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Penetration of Electrons and Associated Bremsstrahlung
through Aluminum Targets*

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This paper contains a brief description of Monte Carlo programs designed to calculate the transport of fast electrons and associated bremsstrahlung through extended media. Two applications are discussed: (1) transmission of electrons through plane-parallel targets, and (2) emergence of secondary bremsstrahlung from such targets. It is shown that the predicted results are in reasonably good agreement with recent experiments for electron beams with energies up to 8 Mev incident normally on aluminum targets. Extensive new calculated data for transmission and thick-target bremsstrahlung production are presented for aluminum targets exposed to an isotropic electron flux.

* Work supported by National Aeronautics and Space Administration under Contract R-80.

1. Introduction

This paper has two purposes: (1) to review the status of electron and photon transport calculations that have been done in recent years at the National Bureau of Standards under the sponsorship of the National Aeronautics and Space Administration; and (2) to present results on the transmission of electrons through aluminum and on the production of thick-target bremsstrahlung in such targets. Comparisons are made with recent experimental data for electron beams incident perpendicularly on the target. In addition, extensive information is presented for a situation of practical importance for which direct experimental data are lacking, namely, aluminum targets exposed to an isotropic electron flux.

The assumed source-medium configuration has been kept simple. It involves a broad incident electron beam, and a plane-parallel target that is finite in one dimension and unbounded in the other two. Results for such a simple configuration provide an understanding of the essential features of electron transport in extended matter, and allow for convenient direct comparison with corresponding experiments. They also provide reference data which may be used to check the validity of more approximate calculational procedures that may have to be used for the solution of complex engineering problems.

The computer programs that have been developed provide information about: (1) transmission and reflection of electrons; (2) production of bremsstrahlung photons in targets of arbitrary thickness, and the emergence of these photons from the target; (3) deposition of energy and charge by the incident electron beam in the target; (4) the energy spectrum of the electron flux (both primary and secondary) as a function of the depth in the medium. In the earlier stages of our work, a number of different programs were developed which treated these problems separately. With the availability of ever larger computer memories the trend has been to combine these into one master program. In the present paper, information of types (1) and (2) only is presented. Preliminary results for items (3) and (4) will be presented elsewhere.^{1/}

2. Method of Calculation

The required task is to solve an electron-photon cascade problem in which each type of radiation acts as a source for the other. The determination of the photon component of the cascade is done by conventional random sampling imitating the physical processes of photoelectric absorption, Compton scattering and pair production. Electron collisions (elastic as well as inelastic) are too numerous to be followed individually. Electron tracks are therefore sampled by

letting the electrons carry out a random walk with transition probabilities derived from analytical multiple scattering theories. Calculations according to such a random-walk model have been carried out already by several authors.^{2-9/} The procedures used by us appear to be more detailed than most others in the literature, and are an elaboration of those described earlier in Ref. 6.

We shall now describe the sampling rules used in our most up-to-date Monte Carlo program (ETRAN 15). Some of the results to be given below were obtained with earlier programs which in some cases have lesser generality and make more approximations. A comparison of these programs is given in Table 1.

2.1. Division of Electron Track into Segments. Each track is divided into many major segments which we call steps. In an aluminum medium the step-size is chosen so that the electron energy, on the average, decreases by a factor 2^{-8} per step. Each step is in turn subdivided into four equal subdivisions which are called short steps. The choice of step sizes is determined by the conditions of validity of the multiple scattering theories used and by the requirement that a further decrease of the step size should not change the final results significantly.

	ETRAN 5	ETRAN 9	THICKBREM	ETRAN 15
<u>Processes taken into account</u>				
Mean energy loss by collision (continuous slowing down approximation)	No	No	Yes	No (*)
Collision energy loss straggling	Yes	Yes	No	No (*)
Mean energy loss by bremsstrahlung	Yes	No	Yes	Yes (*)
Bremsstrahlung energy loss straggling	No	Yes	No	Yes (*)
Histories of secondary bremsstrahlung photons followed	No	No	Yes	Yes (*)
Histories of secondary knock-on electrons followed	No	No	No	Yes (*)
Histories of secondary electrons due to bremsstrahlung followed	No	No	Yes	Yes (*)
<u>Output Information</u>				
Electron transmission and reflection (differential in energy and angle)	Yes	Yes	No	Yes
Electron transmission and reflection coefficients	Yes	Yes	Yes	Yes
Thick-target bremsstrahlung (differential in energy and angle)	No	No	Yes	Yes
Charge deposition in target	No	No	No	Yes
Energy deposition in target	No	No	Yes	Yes
Electron flux as function of depth in target (differential in energy)	No	No	No	Yes

Table 1. Comparison of various Monte Carlo models. Program 15 is flexible and the options accompanied by an asterisk can be changed from no to yes and vice versa.

2.2. Multiple Elastic Scattering by Atoms. At the end of each short step the direction of the electron is allowed to change in conformity with the net multiple scattering angular deflection sampled from the Goudsmit-Saunderson distribution. This distribution has the form of a long Legendre series whose coefficients are determined by the Mott single-scattering cross section. Screening effects are taken into account in the same manner as in the multiple scattering theory of Molière.

2.3. Multiple Inelastic Scattering by Atomic Electrons. The energy loss resulting from the cumulative effect of many inelastic collisions in each step is sampled from the Landau distribution (modified in the manner of Blunck and Leisegang to take into account binding effects).*

* In some of the simpler Monte Carlo models, based on the so-called continuous slowing down approximation, the collision energy loss is taken to be the product of the mean loss (given by the Bethe stopping power formula) and the length of the step.

2.4. Knock-on Electrons. The production of secondary electrons (with energies greater than some chosen cut-off value) is sampled from a probability distribution derived from the Møller cross section.*

* This cross section applies only to the scattering of electrons by free electrons and does not take into account binding effects. It can therefore be used only for primary electron energies that are a good deal larger than the atomic binding energies involved (1.56 kev for aluminum). Reliable information about electron-electron scattering with binding effects is not available.

The histories of the secondary electrons are followed in turn. Eventually all required generations of knock-on electrons are included.

2.5. Bremsstrahlung. The production of bremsstrahlung quanta is sampled from a probability distribution derived from the best available theoretical bremsstrahlung cross sections (Bethe-Heitler theory plus refinements). We have used a cross section package essentially equivalent with that recommended in a review article by Koch and Motz^{10/} which includes, at least approximately, the effects of screening, the Coulomb correction, and the exact high-frequency limit. Koch and Motz also suggest multiplication of the cross section by empirical correction factor that depends on the energy of the electron before the bremsstrahlung

event. For aluminum this correction factor differs from unity most at an energy of 0.5 Mev where it has the value 1.3. We have used this correction factor in some but not in all of our calculations.

The energy given to a bremsstrahlung photon is subtracted from the energy of the electron.* The history of the photons

* In some of the simpler Monte Carlo models we have not sampled the occurrence of bremsstrahlung events, but have simply subtracted the mean radiative energy loss in each short step from the electron energy.

is followed in turn, as are the histories of the photo-electrons, Compton electrons and electron-positron pairs resulting from photon interactions with the medium. In the present version of the program positrons are treated as if they were electrons. A more refined treatment is planned which will take into account electron-positron differences in energy loss, knock-on production and multiple elastic scattering.

2.6. Boundary Crossings. The program is set up so as to treat simultaneously many slab targets with different thicknesses. Boundary crossings (transmission or reflection) of electrons usually occur in the middle of a short step. The energy and direction at the time of crossing are determined by the energy and direction at the beginning of this short step modified in two ways: 1) by a small additional energy loss in the fraction of the step to the boundary (sampled again from the Landau distribution), 2) by a small additional deflection sampled from an exponential approximation to the Goudsmit-Saunderson distribution. The assumption is built into this procedure that the path of the electron is rectilinear in each short step, the entire trajectory having the form of a polygon. Numerical experimentation indicated to us that with the step-size finally chosen the error introduced by this approximation was not significant. For the evaluation of the emergence of the photons from the target such an approximation is not needed. For each sampled photon scattering we compute the probability that the photon, after the collision, will escape from the target without any further interaction. The average value of this probability then provides an estimate of the emergent number of photons.

2.7. Approximations. Certain simplifications are introduced into the Monte Carlo model which involve mainly the neglect of correlations. The electrons are not allowed to be deflected as the result of bremsstrahlung events; this type of deflection is assumed to be included in the large-angle tail of the Goudsmit-Saunderson multiple scattering distribution. Thus we neglect the correlation of sudden large deflections and large bremsstrahlung losses. Similarly, inelastic collisions resulting in the appearance of knock-on electrons are not allowed to result in a deflection of the primary electron; this type of deflection is taken into account approximately by an inelastic scattering due to Fano which is incorporated into the Goudsmit-Saunderson distribution.* Thus the correlation between

* We do not regard our present procedures for treating inelastic scattering as entirely satisfactory, and are working on improvements.

large energy losses and deflections in inelastic scattering events is neglected. The energy of a secondary knock-on electron is not subtracted from the energy of the primary electron producing it; the energy loss of the primary is determined entirely by the Landau distribution. This implies neglect of the correlation between the occurrence of large energy losses of primary electrons and the appearance of energetic delta rays.

In the sampling of the production of bremsstrahlung photons and knock-on electrons the energy of the primary electron at any point within a step is taken to be weighted average of the energies at the beginning and at the end of the step. In other words, energy-loss straggling is allowed only at the end of each step, but within a step the continuous-slowing-down approximation is used.

We were reluctant to introduce these approximations but were finally led to adopt them because they considerably simplify and shorten the calculations, which already are lengthy enough. We convinced ourselves by trial calculations with various models that the errors resulting from the approximations are likely to be small. Our program certainly could be improved in various respects if one wanted to take the trouble, but we think it is sufficiently accurate for many applications in space science and technology, and commensurate in its detail with the precision of the available input cross sections.

2.8. Preparation of Input Data. The sampling procedures outlined above require as input the values of many cross sections and multiple scattering distributions at a large number of energies and

angles. Numerical experimentation indicates that the Monte Carlo results depend quite sensitively on most of the input information, so that approximation of the input by crude and simple formulas is not appropriate. Because of the repetitive nature of the Monte Carlo computations it would be prohibitively time-consuming to evaluate the data every time when needed. We have therefore gone to great lengths to tabulate all the input data once and for all in a form convenient for table look-up. The evaluation and pre-digestion of input data is carried on in a program called DATAPAC which generates typically on the order of 20,000 words of information and stores them on magnetic tape for later use by ETRAN 15. Even DATAPAC does not compute all cross sections and other data from scratch but makes use of an extensive tape library with cross section information for approximately fifty elements, compounds and mixtures.

3. Comparisons of Calculated and Measured Results

3.1. Scaling. When presenting transmission and thick-target bremsstrahlung data as function of the target thickness, we find it convenient to use the scaled thickness z/r_0 , where z is the actual thickness, and r_0 the mean electron range at the source energy T_0 . By this choice of variable the dependence of the results on the source energy is greatly reduced so that interpolation with respect to T_0 is much easier. A short list of r_0 -values for aluminum

is given in Table 2. These values were obtained by integrating the reciprocal of the mean energy loss by collision and radiation, i.e. $r_o = - \int_0^{T_o} (dE/dx)^{-1} dT$.

3.2. Electron Transmission (Perpendicular Incidence). Figures 1 and 2 contain comparisons between Monte Carlo results and recent experiments by Jupiter, Merkel and Lonergan^{11/} (source energy 8.2 Mev) and by Rester and Dance^{12/} (source energy 1 Mev) on the transmission of electrons through aluminum targets. The Monte Carlo results, obtained with the computer program ETRAN 9, are in each case based on a sample of 30,000 electron histories. Comparisons are made for the energy spectra of the transmitted electrons emerging at various angles with respect to the direction of incidence. On the whole there is a reasonably good agreement between the calculated and measured spectra but there are discrepancies which indicate a possible need for further work. The further study of the location and particularly the width of the peak of the spectrum would be of interest. There is a tendency for the experimental width to be somewhat greater than the calculated width. Experimentally one can think of a few effects that might broaden the spectrum, e.g. the energy spread of the incident beam around the nominal source energy, a possible angular divergence of the incident beam, etc.

T_o (Mev)	r_o (g/cm ²)	T_o (Mev)	r_o (g/cm ²)
0.5	0.224	2.5	1.54
0.55	0.255	3.0	1.86
0.6	0.287	3.5	2.17
0.7	0.351	4.0	2.48
0.8	0.417	4.5	2.78
0.9	0.483	5.0	3.08
1.0	0.549	5.5	3.37
1.2	0.683	6.0	3.66
1.4	0.816	7.0	4.23
1.6	0.949	8.0	4.78
1.8	1.08	9.0	5.32
2.0	1.21	10.0	5.84

Table 2. Electron Mean Ranges in Aluminum

Comparisons with other experimental results are now in progress. We show one of them in Fig. 3, with an experiment by Van Kamp^{13/} designed to measure the transmission spectrum in the forward direction with great accuracy in the vicinity of the spectral peak. In this case, for relatively thin aluminum targets and a source energy of 3.66 Mev, the agreement with the Monte Carlo results is rather close.

3.3. Thick-target Bremsstrahlung (Perpendicular Incidence).

Figures 4-6 contain comparisons, for source energies up to 2 Mev, between calculated and experimental results for the distribution in energy and angle of bremsstrahlung photons emerging from thick targets. The Monte Carlo results shown were obtained with the program THICKBREM which employs the continuous-slowing-down approximation. Recent trial calculations with the program ETRAN¹⁵ indicate that the inclusion of energy-loss straggling raises the amount of bremsstrahlung from an aluminum target by only 1-2 percent for a source energy of 2 Mev.*

* The straggling effect in aluminum increases with source energy and is estimated to raise the bremsstrahlung yield by 5-6 percent at 5 Mev and by 7-8 percent at 10 Mev.

Figures 4 and 5 contain comparisons with the experimental results of Dance and Baggerly,^{14/} mainly for aluminum but also for iron and gold. The corresponding Monte Carlo results are based on a sample of 2,500 electron histories and 125,000 photon histories for each case.* For aluminum and iron, a bremsstrahlung

* The number of bremsstrahlung photons per electron was artificially increased to obtain better statistical accuracy, and this increase was compensated by giving the photons appropriate small weight factors.

cross section package without the Koch-Motz empirical correction factor was used, whereas for gold this factor was included. This choice was made to get the best agreement with the experimental results. We have made other calculations that indicate that the inclusion of the correction factor leaves the shape of the bremsstrahlung spectrum essentially unchanged but alters the normalization. For aluminum the spectral values were found to be increased by 28%, 34% and 31% for source energies of 2, 1 and 0.5 Mev, Respectively. Conversely, the omission of the correction factor for gold lowered the spectrum by 42% for a source energy of 2 Mev.

Inspection of Figs. 4 and 5 shows good agreement between calculated and measured results in regard to spectral shape, for various source energies, target thicknesses and directions of emergence.

The absolute normalization can be brought into agreement through the use of a suitable empirical correction factor, depending on the electron energy only, that multiplies the bremsstrahlung cross section. However, there is an inconsistency between the value of the correction factor that one would extract from the cross section measurements reviewed by Koch and Motz, and the value derived from the thick-target experiment of Dance and Baggerly. It should be kept in mind that the experimental uncertainty of the Koch-Motz data in the energy region of interest is estimated to be 20% so that the discrepancy may be more apparent than real, and could very well be resolved by further measurements of the bremsstrahlung cross section. In this connection new measurements by Rester and Dance^{15/} may be of help.

In Fig. 6, further comparisons for low source energies are made between thick-target bremsstrahlung spectra calculated with the program THICKBREM (based on samples of 1,000 electron histories and 25,000 photon histories) with corresponding measurements by Placious.^{16/} The calculations include the Koch-Motz correction factor. Agreement between calculated and measured spectra is good. Attention should be called to the low-energy peak of the

spectrum for tin between 10 and 20 kev, as well as to the peak for the spectra at 70 kev from gold targets in Fig. 6. These peaks are caused by the presence of characteristic x-ray production.

4. Results for Cosine-law Sources

4.1. Definition of Cosine-law Source. The extent to which electrons penetrate through a thick target depends on their direction of incidence. In detailed shielding calculations for spacecraft one must therefore take into account the orientation of the vehicle, and the characteristics of the radiation field, at each point along the trajectory. A simplifying approximation is often made in which the electron flux is assumed to be isotropic. This approximation is justified to the extent that the time-average of the electron flux is isotropic in a coordinate system attached to the shield, and to the extent that the perturbation of the flux by the shield can be disregarded. If the shield has the shape of a plane-parallel plate, the number of electrons entering a unit area of the shield is then proportional to the cosine of the angle between the normal to the shield and the incident-velocity vector, and we speak of a cosine-law source.

4.2. Electron Transmission. Extensive calculation of electron transmission, based on Monte Carlo samples on the order of 100,000 histories per case, have been carried out by M. Lopez^{17/} at NASA (Houston MSC), using the computer program ETRAN 5. They provide the most detailed set of available calculated data. We present here some excerpts from them, taken from a computer print-out put at our disposal.

Table 3 gives a list of number and energy transmission coefficients for various target thicknesses, as well as corresponding reflection coefficients for a semi-infinite medium, all for aluminum and seven source energies between 0.5 Mev and 6.0 Mev. One interesting feature of this table is that the transmission coefficients as functions of the scaled target thickness z/r_0 are rather slowly varying function of the source energy. This is a phenomenon which has previously been found in calculations based on the continuous-slowing-down approximation; the scaling of the transmission curves appears to be preserved to a large extent when energy-loss straggling is taken into account. Fig. 7, for a 2-Mev source, shows the energy spectra of transmitted electrons emerging at various directions. In Fig. 8 corresponding spectra are shown that result from an integration over all forward direction and correspond to the reading of a 2π -detector. The Monte Carlo histograms were smoothed out by eye to obtain spectra curves. It can be seen that the spectra for thin targets

T_o (Mev)	0.50	1.00	2.00	3.00	4.00	5.04	5.99
r_o (g/cm ²)	0.224	0.549	1.21	1.85	2.48	3.10	3.65
z/r_o							
	<u>Number Transmission Coefficient</u>						
0.1	0.841	0.853	0.875	0.889	0.899	0.906	0.914
0.2	0.708	0.732	0.766	0.789	0.807	0.819	0.831
0.3	0.555	0.587	0.634	0.667	0.692	0.711	0.725
0.4	0.394	0.428	0.484	0.522	0.555	0.577	0.593
0.5	0.241	0.271	0.322	0.363	0.399	0.425	0.441
0.6	0.119	0.146	0.181	0.218	0.250	0.276	0.290
0.7	0.042	0.051	0.068	0.090	0.109	0.127	0.135
	<u>Energy Transmission Coefficient</u>						
0.1	0.736	0.735	0.741	0.746	0.751	0.753	0.757
0.2	0.530	0.533	0.542	0.550	0.558	0.562	0.567
0.3	0.356	0.360	0.373	0.384	0.394	0.400	0.405
0.4	0.214	0.220	0.233	0.246	0.257	0.264	0.268
0.5	0.110	0.115	0.126	0.137	0.147	0.155	0.159
0.6	0.045	0.048	0.057	0.065	0.072	0.077	0.079
0.7	0.013	0.014	0.016	0.020	0.024	0.027	0.028
	<u>Reflection Coefficients for Semi-infinite Medium</u>						
Number	0.273	0.251	0.216	0.193	0.172	0.158	0.145
	0.176	0.153	0.122	0.103	0.088	0.078	0.070

Table 3. Transmission and Reflection Coefficients for Aluminum Targets,
for a Cosine-law Source.

are characterized by rather sharp peaks which then broaden with increasing target thickness. The spectra at a given scaled target thickness z/r_0 , when plotted as function of ratio T/T_0 of the spectral energy to the source energy, have a shape that depends rather insensitively on the source energy. This facilitates interpolation to source energies other than those for which calculations have been made. Figure 9 shows angular distributions of transmitted photons, integrated over all spectral energies, for various target thicknesses. For a very thin target, the distribution is given very nearly by a cosine-law, which means that the incident angular distribution is still preserved. For thicker targets, the angular distribution is concentrated more strongly in the forward direction than would be the case for a cosine-law.

4.3. Thick-target Bremsstrahlung. Very recently we have carried out thick-target bremsstrahlung calculations for aluminum targets with program ETRAN 15, using a bremsstrahlung cross section package including the Koch-Motz correction factor. Just as in the case of the Houston transmission results, the bremsstrahlung results are much too voluminous to be reproduced here, and we have merely selected for presentation some typical cases. Figure 10

shows spectra, for various source energies and a target thickness equal to r_0 , for photons emerging in the forward direction ($0-10^\circ$) and at an oblique angle ($55-65^\circ$). The shape of the spectra does not seem to depend very strongly on the source energy or on the direction of emergence. Starting from the top energy T_0 the spectra rapidly increase; in the absence of photon absorption the spectra would tend to rise indefinitely as the spectral energy becomes lower; in fact the spectra have a definite peak at some energy between 30 to 50 Kev whose position depends somewhat on the angle of emergence, and below which the spectral curve falls off rapidly.

Corresponding results of the bremsstrahlung spectra integrated over all forward directions (2π geometry) are shown in Fig. 11 for various target thicknesses. An interesting feature of the spectra can be noted for the highest source energy shown; at 5 Mev, for targets with thicknesses equal to r_0 or $2r_0$, the low-energy part of the spectrum (between 10 and 20 kev) show a sudden increase. By looking at various stages of the electron-photon cascade we have convinced ourselves that this phenomenon is not a numerical fluke but quite real, and must be attributed to photons of the fourth or higher stages of the cascade which happen to be produced by secondary electrons very close to the exit surface.

Another interesting quantity is the forward bremsstrahlung efficiency by which we mean the fraction of the incident electron energy that leaves the target in the forward direction in the form of bremsstrahlung. A plot of the efficiency vs. target thickness for different source energies is given in Fig. 12. It can be seen that after a rapid buildup the efficiency reaches a peak at a target thickness approximately equal to $0.6 r_0$. As the target thickness is further increased, a small decrease of the efficiency occurs due to photon absorption within the target. It is convenient to represent the forward efficiency by a formula*

$$Y = 10^{-4} a Z T_0$$

* A similar formula is often used to describe the conversion of electron kinetic energy to bremsstrahlung energy in an unbounded medium, without regard to geometric factors. It should be kept in mind that our parameter a pertains to a specific situation, namely, a cosine-law source and a plane-parallel target of finite thickness, and takes into account scattering and absorption of the photons within the target.

where Z is the atomic number, T_0 the source energy and a is a proportionality constant that is usually taken to be a constant. Actually, a is somewhat dependent on the source energy and to a greater extent on the target thickness, as can be seen in detail in Table 4.

Acknowledgments

The authors would like to express their thanks for the hospitality accorded to them by the Laboratory for Theoretical Studies at the Goddard Space Flight Center on whose computer some of the calculations were carried out. They would also like to thank M. Lopez and his colleagues of the NASA Manned Spaceflight Center in Houston for their collaboration in the electron transmission calculations.

T_0 (Mev)	10	5	2	1	0.5
z/r_0					
0.2	3.0	3.0	2.8	2.8	2.6
0.4	4.1	4.2	4.1	4.0	4.0
0.6	4.4	4.5	4.4	4.3	4.3
0.8	4.2	4.4	4.3	4.2	4.3
1.0	3.9	4.2	4.2	4.1	4.2
1.2	3.7	4.0	4.0	4.0	4.1
1.4	3.5	3.8	3.9	3.9	4.0
1.6	3.3	3.7	3.8	3.8	3.9
1.8	3.1	3.5	3.7	3.7	3.8
2.0	3.0	3.4	3.6	3.6	3.8

Table 4. Value of the parameter $\underline{a}$ in the formula $Y = 10^{-4} a Z T_0$
for the forward bremsstrahlung efficiency (cosine-law
source, aluminum target).

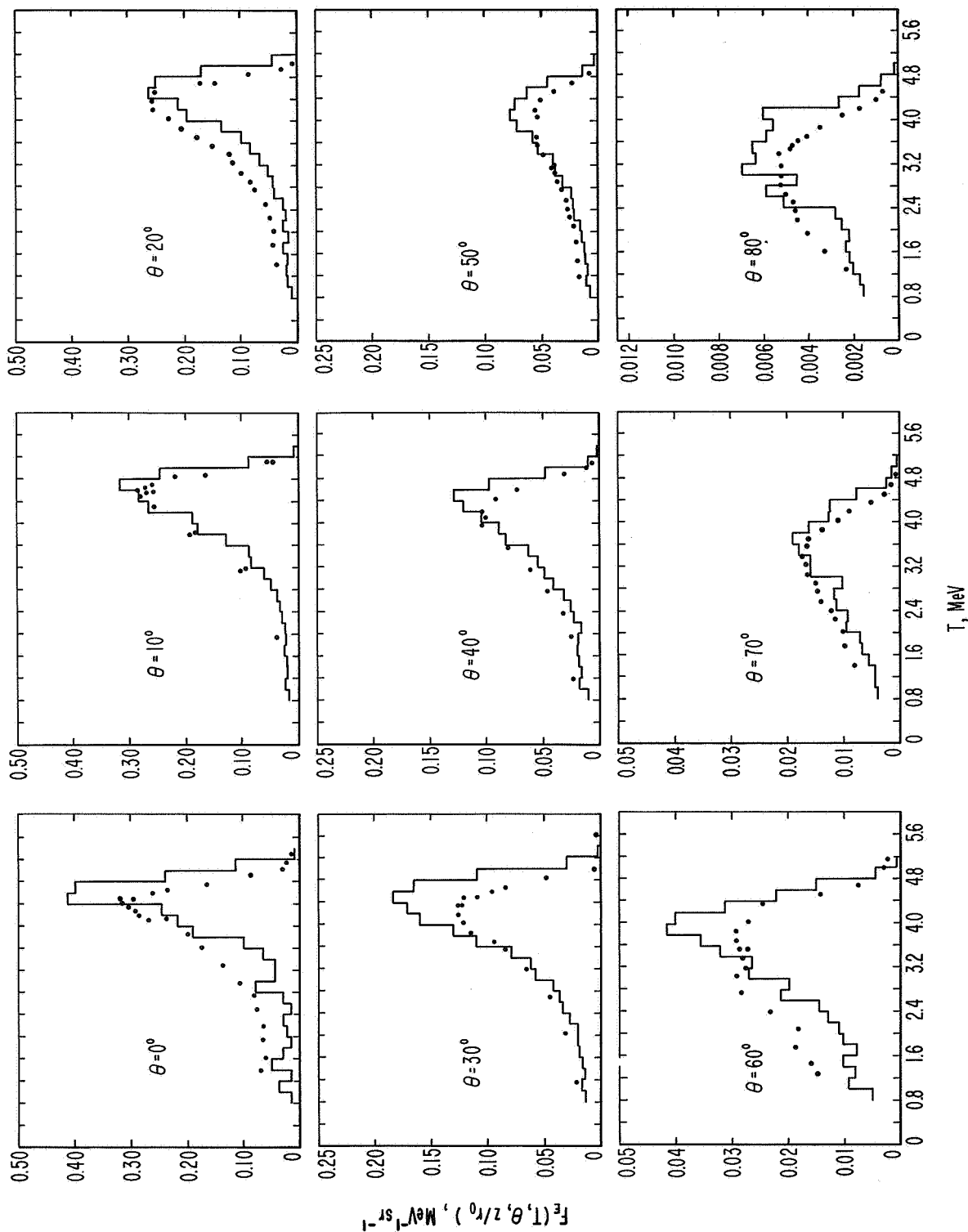


Figure 1. Energy spectra of transmitted electrons emerging in various directions from an aluminum target bombarded with 8.2-Mev electrons. Normal incidence, target thickness 2.38 g/cm² (=0.491 r₀). Points are from experiment by Jupiter, Lonergan and Merkel. Histograms were obtained with Monte Carlo program ETRAN 9.

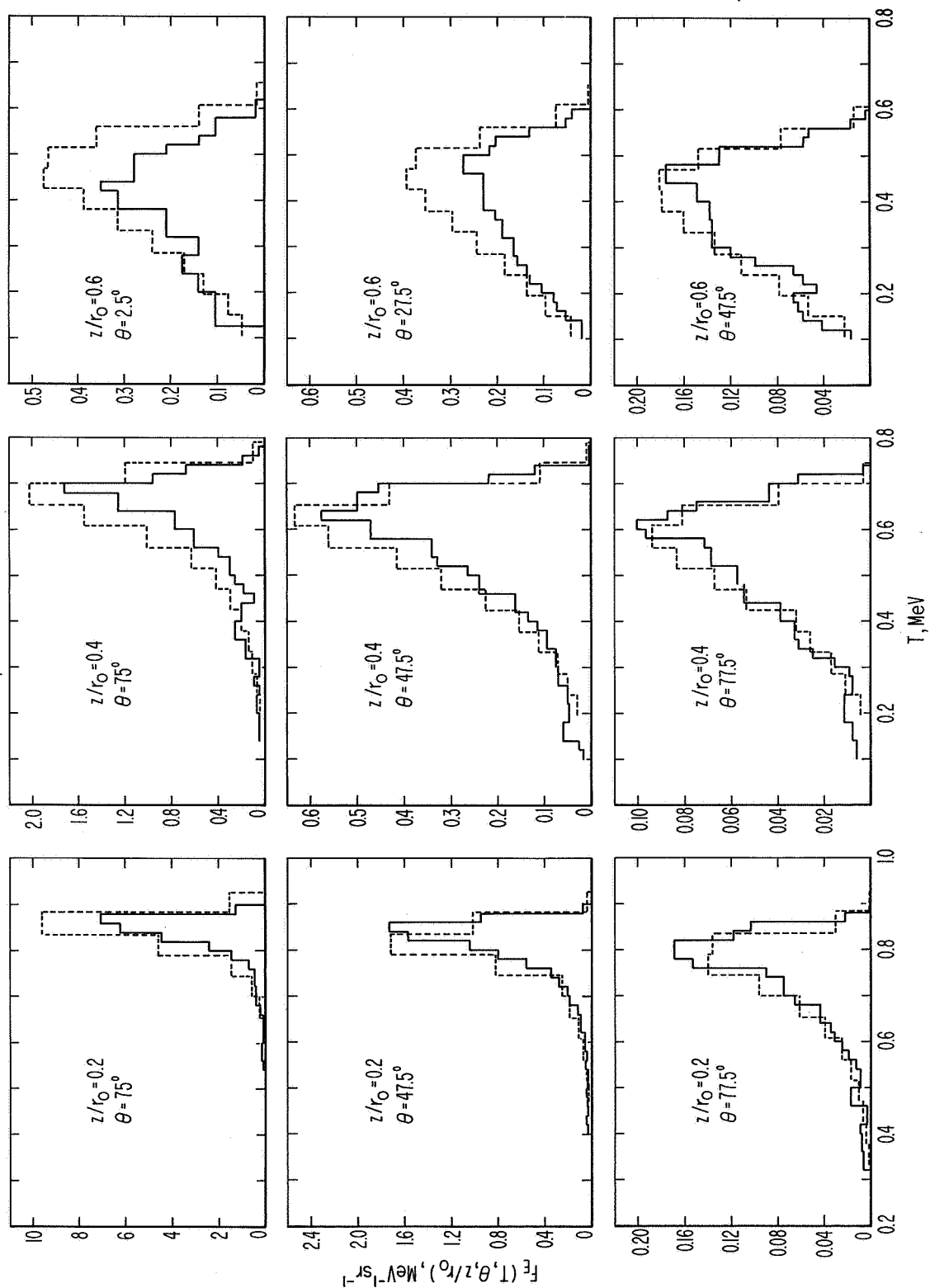


Figure 2. Energy spectra of transmitted electrons emerging in various directions from aluminum targets bombarded with 1-Mev electrons. Normal incidence; target thicknesses are 0.11 g/cm^2 ($\approx 0.2 r_0$), 0.22 g/cm^2 ($\approx 0.4 r_0$) and 0.33 g/cm^2 ($\approx 0.6 r_0$). Dashed histograms represent experimental results of Rester and Rainwater. Solid histograms were calculated with Monte Carlo program ETRAN 9.

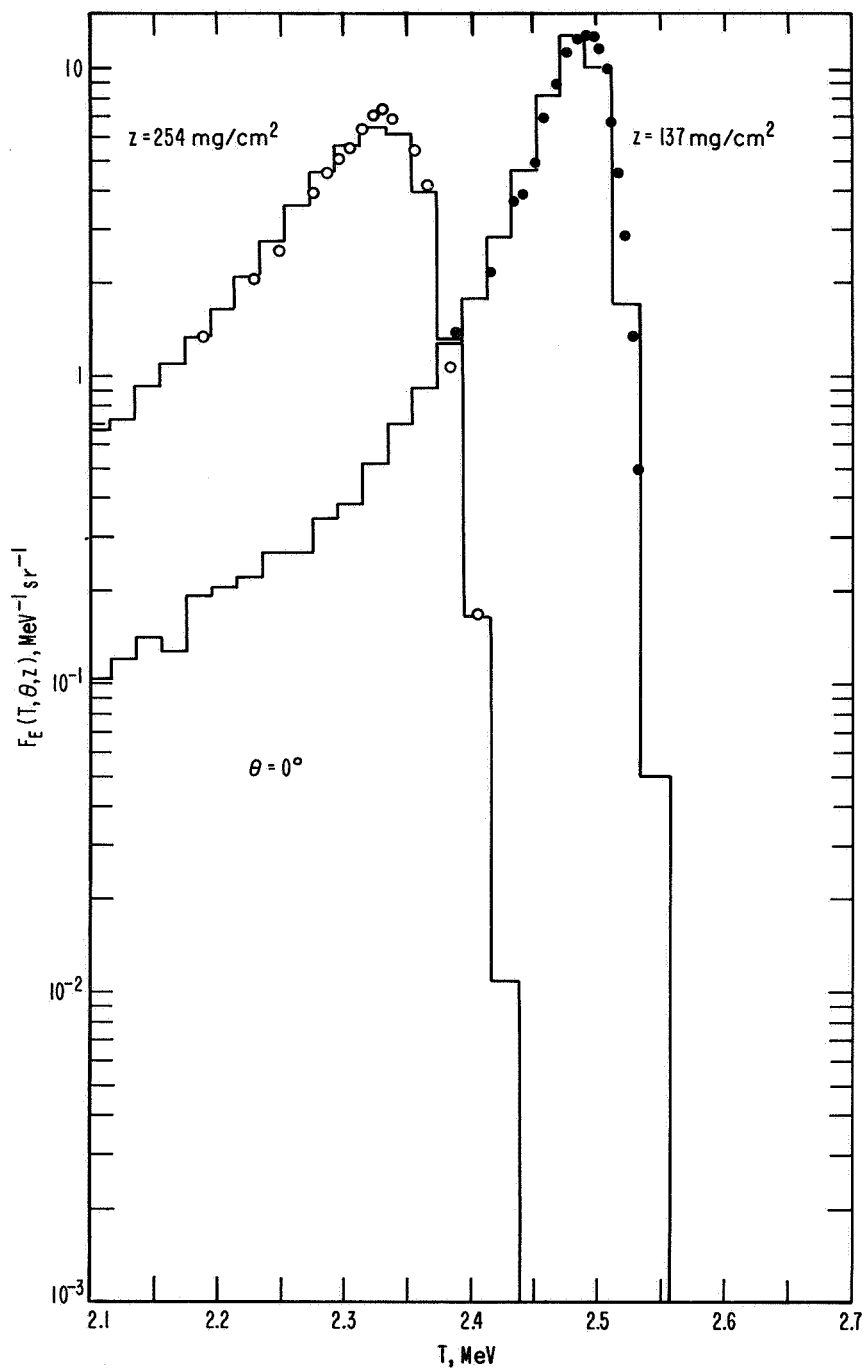


Figure 3. Energy spectra of transmitted electrons emerging in forward direction from aluminum target bombarded with 2.66-Mev electrons. Normal incidence. Target thicknesses are 0.137 g/cm² (=0.084 r₀) and 0.254 g/cm² (=0.15 r₀). Points are from an experiment by Van Camp and Vanhuyse. Histograms were obtained with Monte Carlo program ETRAN 15.

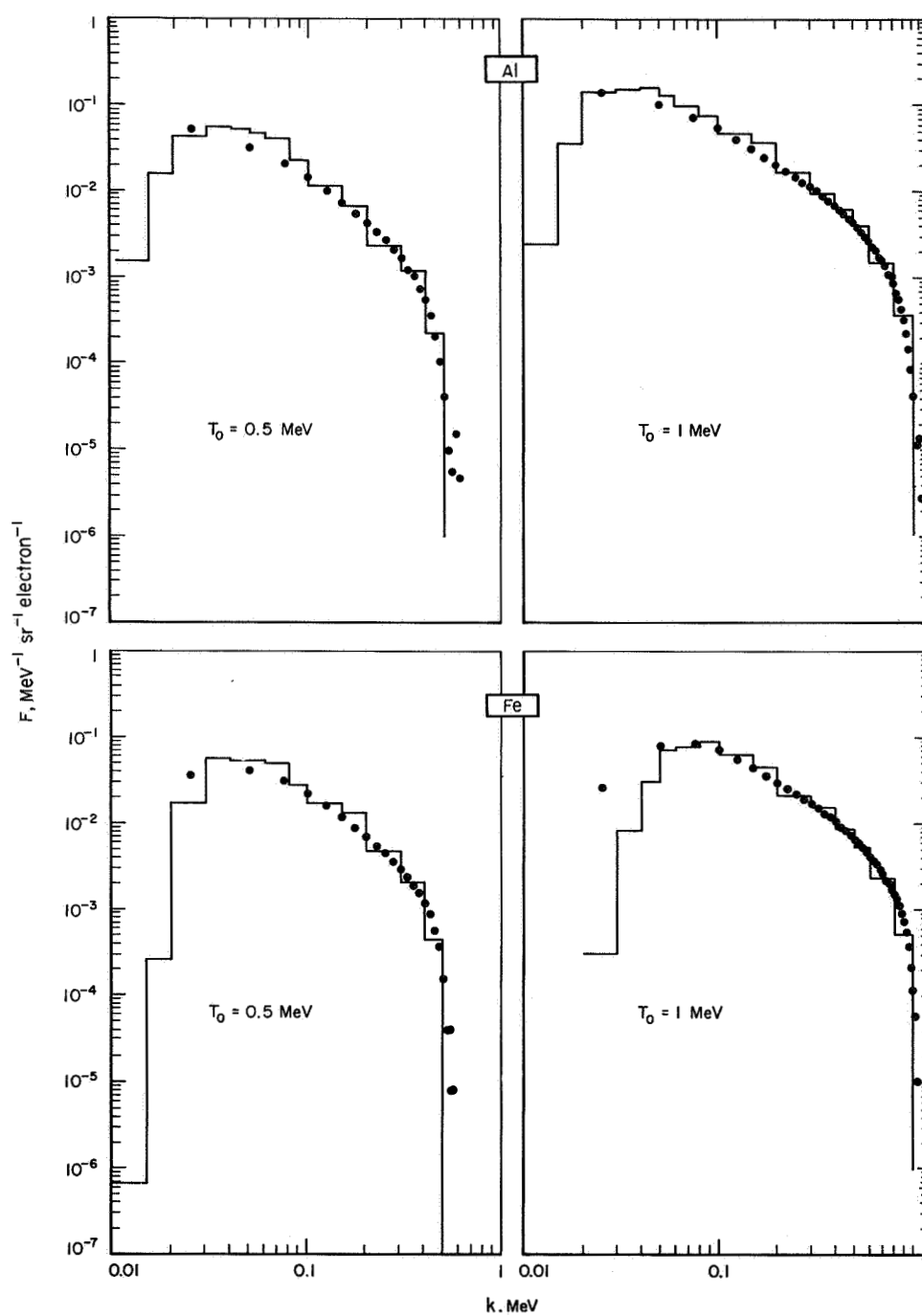


Figure 4. Energy spectra of bremsstrahlung emerging in forward direction (0 degrees). Normal incidence. Aluminum targets with thickness of 0.548 g/cm^2 ($=2.44 r_0$) for $T_0 = 0.5 \text{ MeV}$ and 0.707 g/cm^2 ($=1.29 r_0$) for $T_0 = 1 \text{ MeV}$. Iron targets with thickness of 0.248 g/cm^2 ($=1.0 r_0$) for $T_0 = 0.5 \text{ MeV}$ and 0.870 g/cm^2 ($=1.44 r_0$) for $T_0 = 1 \text{ MeV}$. Points are from experiment of Dance and Baggerly. Histograms were calculated with Monte Carlo program THICKBREM.

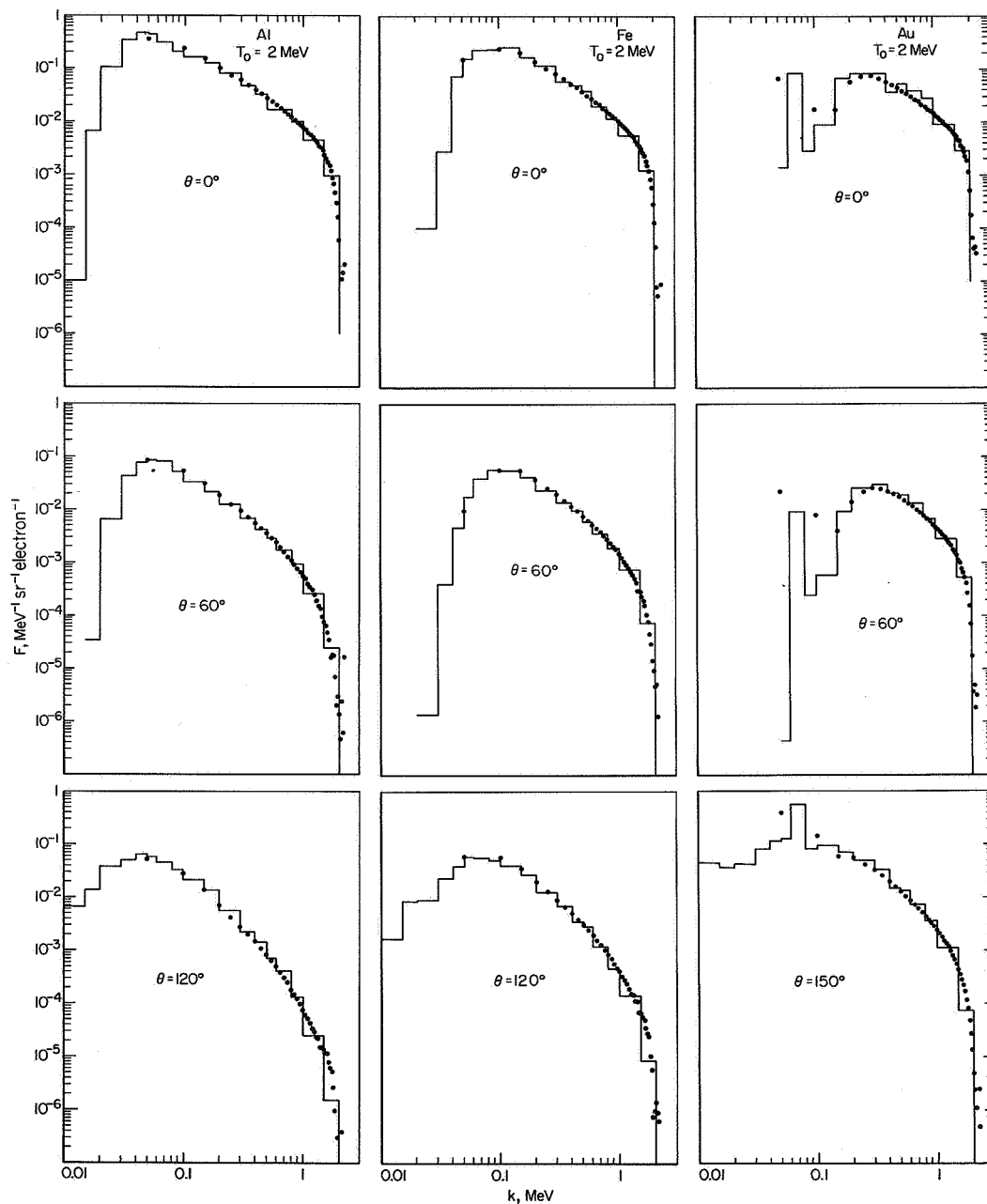


Figure 5. Energy spectra of bremsstrahlung emerging in various directions from thick targets bombarded by 2-Mev electrons. Normal incidence. Target thicknesses are 1.74 g/cm^2 ($=1.43 r_0$) aluminum, 1.30 g/cm^2 ($=0.986 r_0$) iron, and 1.62 g/cm^2 ($=1.04 r_0$) gold. Points from the experiment by Dance and Baggerly. Histograms were calculated with Monte Carlo program THICKBREM.

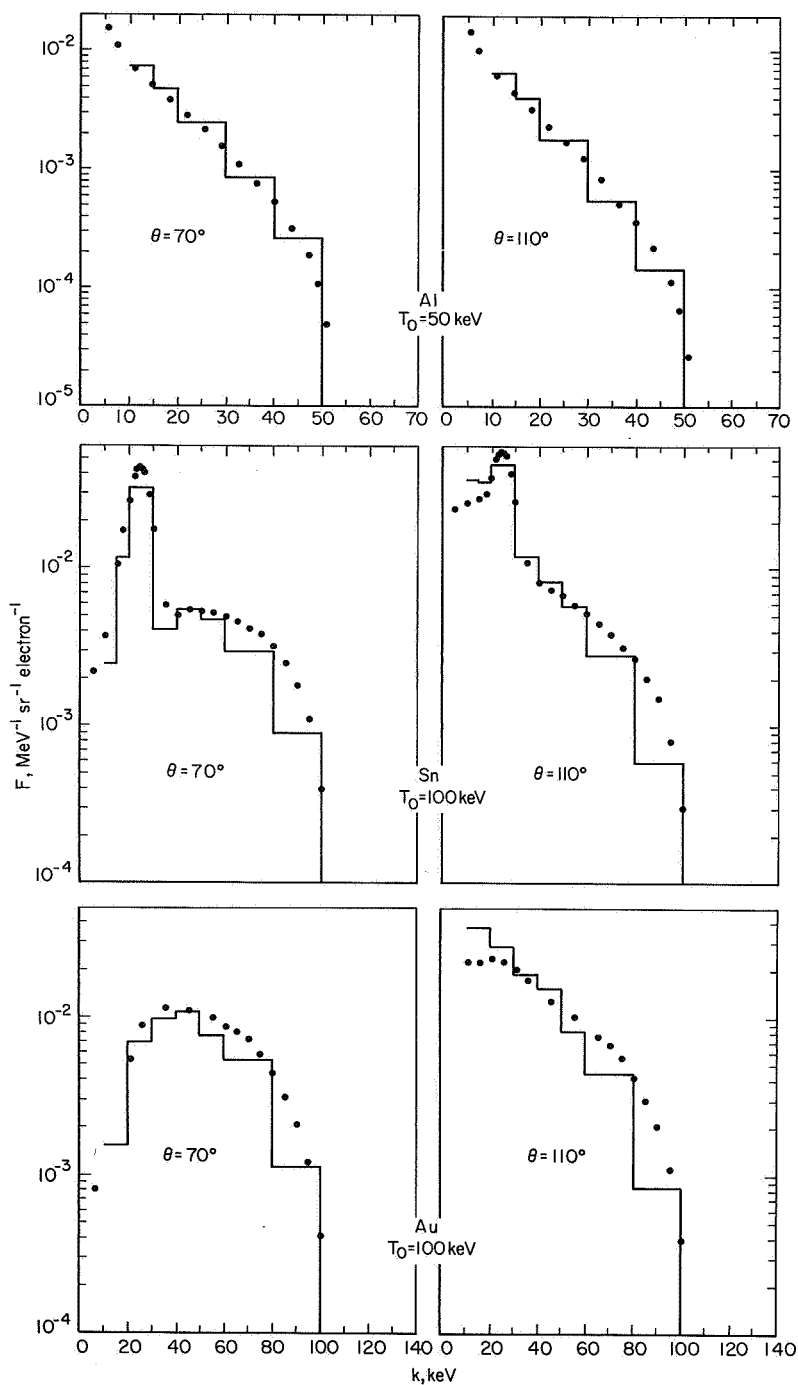


Figure 6. Energy spectra of bremsstrahlung emerging in forward and backward directions from thick targets. Normal incidence. Target thicknesses are 3.8 mg/cm^2 ($=0.67 r_0$) aluminum for $T_0 = 50 \text{ keV}$, 21.6 mg/cm^2 ($=0.82 r_0$) tin for $T_0 = 100 \text{ keV}$, and 19.3 mg/cm^2 ($=0.64 r_0$) gold for $T_0 = 100 \text{ keV}$. Points are from an experiment by Placious. Histograms were calculated with Monte Carlo program THICKBREM.

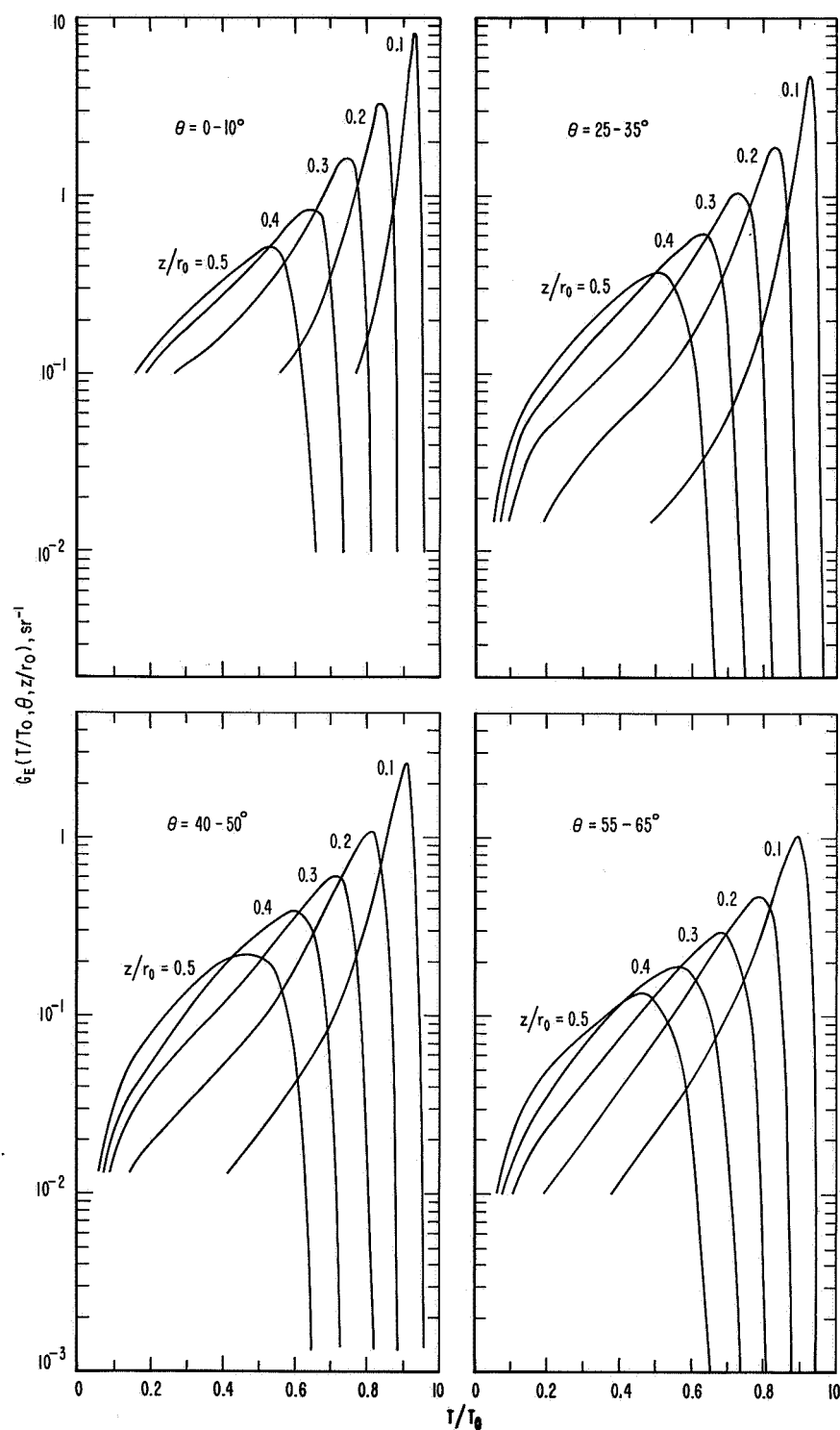


Figure 7. Energy spectra of transmitted electrons emerging in various directions from aluminum targets. Source energy 2 Mev, cosine-law source. Calculated by M. Lopez with Monte Carlo program ETRAN 5.

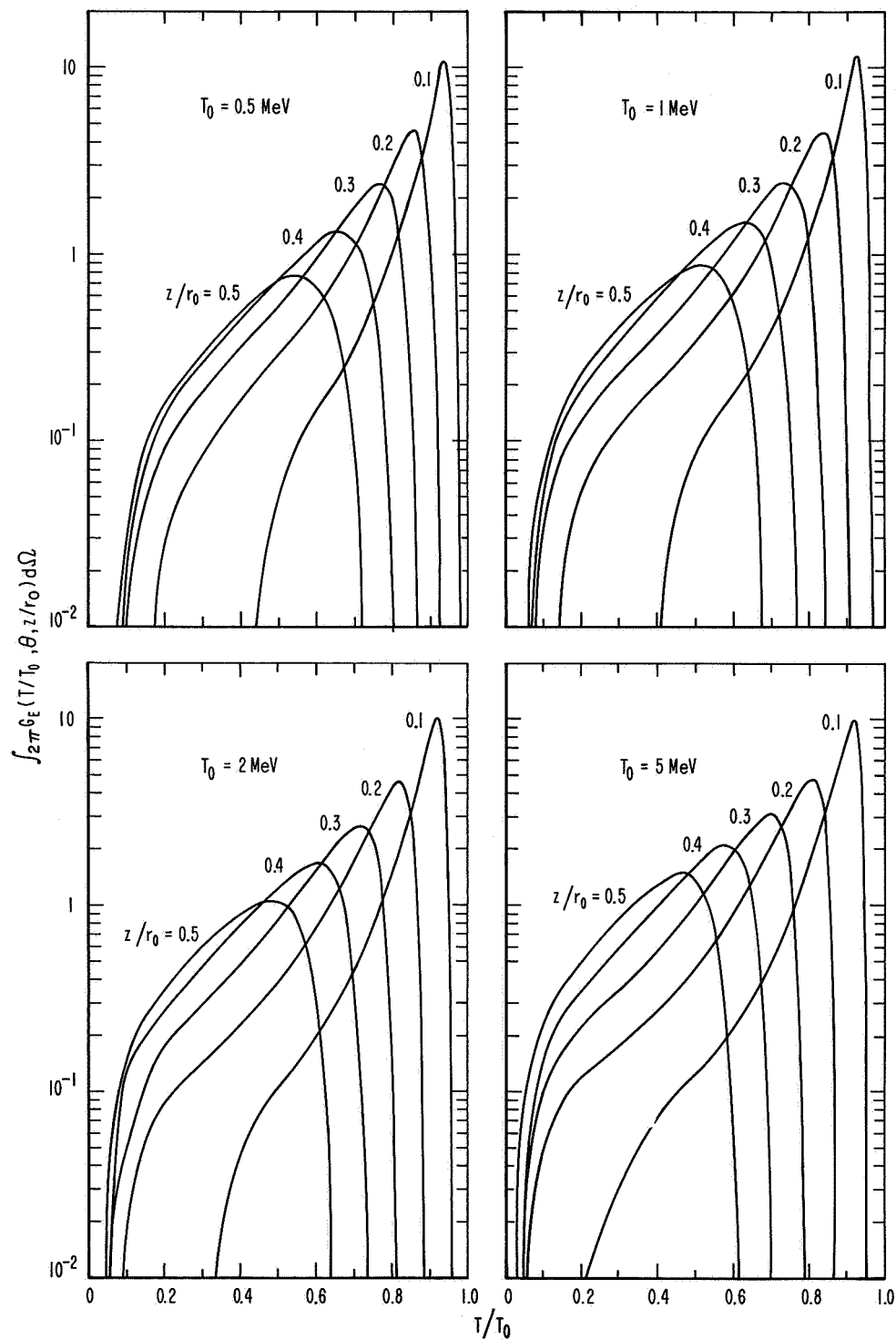


Figure 8. Energy spectra of electrons transmitted through aluminum. Spectra are integrated over all forward directions. Cosine-law source. Calculated by M. Lopez with Monte Carlo program ETRAN 5.

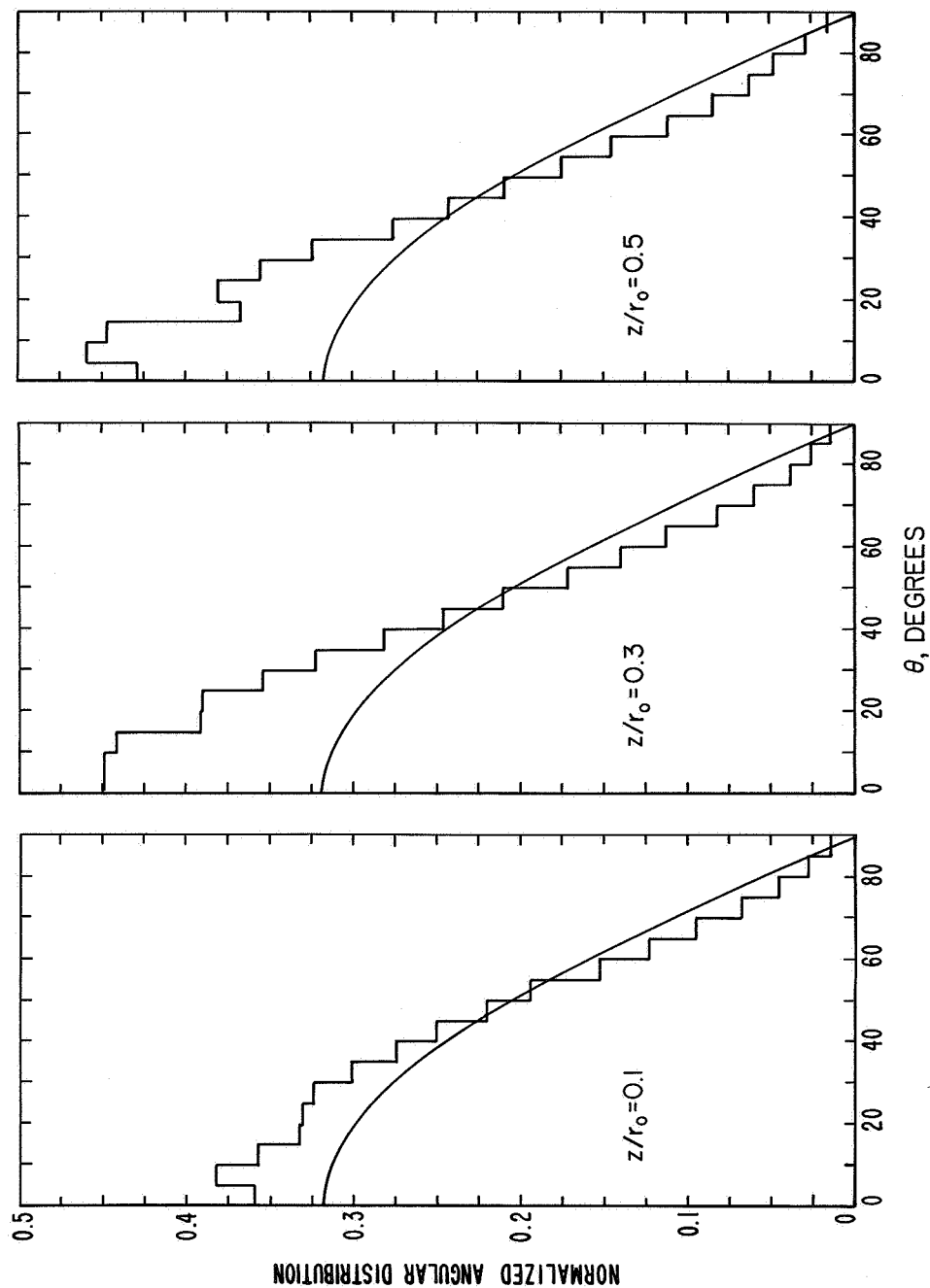


Figure 9. Angular distribution of electrons transmitted through aluminum. Distributions are normalized to unity. $T_0 = 2$ Mev, cosine-law source. Histograms are Monte Carlo results obtained by M. Lopez with program ETRAN 5. The curves represent the distribution $(1/\pi)\cos\theta$.

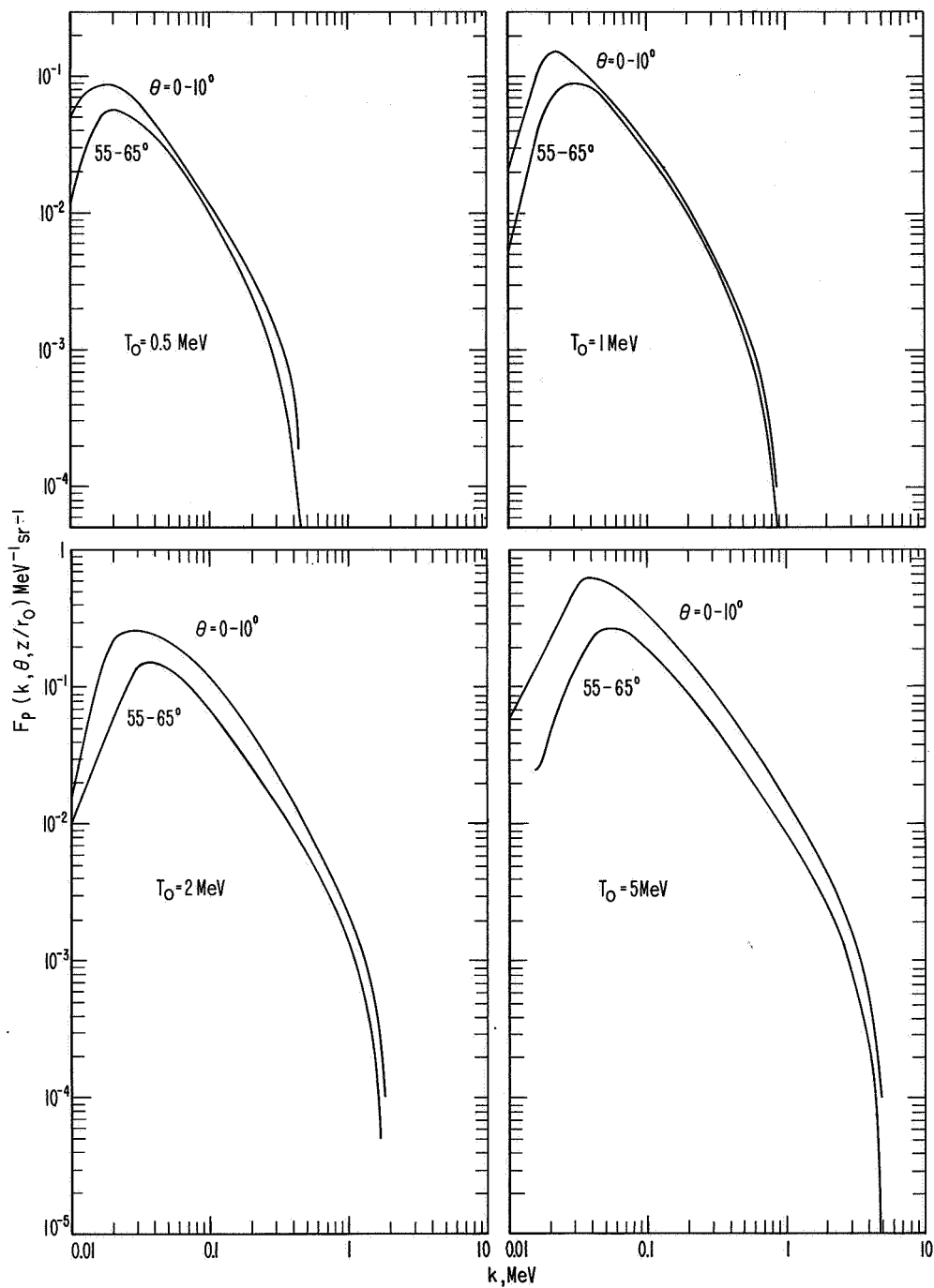


Figure 10. Energy spectra of bremsstrahlung emerging in various directions from thick aluminum targets. Cosine law source, target thickness $0.6 r_0$. Calculated with Monte Carlo program ETRAN 15.

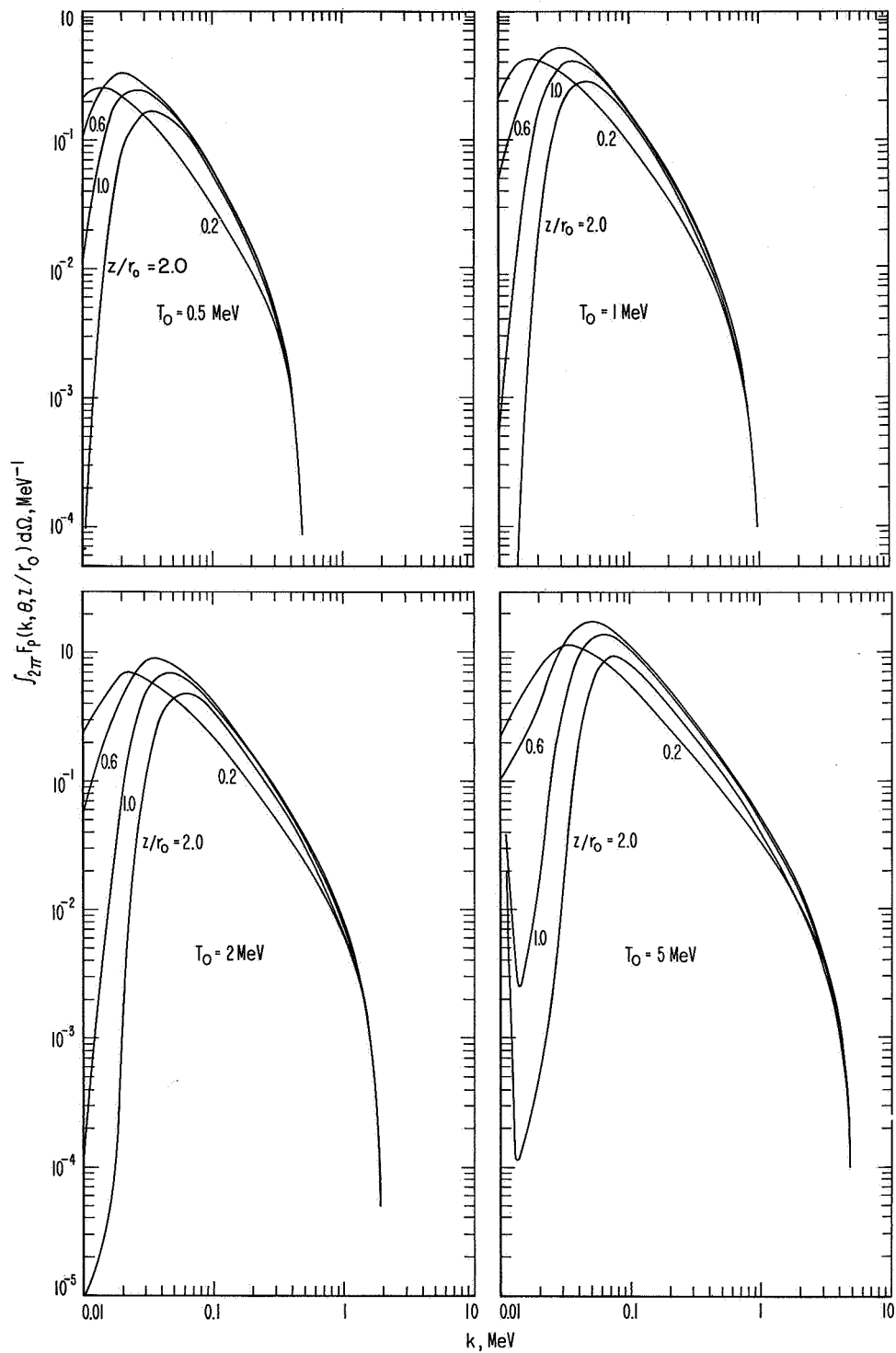


Figure 11. Energy spectra, integrated over all forward directions of bremsstrahlung emerging from thick targets. Cosine law source. Calculated with Monte Carlo program ETRAN 15.

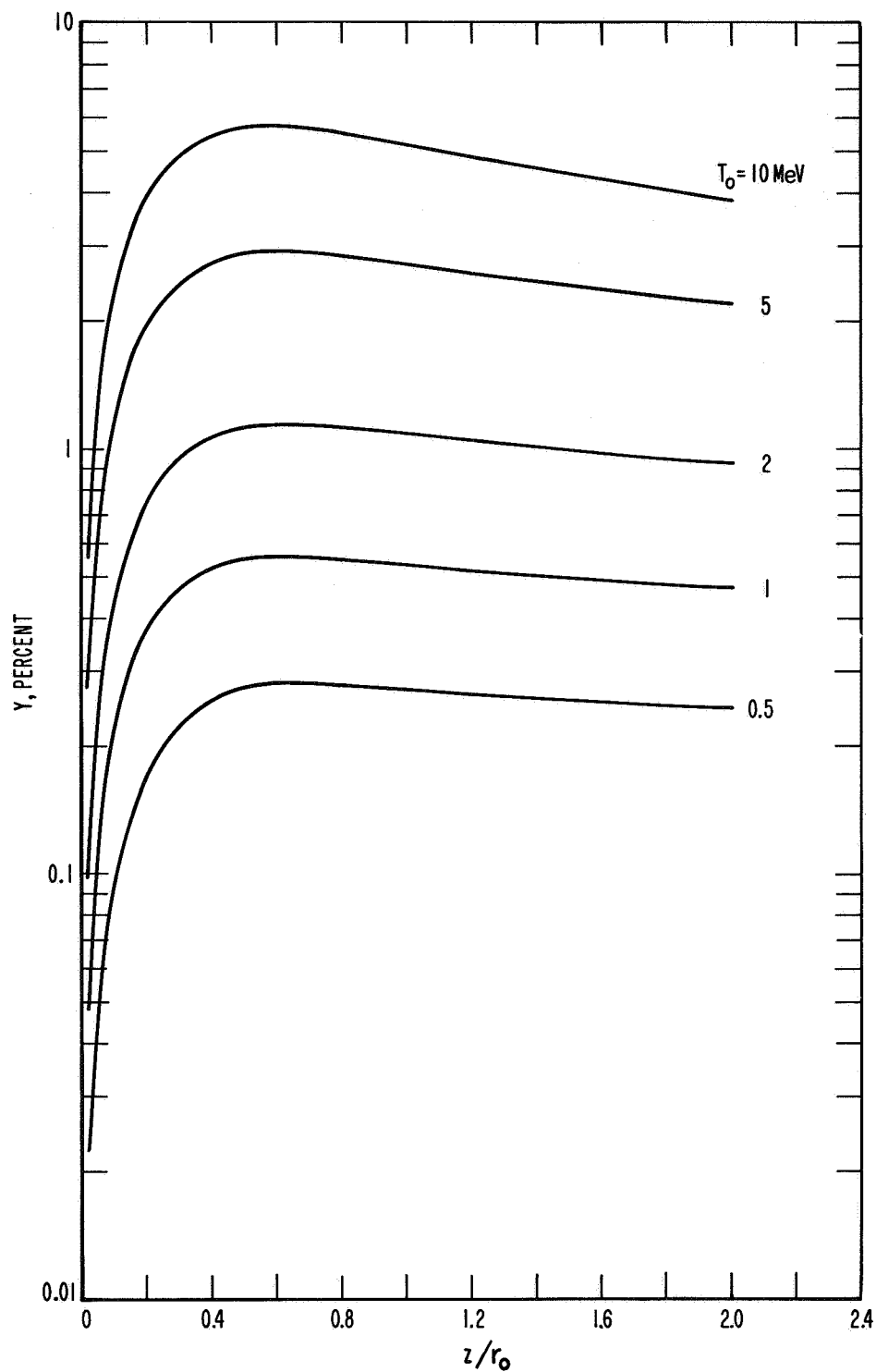


Figure 12. Forward bremsstrahlung efficiency for aluminum, as function of target thickness, for a cosine law source. Calculated with Monte Carlo program ETRAN 15.

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