isotopes Division of the Atomic Energy Commission at Oak Ridge. The Te had been chemically separated from Sb^{125} and was shipped in solution. Despite this, it was not possible to obtain very thin sources since there was a considerable amount of inactive material present when the solution was evaporated.

The scintillation spectrometer consisted of a 16-mm thick NaI crystal and an RCA 5819 phototube. The pulses from the phototube were amplified linearly and then analyzed with a single channel, pulse-height selector. This selector used two vacuum diodes as discriminators and a 6AS6 for an anticoincidence tube. The noise from both the phototube and the amplifier was negligible above 6 kev.

The double thin lens beta-ray spectrometer had a resolution of about 2.2 percent and a transmission of about 1 percent. A Geiger-counter detector was used with amyl acetate vapor filling; Nylon windows of 50 and 150 mg/cm² were used.

Two identical proportional counters were made from 6-inch diameter brass tubing. A 175 mg/cm² circular beryllium window 1 inch in diameter permitted photons

* Assisted by the joint program of the ONR and AEC.
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[1] Friedlander, Goldhaber, and Scharff-Goldhaber, Phys. Rev. **74**, 981 (1948).
[2] Hill, Scharff-Goldhaber, and Friedlander, Phys. Rev. **75**, 324 (1949).
[3] R. D. Hill, Phys. Rev. **76**, 333 (1949).
[4] F. K. McGowan, Oak Ridge National Laboratory Report 952, unpublished.

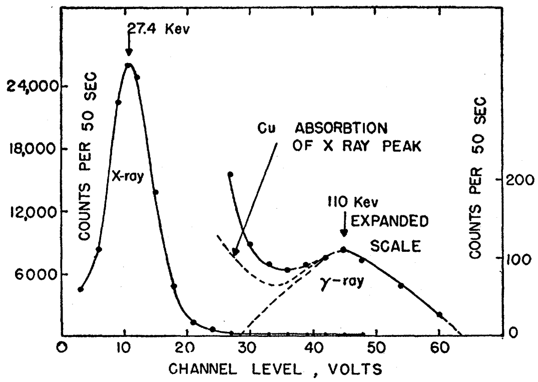

FIG. 2. Photon spectrum, NaI crystal detector. Expanded scale on right applies to gamma-ray. Partial absorption of x-ray by Cu shown by dashed curve. *Note added in proof.*—The expanded scale on the right of Fig. 2 is in error; the number of counts should be one-half of the values listed. This error was pointed out by Dr. A. W. Sunyar.

to enter with a minimum of attenuation. Each counter was 20 inches long and contained 9.2 liters of a mixture of 90 percent argon and 10 percent methane at atmospheric pressure. The counters were operated with a battery voltage of 2500 v on the 4-mil central wire, corresponding to a gas multiplication of about 1000.

The counter voltage pulses were amplified by a factor of 7000 by means of a non-overloading linear amplifier with a rise time of 0.8 μsec and a clipping time of 4 μsec. The amplified pulses were sorted by single channel pulse-height selectors; the output of each selector was a blocking oscillator pulse which activated the coincidence circuit. The coincidence circuit had four independent channels each of which had a different adjustable delay and an adjustable resolving time.[5] The multichannel delay feature constantly showed that the resolving time was sufficiently large to detect all true coincidences. With a resolving time of 1.85 μsec, the first three channels (0, 0.25, and 0.60 μsec delays) always counted the same number of coincidence pulses; the fourth channel was delayed by 1.70 μsec and it recorded fewer coincidence events.

CONVERSION OF 110-KEV GAMMA-RAY

The photon distribution observed with a NaI scintillation spectrometer is shown in Fig. 2. The expanded intensity scale on the right is necessary to show the weak unconverted 110-kev gamma-ray. The detection of this unconverted gamma-ray had not been reported by earlier investigators. Copper absorption curves were taken to ascertain the contribution to the gamma-ray peak made by pulses from the high energy tail of the x-ray distribution. The effect of a thin copper absorber is shown by the dashed curve on the expanded scale. The absorption measurements showed that the x-ray contribution to the upper half of the gamma-ray peak was negligible. Therefore, the relative intensity was determined by comparing the areas of only the upper half of each peak. It was assumed that all of the impinging gamma-rays contribute to the photoelectric peak. Although 9 percent of the gamma-rays undergo a primary Compton process, it is reasonable to expect the crystal to detect almost all of the secondary gamma-rays.

The ratio of the counts due to x-rays to those due to gamma-rays was found to be 320 ± 20. From experiments described below it was found that the fraction of 110-kev and 35.5-kev transitions which decay by K conversion are 0.54 and 0.80, respectively. Using these figures and an x-ray fluorescent yield of 0.82,[6] the K conversion coefficient of the 110-kev transition is 160 ± 20.

110 KEV K TO $(L+M)$ RATIO

The ratio of the K to $(L+M)$ conversion was determined from electron-spectra taken both in a proportional counter and in the lens spectrometer. The proportional counter data, which was taken with a thin internal source, gave a ratio of 1.15 ± 0.08. The lens spectrometer data shown in Fig. 3 gave a K to $(L+M)$ ratio of 1.15 ± 0.05. These results are in excellent agreement with those of previous investigators: 1.17,[2] 1.2[7] and 1.10.[8] This K to $(L+M)$ ratio of 1.15 and the very low intensity of the unconverted gamma-ray indicate that 54 percent of the 110-kev transitions are K converted.

The separation of the L and M conversion electrons has been reported only by Hill *et al.*;[2] they give the L to M ratio as 3.5.

K CONVERSION OF THE 35.5-KEV GAMMA-RAY

The most direct determination of the fraction of 35.5-kev transitions which were K converted involved an

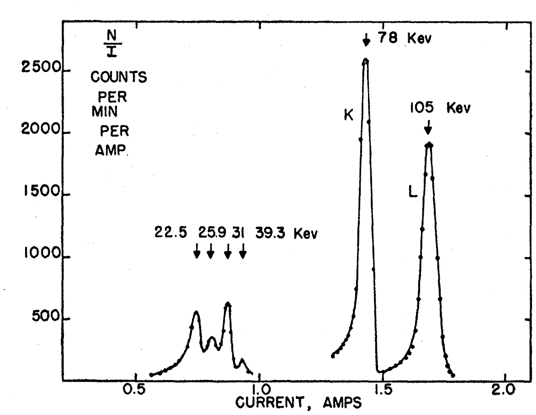

FIG. 3. Electron spectrum taken with lens spectrometer. The 78- and 105-kev lines are due to K and $(L+M)$ conversion electrons from the 110-kev gamma-ray.

[5] We wish to thank Dr. Sherman Frankel of the University of Pennsylvania, who designed and tested the pulse-height selector and the multichannel coincidence circuit.

[6] H. Tellez-Plasencia, J. phys. et radium **10**, 14 (1949); Steffen, Huber, and Humbel, Helv. Phys. Acta **22**, 167 (1949).
[7] Kern, Mitchell, and Zaffarano, Phys. Rev. **76**, 94 (1949).
[8] Siegbahn and Forsling, Ark. Fys. Bd. 1 **No. 24**, 505 (1949).

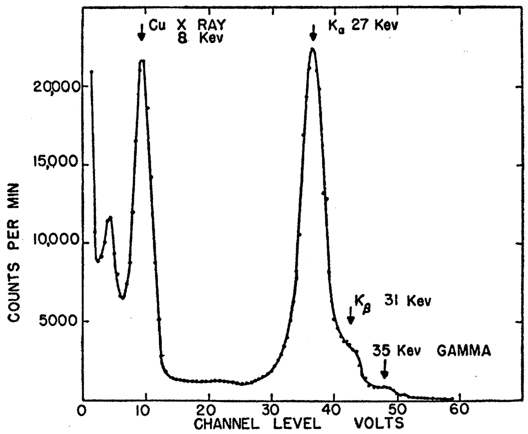

FIG. 4. Photon spectrum, proportional counter detector. The Cu x-ray originates in the counter wall.

analysis of the photon-photon coincidences. The K conversion electrons had too low an energy to be detected conveniently.

Each of the proportional counters was placed with its Be window facing the source. The geometry and detection efficiency of each counter were such that about 1.5 percent of the emitted Te K-x-rays gave pulses in the x-ray peak of the spectrum. Figure 4 shows a typical spectrum obtained with a proportional counter and its pulse-height selector. In addition to the Te K x-rays and the 35.5-kev gamma-ray, the spectrum shows the Te L x-ray and the fluorescent Cu x-ray originating in the counter wall.

During the coincidence measurements, one of the pulse-height selectors was constantly sensitive only to pulses contributing to the lower half of the Te K x-ray peak. The other selector accepted pulses in a three volt channel which had an adjustable level. As this channel level was varied over the x-ray peak x-x coincidences were recorded; when the variable channel level was increased it became sensitive to the 35.5-kev gamma-ray, and x-γ coincidences were detected. The experimental data from a typical coincidence run are shown in the lower half of Fig. 5.

The analysis of these coincidence data is based on the number of coincidences per single count recorded in the variable channel. This ratio is a direct measure of the probability of detecting a coincident event in the fixed channel for each event recorded in the variable channel. Thus, the x-γ coincidence rate per 35.5-kev gamma-ray is a measure of the probability that a K x-ray was emitted during the 110-kev transition preceding the low energy gamma-emission. Similarly the x-x coincidence rate per x-ray is a measure of the probability that a K x-ray was emitted in coincidence with the K x-ray detected in the variable channel level. The number of coincidences per single is plotted in the upper portion of Fig. 5. Since the x-x coincidences per x-ray exceed the x-γ coincidences per gamma-ray, there must be more x-rays associated with the low energy transition than with the 110-kev transition.

Quantitatively, if a_1 and a_2 are the fractions of K conversions in the first (110 kev) and second transitions, respectively,

$$\frac{N_{xx}/N_x}{N_{x\gamma}/N_\gamma}=\frac{2}{1+a_1/a_2}.$$

The experimental value for this fraction was determined as 1.16 ± 0.06. Using the value given above for the fraction of 110-kev transitions which are K converted, $a_1=0.54$; therefore, the fraction of 35.5 kev transitions which are K converted is $a_2=0.75\pm0.09$. This experimental result is a quantitative extension of the earlier qualitative coincidence experiments of Bowe and Goldhaber.[9]

BRANCHING OF 35.5-KEV TRANSITION

A more precise value of the K conversion coefficient can be derived from this preliminary value together with measurements of the other modes of decay. The $L+M$ conversion can be deduced from the ratio of $L+M$ electrons to the Auger electrons. A typical set of lens spectrometer data on these low energy electrons is shown in Fig. 6. After these data are corrected for source and window absorption the ratio is found to be 0.52 ± 0.08. The assigned error includes allowance for uncertainty in the correction factors. From the K conversion results described above and the known fluorescent yield the number of Auger electrons per disintegration is established as 0.23 ± 0.02. These results combine to show that $L+M$ conversion occurs in 13 ± 2 percent of the 35.5-kev transitions.

The number of unconverted gamma-rays was determined from the proportional counter photon spectrum shown in Fig. 7. The ratio of pulses in the $K\alpha$ x-ray

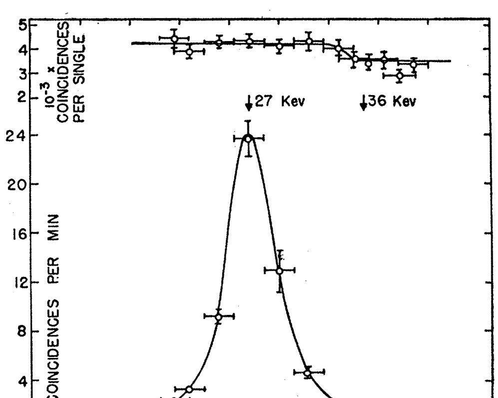

FIG. 5. Photon-photon coincidences. The channel level of one proportional counter is the abscissa. The selector of the other proportional counter detected one-half of the x-ray pulses.

[9] J. C. Bowe and G. Scharff-Goldhaber, Phys. Rev. **76**, 437 (1949).

peak to those in the gamma-ray peak was measured as 29; the $K\beta$ x-ray to 35.5-kev ratio was 3. When these values are corrected for relative efficiencies in argon and for the fluorescent yield, the ratio of all K conversion to the number of 35.5-kev gamma-rays is 20 ± 4. The large uncertainty in this value is mainly because of the uncertainty of the shapes of the individual overlapping peaks. This value is consistent with the value of 17 determined by Friedlander *et al.*[10] The K conversion data indicate that the fraction of the K x-rays originating from the 35.5-kev transition is 0.58 ± 0.03. The 35.5-kev K conversion coefficient is therefore 58 percent of 20 or 11.6 ± 2.5. This in turn implies a 7 ± 2 percent branch of unconverted gamma-ray.

A combination of all of these results gives a more precise value for the K branch; the final branching values are: K conversion $=0.80\pm0.05$; L conversion $=0.11\pm0.02$; M conversion $=0.02\pm0.004$ and unconverted gamma $=0.07\pm0.02$. The indicated accuracy includes a liberal estimate of possible systematic errors.

COMPARISON OF RESULTS WITH THEORY

The spin of the ground state of Te^{125} is known to be $\frac{1}{2}$.[11] The assignments of the spins and parities to the other levels of Te^{125} had been suggested by earlier investigators.[3,9] These assignments were given almost irrefutable support by the classification of nuclear isomers made by Goldhaber and Sunyar.[12] Their classification emphasizes the agreement between shell structure, empirical K/L ratios and the theory of transition rates, particularly for magnetic 2^4 pole ($M4$) radiation.

The data which were determined in this experiment do more than simply add proof to this well-established aspect of isomer classification. These data give information both about internal conversion coefficients where the theory has been previously unchecked and about the $M1$ character of the radiation between the $d_{\frac{3}{2}}$ and the $s_{\frac{1}{2}}$ levels.

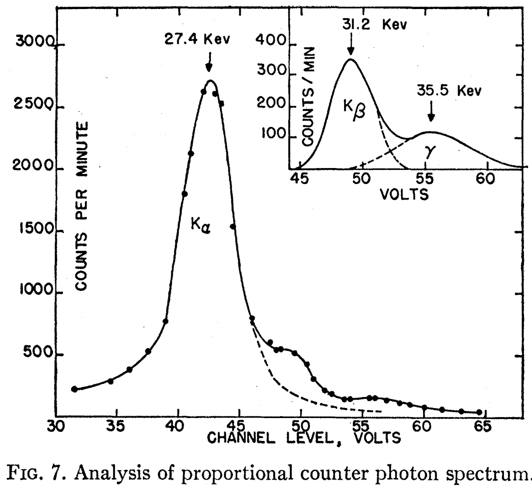

FIG. 7. Analysis of proportional counter photon spectrum.

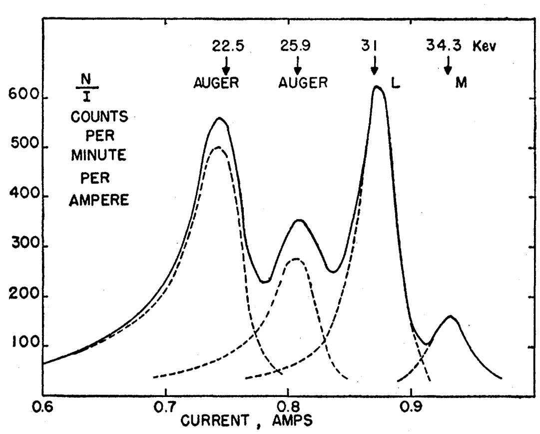

FIG. 6. Low energy electron spectrum taken with lens spectrometer. Dashed curves show the contributions of the four electron groups.

In order to compare experimental conversion coefficients with theory, it is necessary to use five different sources of theoretical calculations. Each of these sources has limitations. (1) Rose *et al.*[13] have calculated K conversion coefficients relativistically for all multipolarities but only for energies above 150 kev. In order to apply these to the energies in Te^{125} a logarithmic extrapolation was made to energies below this value. (2) Hebb and Nelson[14] have made nonrelativistic calculations of K and L conversion coefficients but only for electric type transitions. They used the formula derived by Dancoff and Morrison[15] for K conversion and derived an analogous formula for L conversion. These calculations do not appear to be very inaccurate for low energies.[16] (3) Axel and Goodrich[16] extrapolated the results of Rose *et al.*, to very low energies for magnetic radiation by using the approximate calculations of Drell.[17] The extrapolation procedure is quite questionable. (4) Reitz[18] has calculated $E1$, $E2$ and $M1$ conversion coefficients for $Z=49$ (as well as $Z=84$ and $Z=92$) for low energies. These calculations are very accurate (about 1 percent) and include both relativistic and screening effects. However, the Z dependence might require of the order of a 30 percent increase in Reitz's $Z=49$ value to make it applicable to Te ($Z=52$). In the results quoted below, no attempt is made to correct for this unknown Z dependence. (5) Gellman, Griffith, and Stanley[19] have made accurate relativistic

[10] Friedlander, Perlman, and Scharff-Goldhaber, Phys. Rev. **80**, 1103 (1950).
[11] G. R. Fowles, Phys. Rev. **78**, 744 (1950).
[12] M. Goldhaber and A. W. Sunyar, Phys. Rev. **83**, 906 (1951).
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[14] M. H. Hebb and E. Nelson, Phys. Rev. **58**, 486 (1940).
[15] S. M. Dancoff and P. Morrison, Phys. Rev. **55**, 122 (1939).
[16] P. Axel and R. F. Goodrich, Technical Report on Internal Conversion, University of Illinois, unpublished.
[17] S. D. Drell, Phys. Rev. **75**, 132 (1949).
[18] J. R. Reitz, Phys. Rev. **77**, 10 (1950).
[19] Gellman, Griffith, and Stanley, Phys. Rev. **80**, 866 (1950).

TABLE I. Conversion coefficients for 110-kev gamma-ray.

Radiation type	Theoretical K shell Hebb and Nelson[a]	Rose[b] *et al.* (extrapolated)	K/L ratio Hebb and Nelson[a]
$E4$	24.7	27	0.49
$E5$	134	140	0.20
$M3$		26	
$M4$		190	
$M5$		1100	
Experimental			
	160 ± 20		1.15 ± 0.08

[a] See reference 14. [b] See reference 13.

TABLE II. Conversion coefficients for 35.5-kev gamma-ray.

Radiation type	Theoretical K shell Hebb and Nelson	Reitz (for $Z=49$)	Axel and Goodrich	L shell Hebb and Nelson	Gellman *et al.* (L_I subshell only)
$E1$	2.8	3.1		0.4	0.4
$E2$	17	21		35	2.0
$E3$	38			2900	
$M1$		10	8		1.45
$M2$			190		
Experimental					
	11.7 ± 2.5			$1.6^{+1.2}_{-0.7}$	

calculations for $E1$, $E2$, and $M1$ conversion coefficients for $Z=49$ and only for the L_I subshell. These calculations did not take screening into account but this neglect probably tends to compensate for the unknown Z dependence.

The comparison of the experimental conversion coefficient with theory for the 110-kev gamma-ray is shown in Table I. The conversion coefficient restricts the possible multipolarities to $E5$ and $M4$. However, the lifetime energy relationship and the K to L ratio both eliminate the $E5$ possibility.[12] (The empirical lifetime energy relationship of Goldhaber and Sunyar is strongly supported by the transition rate formulas published by Moszkowski[20] and by Weisskopf.[21])

The conversion coefficient of 160 is the highest to have been reported experimentally. Since the theoretical $M4$ value is an extrapolation, the slight discrepancy between experiment and theory is negligible. It is, in fact, gratifying to find the degree of agreement that does exist and it can be concluded that extrapolations into this energy range introduce only slight errors.

The theoretical values of the conversion of the 35.5-kev gamma-ray are shown in Table II. The K conversion coefficient indicates a preference for $M1$ radiation. Reitz's theoretical values require some upward correction due to the Z dependence. From the experimental results it can be concluded that this correction is less than 50 percent and, therefore, in the expected range.

The L conversion coefficients are more sensitive to electric quadrupole ($E2$) admixture. From the L_I subshell results alone it seems that $M1$ and $E2$ transitions have comparable conversion. However, the $E2$ result of Hebb and Nelson should be accurate. In addition, when the Hebb and Nelson result is separated into subshells,[22] the L_I value is quite close to the value given by Gellman *et al.* It is thus reasonable to conclude that the L_I shell contributes only of the order of 6 percent to the $E2$ conversion. On the other hand, the L_I subshell might well contribute the major share to $M1$ conversion. This is supported by the agreement in the $E1$ transitions and by an analogous case[23] in Sn^{119} where only L_I conversion has been observed by Hill.[24] This is further supported by Mihelich and Church[25] who also find that $M1$ conversion is predominantly due to L_I subshell while $E2$ conversion comes mainly from the L_{II} and L_{III} subshells.

The value of the experimental L conversion coefficient indicates that the L_I contribution is predominant in this case (unless the theory contains gross errors). In addition, if the listed, theoretical values are accepted, the greatest amount of allowable $E2$ admixture would be less than one percent.

We wish to thank Mr. Robert Baer for his assistance in taking and analyzing some of the experimental data. We are also indebted to Dr. Sherman Frankel of the University of Pennsylvania for discussions and aid pertaining particularly to electronic problems.

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[21] V. F. Weisskopf, Phys. Rev. **83**, 1073 (1951).
[22] R. F. Goodrich (private communication).
[23] J. C. Bowe and P. Axel, Phys. Rev. **84**, 939 (1951).
[24] R. D. Hill, Phys. Rev. **83**, 865 (1951).
[25] J. W. Mihelich and E. L. Church, Bull. Am. Phys. Soc. **26**, No. 6, 37 (1951).