THE ENERGY LOSS DISTRIBUTIONS OF 1 MeV ELECTRONS IN ALUMINIUM FOILS

By J. A. McDonell,* M. A. Hanson,* and P. R. Wilson*

[*Manuscript received November* 29, 1954]

Summary

The energy loss distributions for 1 MeV electrons traversing aluminium foils of various thicknesses have been investigated experimentally. Several of the foils were of thicknesses such that the distributions were expected to show considerable effects due to multiple scattering. It was found that the most probable energy losses were in good agreement with those predicted by the calculations of Hebbard and Wilson (1955).

I. Introduction

The failure of the theories of Landau (1944) and Blunck and Leisegang (1950) to give an accurate description of the energy loss distributions for electrons has been discussed in the preceding paper (Hebbard and Wilson 1955), hereafter referred to as I, in which the effect of multiple scattering on the path length in the foil has been considered. Two theoretical distributions were obtained for foils of thickness 0·105, 0·157, and 0·210 g/cm². The first set were derived from a " Monte Carlo " calculation of energy loss and the second by numerically folding the Landau distribution for a particular foil, with a path length distribution obtained from Yang's calculation (1951). Better calculations by Goudsmit and Saunderson (1940) indicated that the mean increase in path length was half that calculated by Yang, and in the folding process the shape of Yang's distribution was retained but the path length increases were reduced by half. For brevity, the results of these calculations will be referred to as the Monte Carlo and the Yang distributions.

The most desirable geometry for experimental investigation of energy loss distributions is that in which a narrow, parallel beam of electrons falls normally on an absorber, and those emerging are detected by a spectrometer whose solid angle of acceptance is known. The two most interesting cases would be those in which the solid angle is either very small, so that only particles passing " straight through " are detected, or approximately 2π, in which case all emergent particles are detected. In either case, a reasonably simple comparison with theory is possible only if the incident beam is parallel.

If the shape of the energy loss distributions is to be measured in detail, apparatus of considerable precision is required, since the distributions (in the region of validity of the Landau theory) are quite narrow; the width at half height is of the order of a few per cent. of the particle energy at most. This

* Physics Department, University of Melbourne.

means that the energy spread of the incident beam and the resolving power of the spectrometer should both be at least an order of magnitude smaller. If they are not, one has to resort to folding techniques to compare experiment with theory, with a consequent loss of accuracy in the comparison. On the other hand, a good deal more latitude is possible if the aim is primarily an investigation of the most probable energy loss. The spread of energy of the incident beam is not nearly so important for energies in the relativistic region, because the most probable energy loss depends on the incident energy only through the term $(v/c)^2$.

II. Apparatus

A monochromatic beam of electrons was selected by a short magnetic lens β-ray spectrometer of a type similar to that described by Deutsch, Elliot, and Evans (1944). Because of its pure β-spectrum, ^{32}P, of 20 mc activity, was used as the electron source, giving a beam of the order of 11,000 electrons per minute. The electron trajectory was defined by baffles shown in Figure 1, and ultimately

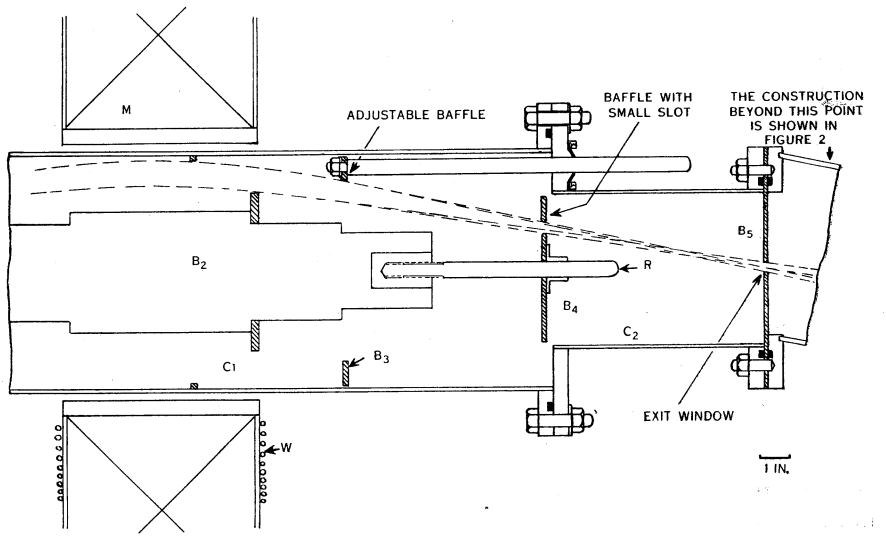

Fig. 1.—Baffle system producing narrow emergent beam.

a rectilinear beam of electrons travelling at an angle of 11° to the axis of the spectrometer was selected by baffles B_4 and B_5. The only opening in B_4 was an eccentric slot whose radial width was slightly wider than the spread of the trajectories at this point, and which subtended an angle of 15° at the spectrometer axis. The baffle B_5 was situated at the focus, and contained a $\frac{1}{4}$ in. diameter circular aperture at its centre. The transmission of the spectrometer was thus reduced by a factor of 1/24, but the remaining trajectories passing through the aperture in B_5 had an angular divergence of less than 1·5°. Although the resultant transmission of this arrangement was low (about 8×10^{-5}) a beam of reasonable intensity could be obtained, since the spectrometer was acting only as an energy selector, and so it was not necessary to use a thin source.

The energy spread of the beam was estimated at 2·3 per cent. at half-intensity, by observing the shape of the conversion line from the 364 keV γ-ray of ^{131}I, and allowing for line broadening due to the thickness of the source.

Figure 2 shows the way in which various absorbers were placed in front of the beam. A short " adaptor " section enabled the foil holder to be set at an angle of 11° to the spectrometer axis, so that the beam fell normally on the foils. The foil holder was an aluminium disk, with six equally spaced holes of 1 in. diameter. A bevel gear and a driveshaft passing through an O-ring seal enabled the foil holder to be rotated from outside the vacuum system. Foils were mounted over four holes in the holder, the fifth hole being left blank, and the sixth blocked off with an absorber thick enough to stop the electrons completely.

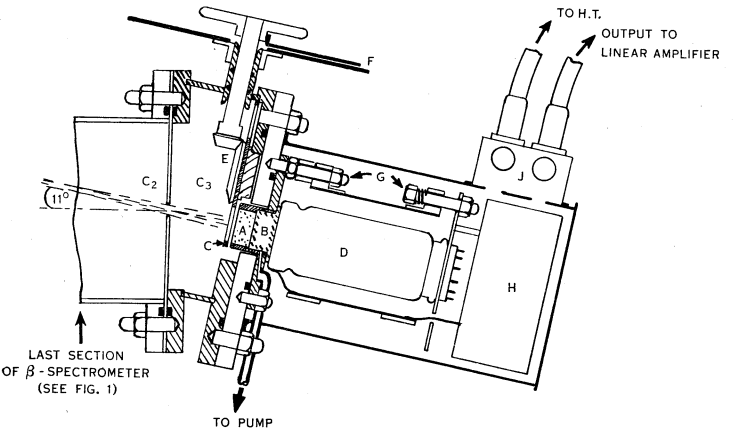

Fig. 2.—" Adaptor " section and scintillation counter. *A*, NaI(Tl) crystal ; *B*, glass light guide ; *C*, aluminium foil holder ; *D*, photomultiplier ; *E*, bevel gears ; *F*, pointer indicating position of foil holder ; *G*, spring-loaded mounting for photomultiplier ; *H*, potential divider ; *J*, preamplifier.

A scintillation counter was used as a spectrometer-detector. In order to obtain maximum counting rates, and also to obtain a greater effect due to scattering, the crystal was mounted as shown in Figure 2 so that its face was 0·10 in. from the plane of the foil holder. To obtain the best resolution with this type of detector, an NaI(Tl) crystal was used. The crystal was 1 in. in diameter and 0·5 in. long ; this length was excessive for the purpose of stopping the electrons, but was used because it was rather easier to handle. Since the source of the electrons was ^{32}P, backgrounds were at all times negligible, so that the size of the crystal was not a disadvantage from that point of view.

The mounting of the crystal presented some difficulties. To obtain good resolution, the crystal must be surrounded by an efficient reflector ; but, on the other hand, the amount of additional absorbing material between the crystal and the foils had to be kept as small as possible. Therefore the reflector next to the plane surface of the crystal had to be a very thin aluminium foil. However, the whole crystal chamber had to be airtight—because of the hygroscopic nature

of sodium iodide—and at the same time capable of being placed inside a vacuum system. The arrangement eventually evolved is shown in Figure 3. The reflector surrounding the crystal consisted of a highly polished aluminium cylinder, with an aluminium foil ($3 \cdot 5$ mg/cm^2) cemented across its end. The crystal was attached to a glass block with silicone grease. The crystal and glass block were then slid into the cylinder (which was made a neat fit to the crystal) and the system was sealed with an O-ring between the flange of the glass block and the brass plate on which the whole arrangement was mounted. The glass block was held secure by a brass ring, overlapping the flange, and held to the brass plate by six screws which could be accurately adjusted so that the crystal

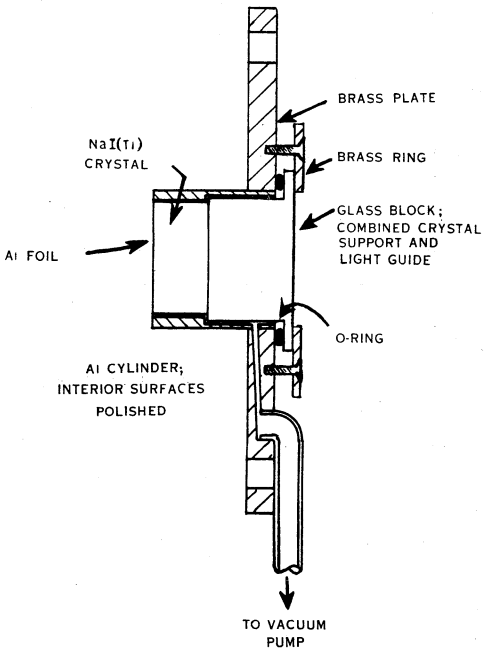

Fig. 3.—Crystal chamber.

penetrated the desired depth into the cylinder. With this adjustment there was very little flexure of the thin aluminium foil as it flattened against the crystal face when the chamber was evacuated. This small vacuum system was independent of that of the spectrometer, and was continuously pumped to a pressure of 10^{-3} mm Hg.

The crystal surfaces were left rough ground as recommended by Borkowski and Clark (1953), except for the face next to the glass block, which was polished. The glass block served as a light guide to the photocathode of an EMI 6260 photomultiplier. It was possible either to remove the photomultiplier and its mounting while leaving the crystal assembly in the spectrometer, or to remove the whole scintillation counter as a unit. The pulses, after amplification, were analysed by a single channel analyser.

III. Experimental Procedure

(*a*) *Adjustment of the Spectrometer*

After adjusting the alignment of the tube and the position of the slotted baffle by the usual criterion, viz. obtaining a maximum count rate for electrons of a given energy, the spread of the beam in the plane of the absorbers was investigated photographically. Its cross section was found to be quite well defined, and of roughly oval shape, with major and minor axes of approximately 0·35 and 0·25 in. Thus there was no danger of scattering from the edges of the holes over which the foils were mounted and, when the beam was central, all electrons scattered through angles less than 73° and most of those scattered through less than 82° should be detected by the crystal. The spectrometer calibration was obtained using a ^{131}I source.

(*b*) *Performance of the Scintillation Counter*

It was found, from comparison of the peak in the differential pulse height distribution for 1 MeV electrons and the peaks produced by irradiation of the crystal with γ-rays from ^{131}I and ^{137}Cs, that, for the particular high tension across the photomultiplier required to produce optimum resolution, the relation between the energy of electrons striking the scintillator and the amplified pulse height from the photomultiplier was non-linear.

It was found that with a low H.T. the ratio of the pulse heights for the ^{137}Cs and the 1 MeV electron peaks was 0·57, whereas we expected a ratio of 0·664.* Furthermore, this ratio increased almost linearly with increasing H.T., and passed through the value 0·664. This effect was at first attributed to some possible peculiarity of behaviour of the photomultiplier in a magnetic field, and the H.T. was adjusted to that value which gave the ratio of 0·664, in order to secure a linear relation between pulse height and energy. Later, at various lower currents in the magnet coil, the pulse heights of the ^{137}Cs peak and of the peaks for electrons of the energy focused in the spectrometer were measured. These were plotted as a function of the energy of the focused electrons, and it was immediately seen that these curves did *not* cross at an energy of 662 keV, as was expected. This meant that the pulse height produced by electrons of energy E incident on the flat face of the crystal was not equal to the pulse height produced by γ-rays of energy E. The difference is presumably due to the different spatial distributions of the scintillations produced in the crystal in the two cases.

It was thus necessary to plot a calibration curve of pulse height against incident electron energy. This was made difficult by the fact that the amplification of the photomultiplier varied with the magnetic field produced by the current in the field coils of the spectrometer. To measure the pulse height of electrons selected from the spectrometer at a particular energy, with the amplification which obtains for 1 MeV electrons, the electron beam was blocked off and the pulse height corresponding to the 661·65 keV γ-ray from ^{137}Cs was

* (Energy of Cs γ-ray)/(Energy of incident electrons) = 0·662/0·997 = 0·664. The use of 0·997 MeV instead of 1 MeV for the incident electron energy is due to an estimated energy loss of 0·003 MeV in the thin aluminium foil covering the crystal face.

determined at the current for 1 MeV electrons. Then, with the magnet current set at the energy under consideration, the photomultiplier H.T. was varied until the original pulse height for the ^{137}Cs γ-ray was obtained. With this H.T. the pulse height for the focused electrons was determined and this procedure was repeated for several values of the electron energy.

(c) *The Energy Loss Runs*

An incident energy of 1 MeV was used throughout. Two sets of four absorbers were used, their thicknesses being 0·010, 0·026, 0·035, 0·052, 0·083, 0·101, 0·153, and 0·215 g/cm². In each run, the pulse height distributions for the four absorbers, the blank hole, and the blocked one were obtained, three runs being done for each of the two sets of absorbers. In each run the count rates for each of the six foil holder positions were taken in turn at every bias setting of the pulse height analyser, so that the readings on all the peaks were taken at about the same time. In this way it was hoped to minimize any effects due to undetected drifts in the circuitry.

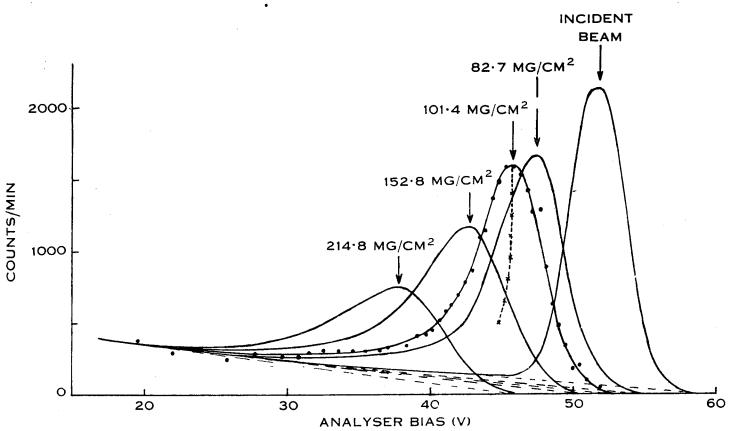

Fig. 4.—Results of one experimental run. The scatter of the points about the estimated smooth curve is shown in one case. The points —×——×— are those used to determine the position of the peak, as described in the text.

The position of the peak of each distribution was determined in the following way. The experimental points were plotted, and a smooth curve drawn through them. The mean abscissa values for pairs of points corresponding to a series of ordinate values throughout the curve were found, and a smooth curve drawn through these mean points. The locus thus formed intersected the top of the curve at a point whose abscissa was taken to be the position of the peak. In this way, the peak position was obtained from the distribution as a whole, and was not strongly dependent on the few points about the top of the peak. Thus the estimated error in locating any particular peak was generally less than $\frac{1}{2}$ per cent. and for the thinnest foils was of the order of 0·1 per cent. The displacement of the peak for each of the absorbers was found as the mean of the displacements in the three runs. Some typical experimental distributions are given in Figure 4.

IV. Comparison with Theory

The distribution obtained from the incident beam (Fig. 4) has a width at half height of 9 per cent. This is made up of the incident energy spread, which was 2·3 per cent. plus the unknown width of the counter resolution curve. Assuming that the widths combine in the same way as standard deviations, this would give a width for the counter resolution curve of approximately 8·7 per cent.

Since the width of the theoretical energy loss curves was of the order of 10 per cent. it was necessary to include the effect of energy spread and counter resolution when comparing theory with experiment. Strictly, the energy spread should first be folded with the energy loss distribution and then the resulting curve folded with the counter resolution curve. However, since the energy spread was small compared with either the energy loss distribution or the counter resolution, it was theoretically satisfactory, and much more convenient, to fold the "energy spread plus counter resolution" curve with the theoretical energy loss distribution. Actually, a Gaussian approximation to the energy spread plus counter resolution curve was used in the folding process.

After the calibration described in Section III (*b*) had been carried out, the complete electron peaks at the various lower energies were investigated, so that information could be obtained about their widths. It was found that the widths in volts (i.e. *not* converted to an energy scale from the calibration curve) were constant, within the experimental error. This somewhat simplified the folding process. If the theoretical distribution of the energies of the particles emerging from the foil is $\varphi(E)\mathrm{d}E$ and if particles of energy E give rise to a pulse height distribution $g(V-v)\mathrm{d}V$, where the (E, v) relation is known from the calibration curve, the expected pulse height distribution is

$$f(V)\mathrm{d}V=\int_0^\infty \varphi(E)g(V-v)\mathrm{d}E\mathrm{d}V=\int_0^\infty F(v)g(V-v)\frac{\mathrm{d}E}{\mathrm{d}v}\mathrm{d}v\mathrm{d}V,$$

where the (v, E) relation is expressed in the form $E=E(v)$, and $F(v)\equiv\varphi(E(v))$. In this expression, $g(V-v)$ is taken to be a Gaussian of constant variance.

In this way, the Landau distribution was found for each absorber, and the Monte Carlo and Yang distributions for each of the three thickest foils. From these folded distributions values of ΔV, the difference between pulse height at the peak, and the pulse height for an energy of 1 MeV as found from the (E, v) calibration were obtained. The same quantity was obtained from the experimental curves. It should be noted that this is not equal to $\Delta V'$, the difference between the pulse height of the peak for each absorber, and the pulse height for the peak obtained with the blank hole in front of the crystal, because of the presence of the thin foil in the crystal mounting. $\Delta V'$ was the quantity obtained from each run (Section III (*c*)). Because the most probable energy loss is very nearly a linear function of thickness for small thicknesses, the voltage corresponding to the energy loss (3 keV) in the foil of the crystal mounting was obtained from the (E, v) curve, and added, in each case, to the mean value of $\Delta V'$, to give the experimental ΔV. The thickness of the foil of the crystal mounting was included in the thicknesses given for the absorbing foils as quoted in Table 1.

The results are shown in Table 1 and Figure 5. For the three thickest absorbers, the experimental and theoretical widths of the pulse height distributions are shown in Table 2. Figure 6 compares the experimental distribution for 0·156 g/cm² with the appropriate theoretical ones.

TABLE 1

EXPERIMENTAL AND THEORETICAL PEAK DISPLACEMENTS IN VOLTS FOR VARIOUS THICKNESSES OF ABSORBER

The numbers in parentheses are the actual thicknesses used in the theoretical calculations

Thickness (mg/cm²)	Experimental	Landau	Monte Carlo using		Landau-Yang
			Molière	Rossi-Greisen	
13·8	0·7±0·1	(10) 0·4			
30·0	1·6±0·1	(26) 1·3			
38·7	2·0±0·2	(35) 1·5			
55·1	3·1±0·2	(51) 2·3			
86·2	4·7±0·2	(83) 3·7			
104·9	6·2±0·3	(101) 4·8	(105) 5·7	6·3	(105) 5·7
156·3	9·2±0·3	(152) 7·3	(158) 8·8	9·5	(162) 9·4
218·3	14·0±0·5	(216) 11·0	(210) 12·4		(210) 13·5

The difference between the experimental distribution and the estimated background was integrated over the voltage range for the resolution curve and the three thicker foils to obtain an estimate of the fraction of the incident

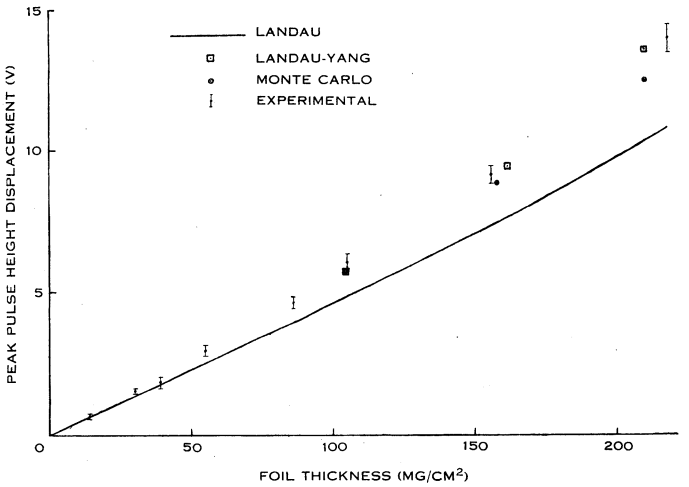

Fig. 5.—Experimental and theoretical peak displacements.

beam absorbed in the foils. Because it was difficult to estimate the tail, these calculations were not precise and all that can be concluded is that no absorption was observable in foils up to 0·158 g/cm² while for the 0·215 g/cm² foil absorption was of the order of 10 per cent. This is consistent with the Monte Carlo calcu-

lation which predicts percentage absorptions of 0·2, 1·5, and 8·4 respectively, but is not in accord with the values which can be interpolated from the absorption curves of Marshall and Ward (1937), viz. 4, 10, and 23 per cent.

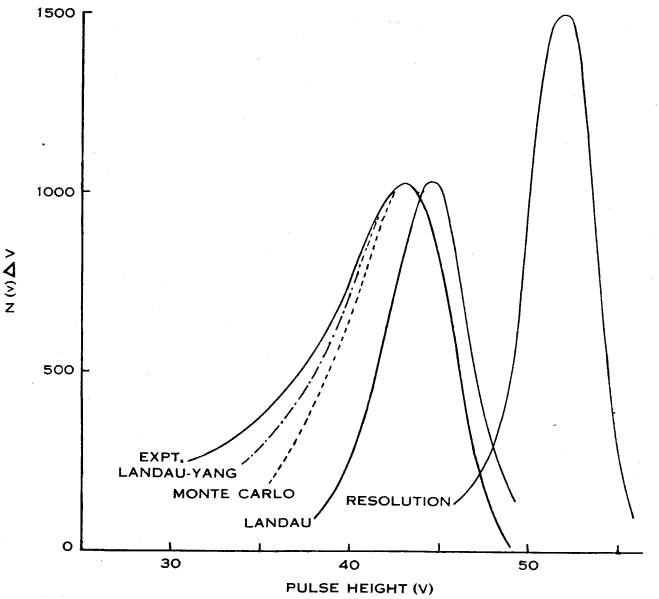

Fig. 6.—Experimental distribution compared with theoretical curves folded with resolution curve.

V. Discussion

The agreement with the appropriate theory is generally satisfactory. For thicknesses less than about 50 mg/cm², the peak pulse height differences agree with the values predicted by the Landau theory. This has been demonstrated with more accuracy elsewhere (Chen and Warshaw 1951). For the region in

Table 2

WIDTHS, IN VOLTS, OF EXPERIMENTAL AND THEORETICAL PULSE HEIGHT DISTRIBUTIONS FOR THREE THICKNESSES OF ABSORBER

The numbers in parentheses are the actual thicknesses used in the theoretical calculations

Thickness (mg/cm²)	Experimental	Monte Carlo	Landau-Yang
104·9	5·5±0·3	(105) 5·6	(105) 5·6
156·3	6·7±0·5	(158) 6·6	(162) 6·8
218·3	8·7±1·0	(210) 9·2	(210) 10·1

which the effect of scattering becomes appreciable, the Landau theory underestimates the energy loss, satisfactory values of which can be obtained by combining the Landau theory with a theory of multiple scattering, even though the energy losses concerned may no longer be a small fraction of the incident energy.

As far as the method of combining the two theories is concerned, our results tend to favour the Landau-Yang folded distribution, rather than those obtained by the Monte Carlo (Molière) calculation. For the two foils to which it was applied, the Monte Carlo (Rossi-Greisen) distribution gave values of most probable ΔV which agreed very well with experiment. These values were not obtained by direct folding, however, but by increasing ΔV (Molière) in the ratio of the peaks of the unfolded curves.

The widths shown in Table 2 do not enable us to decide between the Monte Carlo and Landau-Yang distributions, and we would not expect them to do so, because they are, in effect, the widths of the counter resolution curve with some broadening due to the folding with energy loss distributions. However, from Figure 6 there is once more this tendency to favour the Landau-Yang distribution, as well as a clear broadening beyond that predicted by Landau theory alone.

Thus we find that the Landau-Yang distributions calculated by the techniques described in I, can be expected to be reasonably accurate. In particular, the simple expressions derived there for estimating the most probable energy loss and width of the distribution without going through the folding process, can be used with confidence.

VI. Acknowledgments

We wish to thank Professor L. H. Martin for his advice and guidance throughout the course of this work; also Associate Professor C. B. O. Mohr, Mr. K. C. Hines, and Mr. D. F. Hebbard for useful discussions.

VII. References

Blunck, O., and Leisegang, S. (1950).—*Z. Phys.* **128**: 500.
Borkowski, C. J., and Clark, R. L. (1953).—*Rev. Sci. Instrum.* **24**: 1046.
Chen, J. J. L., and Warshaw, S. D. (1951).—*Phys. Rev.* **84**: 355.
Deutsch, M., Elliot, L. G., and Evans, R. D. (1944).—*Rev. Sci. Instrum.* **15**: 178.
Goudsmit, S. A., and Saunderson, J. L. (1940).—*Phys. Rev.* **57**: 24.
Hebbard, D. F., and Wilson, P. R. (1955).—*Aust. J. Phys.* **8**: 90.
Landau, L. (1944).—*J. Phys., Moscow* **8**: 201.
Marshall, J. S., and Ward, A. G. (1937).—*Canad. J. Res.* A **15**: 39.
Yang, C. N. (1951).—*Phys. Rev.* **84**: 599.