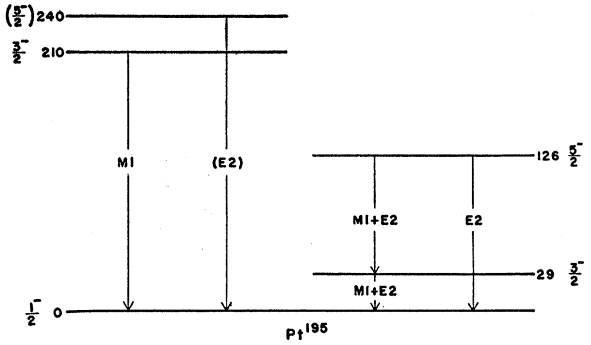

FIG. 9. Level diagram of Pt^{195}, showing transitions observed in electric excitation.

tive but both Au^{197} and Pt^{195} seem to be consistent with such a picture. Using the measured[20] conversion coefficients for the 97-kev transition in Pt and assuming that the 126-kev level cascades 90% of the time, we find $B_{ex}(E2)$ $126=0.5_{-0.3}{}^{+0.1}$ and $B_d(E2)=0.16$. Thus, the reduced $E2$ transition probability for decay of the 126-kev level is much larger than the value to be expected for a single-neutron transition, and of the same order as the enhanced single-proton $E2$ transition probabilities in Au^{197}. This is, of course, to be expected if the major contribution to the transition probability is due to the induced motion of the nuclear surface.[18,19] The enhancement of $E2$ transition probabilities for single neutron transitions has also been observed[6] in Pb^{206} and Pb^{207}.

The writers wish to thank Dr. L. W. Nordheim and Dr. R. M. Williamson for helpful discussions and other members of the nuclear physics group for aid in taking data. We would like to thank also Mr. Fred Egli and Mr. Robert Rummel for assistance in constructing the electronic equipment.

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Angular Correlation Measurements in Te^{121} and Te^{123}†

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Measurements of the angular correlation of the two-step transition in Te^{121} and Te^{123} have been made using a thin Te source ($<1\mu g/cm^2$). K conversion electron-gamma, L conversion electron-gamma and K conversion-K conversion cascades were investigated in both isomers using a thin lens beta spectrometer as the fixed detector and scintillation counters for the movable detector. The measured correlation was found to be of the form $1+A_2P_2(\cos\theta)$ in agreement with the theoretically predicted angular correlation for the known spin sequence in the tellurium isomers ($11/2\rightarrow3/2\rightarrow1/2$). The measured values of A_2 corrected for geometry are -0.097 ± 0.004, -0.092 ± 0.009, -0.06 ± 0.03 for the K-γ, L-γ, and K-K cascades respectively in Te^{123} and -0.015 ± 0.007, -0.007 ± 0.007, and -0.10 ± 0.04 for the same cascades in Te^{121}. Comparison of the results of the K-γ cascades with theory shows that the second transition is a mixture of (1.3 ± 0.1) percent $E2$ and 98.7 percent $M1$ in Te^{123} and (5.6 ± 0.5) percent $E2$ and 94.4 percent $M1$ in Te^{121}. The ratio of reduced matrix elements is plus in both cases using the Biedenharn and Rose notation. The results for the K-K angular correlation are consistent with the K-γ correlations and are used to prove that the correlations, which are smaller than the $M4-M1$ correlation, cannot result from reduction of the $M4-M1$ correlation by the action of extra-nuclear fields.

I. INTRODUCTION

THE radiations from isomeric Te^{121} and Te^{123} have been studied by many investigators.[1] The decay schemes shown in Fig. 1 are well established. Measurement of the K conversion coefficient[2,3] and K/L ratio[2] show that the second transition in both isomers is predominantly $M1$ although a small admixture of $E2$ cannot be excluded. The measurement of the directional correlation of the two-step transition is a sensitive method of determining the amount of this admixture. Preliminary measurements of the K conversion electron-gamma directional correlation in both isomers have been reported previously.[4] This paper describes additional correlation work on these isomers and presents details of the various measurements.

II. SOURCE PREPARATION

The mixed Te^{121} and Te^{123} activity was made via the $(d,2n)$ reaction by cyclotron irradiation of naturally occurring antimony with 15-Mev deuterons. The high specific-activity source required for this experiment to avoid scattering of the low-energy electrons was pre-

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* Now with the Physics Department, Washington University, St. Louis, Missouri.
[1] See Hollander, Perlman, and Seaborg, Revs. Modern Phys. 25, 469 (1953) for a list of references.
[2] Katz, Hill, and Goldhaber, Phys. Rev. 78, 9 (1950).
[3] F. K. McGowan. Phys. Rev. 93, 163 (1954).
[4] N. Goldberg and S. Frankel, Phys. Rev. 93, 1425 (1954).

pared by the following procedure[5]: One gram of the bombarded antimony and 1 mg of tellurium-free selenium were dissolved in aqua regia, heated to dryness, and then redissolved in $3N$ HCl. Both the selenium and the radioactive tellurium were precipitated by bubbling SO_2 through the solution. The selenium acts as a carrier which eliminates the necessity of adding Te carrier in this step. The precipitate is now dissolved in the smallest possible quantity of $12N$ HCl (about 5 ml). One microgram of Te, which had been dissolved in aqua regia, heated to dryness, and then redissolved in $12N$ HCl, was added as a carrier. This very small amount suffices because we have only a very small amount of material at this point, the great bulk of material being removed in the first separation. SO_2 is again bubbled through the solution. Only Se is precipitated with $12N$ HCl, the Te remaining in solution. By this method a source of 100 μcuries activity having a mass of 1 μg was prepared.

The Te was vacuum evaporated from a small pyrex oven onto a thin formvar film (<9 μg/cm^2) which had been coated with either aluminum or silver conducting layers (<4 μg/cm^2). The thickness of the source material itself was less than 1 μg/cm^2.

III. APPARATUS AND MEASUREMENTS

In each of the cascades studied conversion electrons were the detected radiation in at least one of the transitions. A thin-lens beta spectrometer was employed in order to separate the conversion electrons of Te^{121} and Te^{123} unambiguously. A scintillation counter using a terphenyl crystal and an E. M. I. photomultiplier tube was used for the detection of the electrons. An electron spectrum taken with the lens spectrometer is shown in Fig. 2. A comparison of the shape of the low- and high-energy electron lines shows that inelastic scattering is completely negligible.

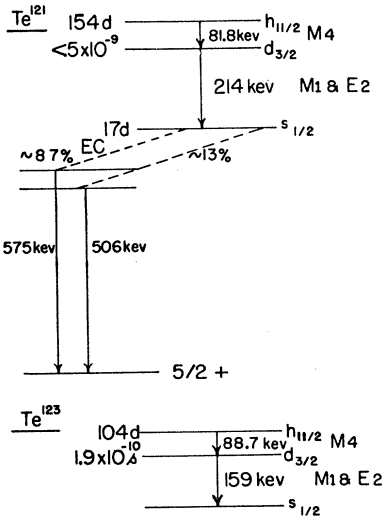

FIG. 1. Decay schemes of Te^{121} and Te^{123}.

[5] We are indebted to Dr. G. Friedlander, Brookhaven National Laboratory, who suggested this method.

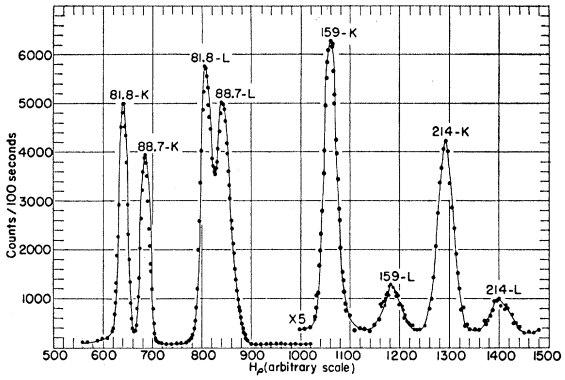

FIG. 2. Conversion electron spectrum of Te^{121} and Te^{123}.

Electron-Gamma Cascades

A scintillation counter consisting of a thallium-activated NaI crystal mounted on an RCA 5819 photomultiplier was used to detect the gamma ray from the second transition. The source chamber used in these measurements was made of Lucite to minimize the absorption and scattering of the gamma rays. A diagram of the source chamber, which is mounted on the lens spectrometer and is a part of the vacuum system of that instrument, and the phototube used to detect the gamma rays is shown in Fig. 3. A gamma spectrum taken with a single-channel pulse-height selector is shown in Fig. 4. The peak at 80 volts is due to gamma rays in Sb^{121} not in coincidence with the two-step cascade in Te^{121}. There is no evidence of the 82- and 88-kev transitions in the gamma spectrum because they are very highly converted.

The electronic components of the two counting channels and the coincidence circuit were of conventional design. The resolving time of the four-channel coincidence circuit was 0.2 microsecond. The accidental coincidence rate was less than 5 percent of the total coincidence rate in all the cascades measured.

In measuring the K electron-gamma cascade in Te^{123}, the lens spectrometer was set on the K conversion electron peak of the 89-kev transition while the gamma detector discriminator level was set below the full-energy peak due to the 159-kev gamma as indicated in Fig. 4. Enough coincidences were collected at the 90°, 120°, 135°, 150°, and 180° positions of the movable gamma detector to confirm that the correlation was of the form $1+A_2P_2(\cos\theta)$. The remainder of the data was collected at the 90° and 180° positions only.

To check the possibility that the anisotropy was sensitive to the backing material, this cascade was measured with two different sources, one with silver, the other with an aluminum conducting layer. The anisotropy was also measured with the source reversed so that the detected electrons went through the backing

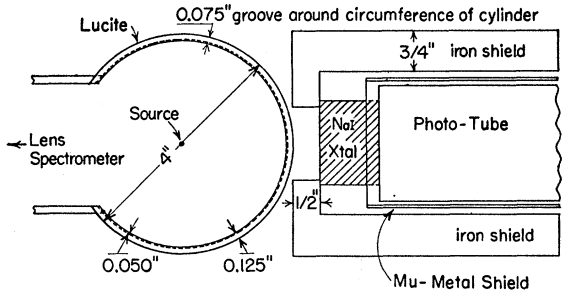

FIG. 3. Source chamber and gamma detector. Thickness of Lucite between source and NaI crystal is 0.050 in.

material. The attenuation of the anisotropy due to the scattering of the electrons by this amount of material was estimated[6] to be less than 1 percent. The results of these measurements are shown in Table I in terms of A which is defined as $[W(\pi)/W(\pi/2)]-1$, where $W(\pi)$ and $W(\pi/2)$ are the true coincidence rates at the π and $\pi/2$ positions of the movable counter respectively, normalized with the product of the singles rates in each detector. These results are consistent with the scattering calculations and the assumption that the anisotropy is independent of the backing material.

Measurements of the K electron-gamma cascades in Te^{121} were made by setting the lens spectrometer to detect the K electrons from the 82-kev transition and fixing the discriminator level of the gamma detector as indicated in Fig. 4, by the arrow marked Te^{121}.

The measurements of the L electron-gamma cascade were made in an exactly analogous manner except that the lens spectrometer current was set to detect L instead of K conversion electrons.

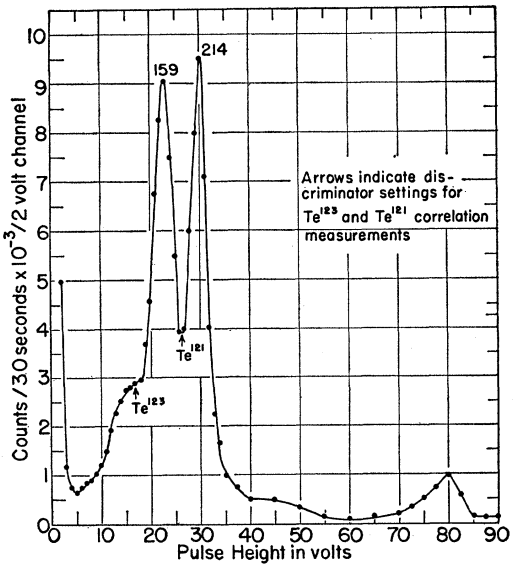

FIG. 4. Gamma-ray spectrum of Te^{121} and Te^{123}.

[6] S. Frankel, Phys. Rev. 83, 673 (1951).

K Electron–K Electron Cascades

A diagram of the source chamber used for these measurements is shown in Fig. 5. A scintillation counter consisting of $\frac{1}{16}$ in. thick terphenyl crystal and a 6292 Dumont photomultiplier was employed to detect the conversion electrons from the first transition. The crystals are mounted inside the source chamber, which is open to the vacuum system of the lens spectrometer, in order to avoid absorption and scattering of the electrons by air and the chamber walls. These crystals are fixed at angles of 90°, 135°, and 180° with the axis of the spectrometer. Thus the movable counter was not continuously variable. Light from the crystal was transmitted to the photomultiplier outside the source chamber by a $\frac{3}{8}$ in. long Lucite light pipe. A shield, not shown in the diagram, could be manipulated from outside the vacuum through an O-ring seal to cover the two crystals not being used. A pulse-height spectrum made with this detector is shown in Fig. 6. In order to measure the coincidence rate for K electrons only, the output of this detector was fed into two separate coincidence circuits. The discriminator level on one was set so that both K and L electrons were counted; the other accepted only the higher-energy L electrons.

TABLE I. Anisotropy of the K electron–gamma cascade in Te^{123} under various conditions.

Experimental condition	$A=[W(\pi)/W(\pi/2)]-1$
Aluminum backing	-0.132 ± 0.006
Silver backing	-0.143 ± 0.020
Source reversed	-0.140 ± 0.017

The discriminator positions are shown by arrows in Fig. 6. Two separate circuits, counting simultaneously, detected coincidences of these pulses with the output of the lens spectrometer which was set to detect K electrons from the second transition, i.e., the 214-kev transition when measuring the Te^{121} cascade and the 159-kev transition for the Te^{123} cascade. The difference of the coincidence rates in the two channels was due to the K electron–K electron cascade. From the spectrum in Fig. 6, it is clear that by biasing one electron detector in the valley above the slight K-electron peak complete elimination of L electrons cannot be obtained, although analysis of the spectrum shows that this number is small. The presence of L electrons would not appreciably affect the correlation since our L-gamma angular correlation in Te^{123} shows that the K-gamma and L-gamma correlations are the same within ±10 percent.

Values of A_2, the coefficient of the $P_2(\cos\theta)$ term in the angular distribution, were determined for each cascade and are displayed in Table II. These results have been corrected for the finite solid angle of the detectors.[6] Corrections for the finite size of the source[7] are negligible.

[7] A. M. Feingold and S. Frankel, Phys. Rev. 97, 1025 (1955).

IV. INTERPRETATION AND DISCUSSION

The angular correlation for all of the tellurium cascades is of the form

$$W(\theta)=1+A_2P_2(\cos\theta).$$

If one of the transitions is not a pure multipole, e.g., a mixture of $M1$ and $E2$, the A_2 is a function of β where

$$\frac{\beta^2}{1-\beta^2}=\frac{\text{intensity } E2\ \gamma/\text{ray}}{\text{intensity } M1\ \gamma\text{-ray}}. \quad (1)$$

It has been shown that β is a real number,[8] but that it can have either a positive or negative sign. In addition, if one of the transitions is detected via the conversion electrons instead of by the gamma ray, the A_2's are changed from their values for a gamma-gamma cascade. Rose, Biedenharn, and Arfken[9] have given the coefficients when the gamma rays are replaced by K conversion electrons. If the transition in which the K conversion electron is detected is a pure multipole, the coefficient is found by multiplying the coefficient for the gamma-gamma case by a parameter. $A_2(e-\gamma)=b_2(e^-)A_2(\gamma-\gamma)$. The parameter $b_2(e^-)$ does not depend on β^2 if the other transition is a mixture of multipoles. However, if the transition in which the electron is detected is not a pure multipole, the functional dependence of the A_2 on β is changed. Tables for finding the A's for all of these cases appear in the review paper of Biedenharn and Rose.[10] Figure 7 shows the dependence of A_2 on β for the K electron–gamma (mixed) and K electron–K electron (mixed) cascades in Te^{121} and Te^{123}.

TABLE II. Experimental values of angular correlation coefficient A_2 corrected for finite solid angle of detectors.

Isomer	Cascade	A_2
121	$Ke^--\gamma$	-0.015 ± 0.007
121	$Le^--\gamma$	-0.007 ± 0.007
121	Ke^--Ke^-	$-0.10\ \pm0.04$
123	$Ke^--\gamma$	-0.097 ± 0.004
123	$Le^--\gamma$	-0.092 ± 0.009
123	Ke^--Ke^-	$-0.06\ \pm0.03$

It is interesting to note that the measurement of both the electron-gamma (mixed) and electron-electron (mixed) correlations enables one to determine, in addition to the mixing ratio, β, that most elusive quantity, the attenuation of the correlation due to extra nuclear fields. This attenuation can be caused by a number of different factors.[11] The attenuation cannot be determined when electron-gamma (mixed) and gamma-gamma (mixed) correlations are measured in the same isomer. This can be seen as follows: we let g ($g=1$ indicates no attentuation) be the attenuation factor; then the experimentally measured quantities in the three cases are

$$A_2(\gamma-\gamma \text{ mixed})=g_2f_2(\beta),$$
$$A_2(e-\gamma \text{ mixed})=g_2b_2f_2(\beta),$$
$$A_2(e-e \text{ mixed})=g_2b_2h_2(\beta), \quad (2)$$

where f and h are two different functions of β which are known from the theory. The measurement of the first two yields only the product of $g_2f_2(\beta)$ and an experimental value of b_2 which is also known theoretically. Thus β^2 can be determined only if g is known. However, measurement of the last two cascades leads to a unique value of both β and g. This is due of course to the fact that the functional dependence of the coefficient on β is different in the two cases.

The large uncertainty in our measured A_2's for the electron-electron cascades prevents an accurate deter-

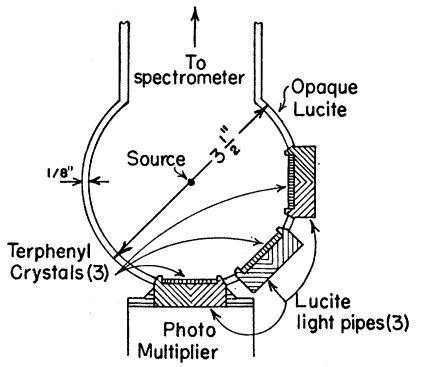

FIG. 5. Source chamber for e–e correlation measurements.

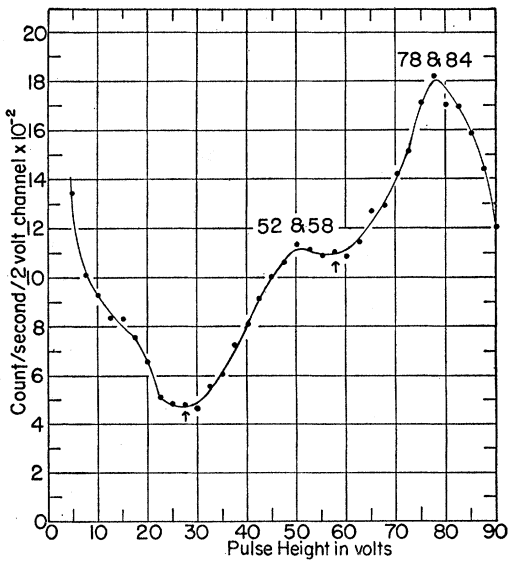

FIG. 6. Pulse-height spectrum of low-energy conversion electrons in Te^{121} and Te^{123} using terphenyl scintillation detector. The arrows indicate the settings of the two discriminator circuits.

[8] S. P. Lloyd, Phys. Rev. **81**, 161 (1951).
[9] Rose, Biedenharn, and Arfken, Phys. Rev. **85**, 5 (1952).
[10] L. C. Biedenharn and M. E. Rose, Revs. Modern Phys. **25**, 729 (1953).
[11] H. Frauenfelder in *Beta and Gamma Ray Spectroscopy*, edited by Kai Siegbahn (North-Holland Publishing Company, Amsterdam, 1955), Chap. XIX.

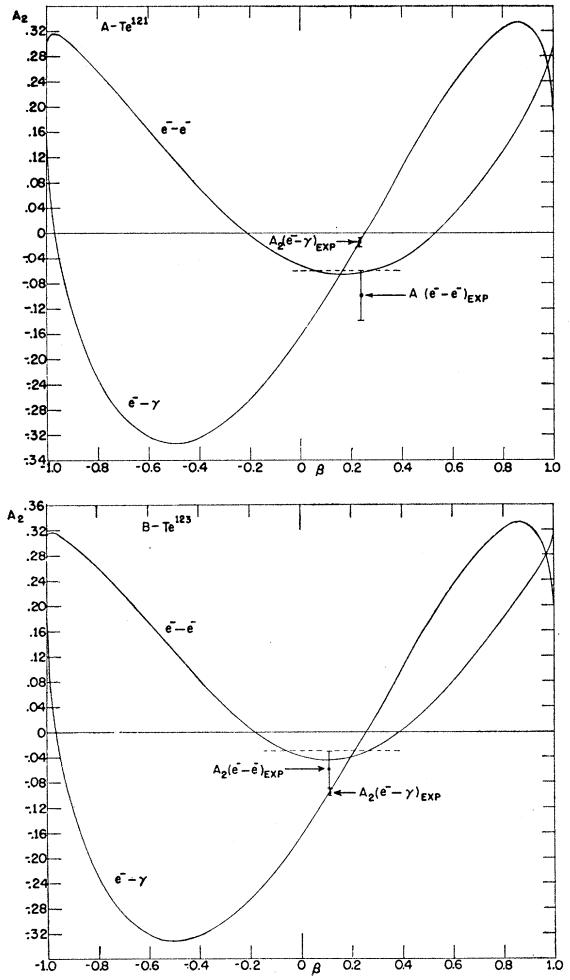

FIG. 7. Angular correlation coefficient A_2 for the Ke^-—γ and Ke^-—Ke^- cascades as a function of β. A (Te^{121}); B (Te^{123}).

mination of the attenuation factor g by the method outlined above. In spite of this large uncertainty the electron-electron results do confirm that β^2 is small in agreement with K conversion and K/L ratio measurements. The electron-electron results also show that attentuation of the correlation by extra nuclear fields cannot account for the observed anisotropies in both cascades which are lower than the theoretical $M4-M1$ prediction. The measured values of A_2 in the electron-electron correlations are larger than the theoretical values obtained if one were to assume that the reduced electron-gamma correlations resulted from perturbation of the intermediate state. The absence of perturbations due to extra nuclear fields is perhaps expected in view of the short lifetime of the intermediate states.[12] Only if the moments of the excited states in Te^{121} and Te^{123} were appreciably different could we expect extra nuclear fields to produce a factor of six in the measured correlations for Te^{121} and Te^{123} since the physical environment for both isotopes in our source was identical. From the K-γ results shown in Table II, the mixture ratio [Eq. (1)] is found to be 0.013 ± 0.001 in Te^{123} and 0.056 ± 0.005 in Te^{121}. To obtain these results, we have had to extrapolate the values of b_K to low energies. We have used the value $b_{2K}=1.070\pm0.005$ for both isomers.

The absolute value of the $E2$ matrix element of Te^{123} may be obtained from the ratio of $E2$ to $M1$ intensities found in our experiments and the measured lifetime of the intermediate state.[12] The lifetime of this state in Te^{121} has not been measured but can be estimated by assuming the radial matrix elements to be identical with those in Te^{123}. The $M1$ transition probabilities are assumed to follow the theoretical energy dependence as shown experimentally by Graham and Bell.[12] We find that the square of the $E2$ matrix element for Te^{123} is four times larger than that predicted by the generous Blatt and Weisskopf[13] estimate for odd-proton transitions. For Te^{121} the square of the $E2$ matrix element is eight times larger. Both are much larger than the crude single-particle prediction for odd-neutron transitions.[14]

With a knowledge of β^2, the L electron–gamma results can be used to determine the b_{2L}, the number which multiplies the A_2 for the gamma-gamma cascade to change it to the A_2 for the L electron–gamma cascade. We find b_{2L} is 1.0 ± 0.1 from the Te^{123} data and 0.6 ± 0.6 from the Te^{121} data. These values should be about the same for both isomers. Theoretical calculations of the values have not yet been made.

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We also wish to take this opportunity to thank Professor A. M. Feingold in our department for innumerable informative discussions in our general field of interest.

[12] R. L. Graham and R. E. Bell, Can. J. Phys. **31**, 377 (1953).

[13] J. M. Blatt and V. E. Weisskopf, *Theoretical Nuclear Physics* (John Wiley and Sons, Inc., New York, 1952).

[14] S. A. Moskowski, Phys. Rev. **89**, 474 (1953).