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Electron Energy and Charge Albedos--Calorimetric Measurement vs Monte Carlo Theory

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Grant J. Lockwood, Laurence E. Ruggles,
Glenn H. Miller, John A. Halbleib

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ELECTRON ENERGY AND CHARGE ALBEDOS--
CALORIMETRIC MEASUREMENT VS MONTE CARLO THEORY

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ABSTRACT

A new calorimetric method has been employed to obtain saturated energy albedos for Be, C, Al, Ti, Mo, Ta, U, and UO_2 over the range of incident energies from 0.1 to 1.0 MeV. The technique was so designed to permit the simultaneous measurement of saturated charge albedos. In the cases of C, Al, Ta, and U the measurements were extended down to about 0.025 MeV. The angle of incidence was varied from 0° (normal) to 75° in steps of 15° , with selected measurements at 82.5° in Be and C. In each case, state-of-the-art predictions were obtained from a Monte Carlo model. The generally good agreement between theory and experiment over this extensive parameter space represents a strong validation of both the theoretical model and the new experimental method. Nevertheless, certain discrepancies at low incident energies, especially in high-atomic-number materials, and at all energies in the case of the U energy albedos are not completely understood.

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ELECTRON ENERGY AND CHARGE ALBEDOS-- CALORIMETRIC MEASUREMENT VS MONTE CARLO THEORY

I. Introduction

Over the past few decades, an abundance of electron charge backscattering data, both integral and differential, has become available.¹ However, a similar claim cannot be made in the case of electron energy backscatter. The only known attempt at a direct integral measurement is that of Wright and Trump.² Integral energy reflection information is usually obtained either from two-dimensional integration of angular-dependent pulse-height distributions or from theoretical models. The former method involves angular interpolation and/or extrapolation and careful corrections for detector response. The latter alternative will remain especially undesirable until the backscatter predictions of these models have themselves been adequately verified through comparison with accurate experimental measurements.

For material thicknesses greater than the range of the source electrons and where bremsstrahlung losses are small, the complements of absolute, high-precision, electron energy deposition data should yield indirect, though more reliable, values of saturated integral electron energy albedos. This follows from the identity

$$R_e \equiv 1 - (D + E_\gamma)/E_0, \quad (1)$$

where

- R_e = desired reflection coefficient
- D = total deposited energy
- E_γ = escaping bremsstrahlung energy
- E_0 = kinetic energy of the incident electrons

However, most methods of measuring energy deposition that might be considered absolute (e.g., passive dosimetry) are not precise enough to yield accurate backscatter data for low atomic number media. Other methods such as ionization chambers are more precise, but not generally considered absolute. Indeed, the complement of the integral energy reflection coefficient, which now can only be obtained in one of the two ways described above, is often used to normalize the energy deposition data.

Recently, an improved technique for the absolute measurement of energy deposition using calorimeters was developed.³ This paper presents the results of a series of experiments in which backscattered energy was determined from precise energy deposition measurements using this technique. The fraction of the energy backscattered for electrons incident on beryllium (Be),

carbon (C), aluminum (Al), titanium (Ti), molybdenum (Mo), tantalum (Ta), uranium (U), and uranium oxide (UO_2) were determined as a function of the energy and angle of incidence of the source electrons. The energies used were nominally 0.1, 0.3, 0.5, and 1.0 MeV for all materials. Additional results at about 0.025, 0.050, and 0.075 MeV were obtained for C, Al, Ta, and U. The angle of incidence was varied from 0° to 75° in steps of 15° with additional measurements at 82.5° in Be and C. As far as we know, these data represent the first systematic integral measurements of electron energy albedos.

To complement the determination of backscattered energy in the situations described above, we also measured the fraction of electrons backscattered. Significant discrepancies remain in the existing data; for example, there is a scatter of at least 25% in the results given in Reference 1 for 1.0-MeV electrons normally incident upon Al.

The calorimetric method is reviewed in Section II. The experimental apparatus and procedures are described in Section III. Code verification is an important application of these data. In Section IV we describe how the TIGER code⁴ was used to generate a state-of-the-art prediction for each experimental albedo and to estimate the small corrections for bremsstrahlung escape. Section V is a complete systematic, graphical and tabular presentation of both experimental and theoretical results, including excerpts that have appeared in previous publications.^{5,6} Concluding remarks are contained in Section VI.

II Calorimetric Method

The analysis of the calorimetric response for the particular method used in this experiment was given in some detail in a previous report.³ The major part of that discussion is reproduced here with small changes as appropriate to this particular problem. The reader may refer to the previous report if he is interested in the more complete discussion.

For our purpose, we consider a circular calorimeter of uniform thickness (w)*, radius (r_0), density (ρ), specific heat (c), thermal conductivity (K_1), and thermal emissivity (ϵ), where cgs units are used throughout. The calorimeter is supported by a number of short wires, each of length L and thermal conductivity K_2 ; the total cross sectional area of all support wires combined is A . These wires are assumed to terminate in a perfect heat sink. It is assumed that there is no azimuthal temperature variation. The difference between the temperature at radius r and that of the heat sink as a function of radius and time is $u(r, t)$.

* w was chosen to be greater than the range of the most energetic electrons.

Simple considerations lead to the following differential equation³:

$$\frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial u}{\partial r} \right) - \alpha^2 u = \beta^2 \frac{\partial u}{\partial t} - \frac{\dot{q}(r, t)}{wK_1} \quad (2)$$

where

$$\alpha^2 = \frac{8\sigma\epsilon T_o^3}{wK_1} \quad \text{and} \quad \beta^2 = \frac{\rho c}{K_1} \quad .$$

In these expressions all symbols have been defined except the following:

σ = the Stefan-Boltzmann constant

T_o = the Kelvin temperature of the enclosure and heat sink

$\dot{q}(r, t)$ = the rate of heat input per unit area

NOTE: $T^4 - T_o^4$ has been approximated by $4T_o^3 u$

Our method employs beam modulation where the beam is a 100% modulated square wave (on-off) of period t_o . The areal rate of heat input is then given by

$$\dot{q}(r, t) = \dot{q}(r) \quad \text{for} \quad Nt_o < t \leq (N + 1/2)t_o \quad (3)$$

$$\dot{q}(r, t) = 0 \quad \text{for} \quad (N + 1/2)t_o < t \leq (N + 1)t_o \quad ,$$

where N is an integer. The initial condition is

$$u(r, 0) = 0 \quad , \quad (4)$$

and the boundary condition is

$$\left. \frac{\partial u(r, t)}{\partial r} \right|_{r=r_o} = -\gamma^2 u(r_o, t) \quad . \quad (5)$$

Here γ is defined by

$$\gamma^2 = \frac{K_2 A / L}{2\pi r_o wK_1} \quad .$$

The equilibrium solutions ($N \rightarrow \infty$) to Eq (2) are given by

$$u(r, t) = \sum_{n=1}^{\infty} A_n J_o(k_n r) \left[1 - \mu_n e^{-t'/\tau_n} \right], \quad Nt_o < t \leq (N + 1/2)t_o \quad (6a)$$

and

$$u(r, t) = \sum_{n=1}^{\infty} A_n J_0(k_n r) \mu_n e^{-t''/\tau_n}, \quad (N + 1/2)t_0 < t \leq (N + 1)t_0. \quad (6b)$$

Here t' and t'' are the times measured from Nt_0 and $(N + 1/2)t_0$, respectively. The k_n 's are the roots of Eq (5), which are obtained from

$$k_n J_1(k_n r_0) = \gamma^2 J_0(k_n r_0), \quad (7)$$

and the τ_n 's are given by

$$\tau_n = \frac{\beta^2}{\alpha^2 + k_n^2}. \quad (8)$$

The μ_n 's are defined by

$$\mu_n = \left[1 + e^{-t_0/2\tau_n} \right]^{-1}. \quad (9)$$

J_0 and J_1 are the zero- and first-order Bessel functions. The A_n 's are the Fourier-Bessel coefficients that are given by

$$A_n = \frac{2\tau_n}{w\rho c r_0^2} \frac{1}{J_0^2(k_n r_0) + J_1^2(k_n r_0)} \int_0^{r_m} \dot{q}(r) J_0(k_n r) r dr, \quad (10)$$

where r_m is the maximum radius at which there is heat input. It is convenient to define $f(r)$, so that

$$\dot{q}(r) = \frac{\dot{Q}_0}{\pi r_m^2} f(r), \quad \text{and} \quad \int_0^{r_m} f(r) 2\pi r dr = \pi r_m^2. \quad (11)$$

Here $\dot{Q}_0$ is the total rate of heat input. Then we obtain

$$A_n = \frac{2\dot{Q}_0 \tau_n}{\pi r_0^2 w\rho c} \frac{1}{J_0^2(k_n r_0) + J_1^2(k_n r_0)} \frac{1}{r_m^2} \int_0^{r_m} f(r) J_0(k_n r) r dr. \quad (12)$$

For the special case where $f(r) = 1$ (i.e., the energy is put in uniformly over a circle of radius r_m), we obtain

$$A_n = \frac{2\dot{Q}_0 \tau_n}{\pi r_o^2 \rho c} \frac{1}{J_0^2(k_n r_o) + J_1^2(k_n r_o)} \frac{J_1(k_n r_m)}{k_n r_m} \quad (13)$$

We will assume such an input for the discussion that follows. At critical points the consequences of this assumption will be noted.

It was shown in Reference 3 that a measurement of the amplitude of the modulated temperature signal in many cases does not give a satisfactory measurement of the energy deposition. This is true because the amplitude is very dependent on the geometry of the energy input term. Thus, the sensitivity is dependent on the radius over which energy deposition occurs. We search for an alternative method of determining deposition from calorimeter temperature variation.

Equation (8) indicates that the time constants of successive terms in Eq (6) decrease rapidly as k_n increases. Examination of a table of roots of Eq (7)⁷ shows that k_n increases rapidly with n , thus causing a rapid decrease in τ_n . In a typical case, successive time constants were calculated to be 75, 1.25, 0.4, and 0.2 s for $n = 1, 2, 3$, and 4, respectively. This immediately suggests that, due to the negative exponential, all terms other than the first can be depressed by taking the time derivative at a time $(t_d)^*$ in each half-cycle that is large compared to τ_2 . We would then have

$$\left. \frac{du}{dt} \right|_{t=t_d} = \pm \sum A_n J_0(k_n r_o) \frac{\mu_n}{\tau_n} e^{-t_d/\tau_n} \quad (14)$$

The plus or minus algebraic signs are obtained for the two half-cycles in Eq (6). If the condition $t_d \gg \tau_2, \tau_3$, etc, prevails, then

$$\left. \frac{du}{dt} \right|_{t=t_d} \cong \pm A_1 J_0(k_1 r_o) \frac{\mu_1}{\tau_1} e^{-t_d/\tau_1} \quad (15)$$

This solves no problem unless A_1 is a constant (independent of r_m); it is, in fact, a good approximation. Since $r_m \leq r_o$, we consider the range of $k_1 r_o$.

Because of the small value of $k_1 r_o$ (< 2.405), the value of the factor

$$\frac{2J_1(k_1 r_o)}{k_1 r_o}$$

* t_d is a particular value of either t' or t'' .

is limited by

$$1 \geq \frac{2J_1(k_1 r_m)}{k_1 r_m} \geq 0.43 ,$$

with the limits arranged in order of increasing $k_1 r_m$. While this is a large change, it is also unrealistic. In general, the characteristics of the support wires that determine γ^2 in Eq (7) will be chosen so that $k_1 r_o$ will be no more than about 0.5, resulting in a lower limit of

$$\frac{2J_1(k_1 r_o)}{k_1 r_o} = 0.97 .$$

While this is very satisfactory, this lower limit is still overly generous. In most cases, r_m will never be greater than $0.3 r_o$; then the lower limit is about 0.997 instead of 0.97.

The foregoing makes it clear that the derivative method provides a sensitivity that is very nearly constant. At this point one must reexamine the assumption that the energy is deposited in a manner independent of azimuth. Without attempting to solve the more general problem where $\dot{q} = \dot{q}(r, \phi)$, we can make an observation. If there is a ϕ -dependence either by displacing the deposition axis or by making the beam asymmetrical, then the result is to introduce Bessel functions of order greater than zero into the series of Eq (6). These terms will also have time constants short compared to τ_1 , and therefore will be removed by the derivative process. Experimentally, the beam position was varied over a wide range ($\sim 30\%$ of r_o) with only small ($\sim 2\%$) variations in sensitivity. Typically the alignment in an experiment is maintained to within $0.05 r_o$. However, asymmetries may become large for oblique incidence.

From Eqs (13) and (15), one may now obtain an expression for $\dot{Q}_o$. The approximations

$$\frac{2J_1(k_1 r_m)}{k_1 r_m} = 1 ,$$

and

$$\frac{J_o(k_1 r)}{J_o^2(k_1 r_o) + J_1^2(k_1 r_o)} = 1$$

are made. These are both good within a few tenths of a percent for typical cases. This gives

$$\dot{Q}_o = \pi r_o^2 w \rho c \left(1 + e^{-t_o/2\tau_1} \right) e^{t_d/\tau_1} \left. \frac{du}{dt} \right|_{t=t_d} . \quad (16)$$

Equation (16) indicates that one is to take the derivative at $t = t_d$, calculate e^{t_d/τ_1} , and insert these as factors into the equation. Several considerations enter into the choice of t_d ; it must be large compared to τ_2 . In addition, it might be chosen to minimize variations in (or errors in the value of) τ_1 . By differentiating the τ_1 -dependent factors with respect to τ_1 and setting the derivative equal to zero, one finds that

$$t_d = \frac{t_o}{2} e^{-t_o/2\tau_1} \left[1 + e^{-t_o/2\tau_1} \right]^{-1}.$$

However, this criterion is not generally compatible with $t_d \gg \tau_2$. The problem was finally solved in the following manner. The data were processed in real time by an on-line digital computer (see Section III). The derivative was calculated continuously for $t_d \gg \tau_2$, and the computer produced a least-squares linear fit of $\ln \left(\frac{du}{dt} \right)$ as a function of t_d . From this, the derivative could be calculated at any given time (even at $t_d \leq \tau_2$) with maximum precision, since all available data were used.

The calorimeters used in this experiment were calibrated by means of a 100-keV positive ion accelerator. The same modulation rate and energy-deposition rate was used in each case. The use of positive ions is advantageous because (a) the range at this energy is much less than the calorimeter thickness, (b) backscatter is very small, and (c) bremsstrahlung production is negligible.

The design of total stopping calorimeters is much less complicated than that of thin-foil calorimeters. In the latter case, it was important to have large thermal conductivity and low thermal emissivity. While these are still desirable for thick calorimeters, the importance is diminished. Thus, materials that are marginal for thin calorimeters because of these properties are quite satisfactory for total stopping purposes. The thermal-coupling problem³ that was so important in the thin-foil case is nearly nonexistent here. The discussion concerning support wires, thermocouples, and modulation period in connection with thin foils³ is also applicable here.

III. Apparatus and Procedures

The experimental method employed to determine back scattered energy uses the complements of absolute, high-precision, electron energy deposition measurements. These measurements use a square-wave modulated (on-off) electron beam and a calorimeter. The calorimeter is made of the material under investigation and is thicker than the range of the most energetic electrons used. The apparatus consists of a 1.0-MeV electron accelerator, a large vacuum chamber with a beam-measuring Faraday cup, and an experimental package.

The electron accelerator delivers monoenergetic electron beams of up to 34 μA . The energy range is from 0.025 to 1.2 MeV. Because of the charging system design, the voltage ripple is less than 100 V at 1.0 MeV. A Sandia-designed voltage regulator has been incorporated that provides regulation within 1 kV at 1.0 MV. The beam energy is known to approximately 0.5%. A high-precision calorimetric system was developed for determining beam energy.⁸ Prior to this development, the electron energy was calibrated by comparing pulses produced in a solid-state ion chamber by electrons from thin conversion sources with those produced by electrons from the accelerator. The energy determined by the solid-state ion chamber system was found to be high by a few percent. Since the reflected energy is obtained by dividing the energy deposited by the incident energy, all such determinations were made using the actual incident energy. These determinations are shown for each material in Section V.

The stainless-steel vacuum chamber is 1.22 m in diameter, contains a Faraday cup, and has an experimental mounting platform (Figure III-1). The Faraday cup, which is in line with the beam, precedes the mounting platform and is equipped with a solenoid-actuated end plate. This end plate is used to electromechanically modulate the beam that is measured by the cup during the "off" half-cycle. Since the cup subtends only a very small solid angle for electrons backscattered from the experimental package (located on the mounting platform), there is negligible probability of interference in the measurement of energy or charge deposited. The position of the mounting platform, which follows the Faraday cup, is adjustable and permits the experimental package to be located on the beam axis and positioned with the face of the calorimeter at the platform's axis of rotation. With this arrangement, the experimental package can be rotated about the beam axis in order to vary the angle of incidence. With the separated in-line Faraday cup, the beam-current measurement is not affected by the position of the experimental package. When energy deposition was measured for incident angles other than zero degrees, two methods of setting and determining the angle were employed. At first, the angle was set by physically rotating the mounting platform and reading the angle from the scale and vernier located on the shaft. Since the radiation cell had to be entered to change angles, the data were taken with the angle set to one side of 0° only. This meant that if there was a small uncertainty in 0° that would not significantly affect the normally incident data, this uncertainty would be added to the angle determination. The angle was read to $\pm 0.5^\circ$, and we estimate the uncertainty in 0° to be $\pm 0.5^\circ$. When we used this method, we made at least one measurement of reflected energy and charge at a large angle set on both sides of 0°

and the percent difference was determined. For reflected energy and number, this difference was generally less than 1% and 2%, respectively. To correct this problem, a new system was installed. In this system, the angular position of the mounting platform is continuously adjustable from the control room by means of an electric motor. The angle of rotation was measured to 0.1° with a shaft encoder. With this arrangement, all angular measurements were obtained from the average of two determinations made when the platform was set at the desired angle on either side of 0° . Thus, any small uncertainty in 0° would essentially be removed by this method. For each material, a list is given in Section V that identifies the angle determination method used as either hand or remote set. The beam axis is defined by an aperture located in front of the Faraday cup and a similar aperture on the movable mount at the front edge of the platform. The second aperture is movable and so can be used to locate the beam on axis; it can then be moved from the path so that electron scattering from it does not occur and hence does not affect the measurement.

Figure III-1 Faraday Cup and Experimental Mounting Platform

The experimental apparatus used to make the deposition measurements is shown in Figure III-2. The main components are the calorimeter, thermocouple, and reference junction. The apparatus could be fitted with a Faraday cup shield for calibration. This will be discussed later.

The calorimeters are circular and serve as targets for both energy- and charge-deposition measurements. For each material the selected thickness was slightly greater than the range of electrons at maximum energy. The diameter was made large enough to tolerate a slight misalignment to the beam at incidence angles of 75° or greater. This resulted in a typical diameter of 5 cm.

Figure III-2 Experimental Apparatus

The thermocouple was made of No. 40, Chromel-Constantan thermocouple wire. The thermocouple junction was usually located on the circumference of the calorimeter. In several cases, however, the properties of the calorimeter material resulted in an abnormally large second time constant. After the beam current switched, the large second time constant produced a very long turn-around time for the thermocouple signal. In these cases, the thermocouple junction was located at the zero of the Bessel function in the second term of the expression for equilibrium temperature (Eq (6)) so that this term did not contribute. This location is at about 0.6 of the calorimeter radius; placing the thermocouple junction there resulted in a faster turnaround. The reference junction was located in the mounting-ring heat sink (see Figure III-2).

The calorimeter and mounting ring were mounted to a base plate, but electrically insulated from it. Each element was connected to a hermetically sealed BNC connector mounted in the base plate. This allowed for the measurement of total electron current deposited as well as the calorimeter thermocouple signal. The base plate was compatible with both the mounting platform in the vacuum chamber on the electron accelerator and the vacuum chamber on the heavy-ion accelerator used for calibration. This arrangement allowed the experimental apparatus to be moved from the electron accelerator to the heavy-ion accelerator without disturbing any of the internal electrical connections.

Calibration of the calorimeter was accomplished by means of a heavy-ion accelerator. Since the range of heavy ions of 100-keV energy is much less than the thickness of any of the calorimeters and since the reflection coefficient and the bremsstrahlung production are very small, the energy deposited in the calorimeter was determined by multiplying the incident beam current by the accelerating potential. The beam current measurement was made using a Faraday cup shield (FCS) attached to the experimental apparatus (Figure III-2). The FCS satisfied the requirements for a deep Faraday cup, insuring that the escape of secondary electrons ejected from the calorimeter by impact of the heavy ions was negligible. The accelerating potential was measured with a calibrated voltage divider and corrected for ion-source potentials. This accelerating potential is known to within $\pm 1\%$. The incident ion beam was modulated in calibration to produce a symmetric square wave having the same period used with the electron measurements. Thus, the response of the calorimeter was determined for a well-defined rate of energy input.

The fraction of electrons backscattered was determined using a very straightforward method. The incident beam current (i_b) was measured in the in-line Faraday cup. The deposited current (i_d) was measured with the target (calorimeter) maintained at a positive potential of approximately 55 V. This was adequate to return the great majority of secondary electrons without significantly affecting the backscattered primaries. The fraction of electrons backscattered is given by $1 - i_d/i_b$. Data acquisition and reduction was performed with an on-line computer.

The fraction of energy backscattered was obtained by subtracting the deposited energy from the incident energy and dividing the result by the incident energy. This was corrected for energy escaping in the form of bremsstrahlung as discussed in Section V. The data for determining the energy deposited was collected and processed by the on-line computer. A block diagram of the system is shown in Figure III-3. All measuring instruments used in the calibration are the same as those used to obtain the experimental data. The beam modulation period (t_0) was selected to satisfy the requirement that t_0 should be a few times the first time constant (τ_1) of the calorimeter. Several cycles were examined by the computer. The rate of change of the thermocouple voltage (dv/dt) with time, normalized to the beam current (i_b), was calculated continuously for times $\gg \tau_2$ (the second time constant), and the computer produced a linear least-squares fit of

$$\left(\ln \frac{1}{i_b} \frac{dv}{dt} \right)$$

as a function of time. From this the derivative could be calculated at any given time with maximum precision, since all available data were used. In practice the derivative was either calculated at a desired time, t_d , or at the intercept. When the intercept was used, it was corrected for variations in the first time constant τ_1 . Thus, a quantity S is defined as

$$S = \text{Intercept} \left(1 + e^{-t_0/2\tau_1} \right)$$

The method of data reduction used with each material will be given in Section V as either t_d or S.

Figure III-3 Data Collection and Processing System

IV. Theoretical Model

All theoretical results were obtained from the one-dimensional, coupled, electron/photon, Monte Carlo transport code, TIGER.⁴ The TIGER code describes the generation and transport of the electron/photon cascade in multislabs geometries from several megaelectronvolts down to 1.0 keV for electrons and to 10.0 keV for photons. It combines condensed-history electron Monte Carlo⁹ with conventional single-scattering photon Monte Carlo. The electron transport includes energy-loss straggling, elastic scattering and the production of knock-on electrons, continuous bremsstrahlung radiation, characteristic x-rays, and annihilation radiation. Photon transport includes the photoelectric, Compton, and pair-production interactions along with the production of the corresponding secondary particles. Electron cross sections and sampling distributions are obtained from a modified version of DATAPAC-4 and LIBRARY TAPE 2 of the ETRAN Monte Carlo code system.¹⁰ The photon cross sections are the analytical fits of Biggs and Lighthill.¹¹ The method is more accurate at higher energies with a less rigorous description of the particle cascade at lower energies where the atomic shell structures of the transport media become important. The only shell effects considered are ionization of, fluorescence of, and Auger emission from the K-shell of the highest-atomic-number element in each material.

For each choice of target, incident energy, and incident angle, a single TIGER calculation yields the electron energy albedo (R_e) and bremsstrahlung escape energy (E_γ) appearing in Eq (1). The number of primary histories ranges from 6000 for high-Z targets at high angles of incidence to 200 000 for Be at normal incidence. The resulting one-sigma statistical uncertainties in the calculated albedos are 1% to 2%. Uncertainties in the bremsstrahlung escape energies were less than 10% as long as these energies were greater than 0.5% of the incident energies. As discussed in Section V, at incident energies ≥ 0.1 MeV, the "experimental" albedos were obtained by substituting these bremsstrahlung escape energies, along with the measured energy depositions and incident energies, into Eq (1).

The theoretical albedos include all backscattered electrons with energies greater than 0.004 and 0.002 MeV for incident energies of 1.0 and 0.5 MeV, respectively. At lower incident energies, they include all backscattered electrons with energies >0.001 MeV. In order to make the albedo calculations more efficient, a trapping procedure was employed. When the energy of an electron became so low that it could no longer escape from the target, this energy was deposited and the history was terminated. A special calculation without trapping for U at an incident energy of 1.0 MeV and normal incidence verified that this trapping procedure had no effect on the prediction of bremsstrahlung escape.

The cross section data used in the theoretical model become less reliable as the incident energy decreases, especially for high-Z targets. In particular, the Mott elastic-scattering cross section with Moliere screening becomes less accurate. Using improved numerical cross sections,¹² we carried out additional calculations of electron backscatter in Ta and U for source energies in the 0.01- to 0.10-MeV range at incident angles of 0° and 60° . In subsections V-F and V-G we present tabulated and graphical comparisons of the results obtained with the standard and improved cross sections, as well as a comparison with the measured data. Predictions obtained with the improved cross sections are consistently higher than those obtained with the standard cross sections. Still, at 0.033 MeV (the lowest energy at which experimental results were obtained), the maximum difference between the two theoretical predictions (occurring for the energy albedo in Ta at normal incidence) is only about 10%. On the other hand, the experimental result for this same case is about 40% higher than the standard prediction. Disagreement among the three results decreases at higher source energies and incident angles. However, at 0.010 MeV (where we have no experimental data), predictions with the new cross sections are (a) 25% higher for Ta-number albedos, (b) 50% higher for Ta-energy albedos and U-number albedos, and (c) 100% higher for U-energy albedos than those obtained with the old cross sections.

V. Results

Absolute electron energy and charge albedos have been measured for eight materials. Measurements were made as a function of energy and angle of incidence. The energy range was from 0.025 MeV to 1.0 MeV. The angle of incidence was varied from 0° to 75° in steps of 15° , and was extended for selected materials to 82.5° . These measurements are compared with the predictions of the electron-photon Monte Carlo transport code, TIGER.⁴ The results are presented graphically and tabulated in subsections V-A through V-H at the end of this section. For each material, variations both in the experimental system and data reduction that affect the data are listed. To present an overview of the results, Figures V-1a and V-1b show the fraction of energy backscattered at angles of incidence of 0° and 60° for 1.0 and 0.1 MeV, respectively, as a function of atomic number. Figures V-2a and V-2b present corresponding results for the fraction of electrons backscattered.

a. 1.0-MeV Electrons

b. 0.1-MeV Electrons

Figure V-1 Comparison of Experimental and Theoretical Energy Backscatter for Electrons Incident at 0° and 60° as a Function of Target Atomic Number

Figure V-2 Comparison of Experimental and Theoretical Number Backscatter for Electrons Incident at 0° and 60° as a Function of Target Atomic Number

The experimental results were obtained by subtracting the measured, deposited energy from the incident energy and dividing the result by the incident energy. From this was subtracted the fraction of energy escaping in the form of bremsstrahlung as determined by the TIGER code. The bremsstrahlung corrections are tabulated as a function of incident energy and angle, and are presented for each material at the end of this section. This bremsstrahlung correction is quite small for the energy range covered in these experiments. The estimated statistical accuracy of this calculated correction is better than 10%, except at low energies and low atomic numbers where the correction becomes negligible. We could have added the corrections to the predicted results instead of subtracting them from the measured escape fraction. However, the quantity of more practical importance is the energy that escapes in the form of reflected electrons only.

The estimated one-sigma statistical error in the TIGER results was maintained at approximately 1% to 2% by following the appropriate number of histories. The percent experimental uncertainty is estimated by the expression,

$$100 K_i (1 - R)^{-1} \left[1 + (K_d/K_i)^2 R^2 \right]^{1/2},$$

where R is the ratio of the deposited to the incident energy, and K_d and K_i are the fractional uncertainties in the deposited and incident energies, respectively. This expression follows directly from the assumption that the total uncertainty is just the square root of the sum of the squares of the uncertainties in the measurements of the deposited and incident energies. It is the factor $(1 - R)^{-1}$ that explicitly demonstrates the high precision required as the deposited energy approaches the incident energy at small angles of incidence for materials of low atomic number.

For each material presented, a list is given that identifies the analysis method and angle determination method used as discussed in Section III; also listed are the physical dimensions of each calorimeter. In addition, for Be, Al, Mo, Ta, and U, electron energy deposition profiles have been measured³ and integrated to obtain the total energy deposited. These values are listed along with the values from the TIGER calculation and the total energy deposited as measured with the total stopping calorimeters.

Finally, the theoretical predictions of the TIGER code calculations were performed using improved numerical cross sections for electron backscatter in Ta and U at low energies. For a discussion of these calculations, see Section IV. The results obtained with the standard and improved cross section are tabulated and compared graphically with the measured data in subsections V-F and V-G.

A. Electron Energy and Charge Albedos in Beryllium (Be)

Energies (MeV): 1.033, 0.521, 0.314, and 0.109

Angles (°): 1, 16, 31, 46, 61, 76, and 83.5

Analysis Method: t_d

Angle Determination Method: Hand set

Calorimeter

Diameter: 2.54 cm

Thickness: 0.381 cm

Table V-A(i)

A Comparison of Total Energy Deposited in Beryllium

Nominal Energy (MeV)	Angle (deg)	Fraction of Energy Deposited		
		TIGER Calculation	Total Stopping Measurement	Integrated Differential Measurement
0.5	0	0.994	0.995	0.998
0.3	0	0.993	0.993	0.994
0.1	0	0.991	0.990	1.00

Table V-A(ii)

Theoretically Calculated Fraction of the Incident Electron Energy
That Escapes From Beryllium in the Form of Bremsstrahlung

Energy (MeV)	Angle of Incidence						
	1°	16°	31°	46°	61°	76°	83.5°
1.0	1.86×10^{-3}	-	2.00×10^{-3}	1.91×10^{-3}	2.17×10^{-3}	1.62×10^{-3}	1.58×10^{-3}
0.5	9.74×10^{-4}	-	9.31×10^{-4}	1.00×10^{-3}	1.06×10^{-3}	7.25×10^{-4}	7.25×10^{-4}
0.3	5.85×10^{-4}	-	5.40×10^{-4}	6.91×10^{-4}	7.06×10^{-4}	5.64×10^{-4}	-
0.1	1.72×10^{-4}	-	1.75×10^{-4}	2.64×10^{-4}	1.72×10^{-4}	-	-

a. Comparison as a Function of Incident Energy

b. Comparison as a Function of Incident Angle

Figure V-A.1 Comparison of Experimental and Theoretical Energy Backscatter in Beryllium

Table V-A.1

Fraction of Energy Backscattered From Beryllium^{1,2}

	Energy (MeV)	Angle of Incidence						
		1°	16°	31°	46°	61°	76°	83.5°
Exp	1.033	-	1.16×10^{-2}	1.59×10^{-2}	3.16×10^{-2}	7.85×10^{-2}	2.36×10^{-1}	4.06×10^{-1}
Theory	1.0	3.40×10^{-3}	-	9.58×10^{-3}	2.68×10^{-2}	8.0×10^{-2}	2.39×10^{-1}	4.05×10^{-1}
Exp	0.521	-	1.34×10^{-3}	2.15×10^{-2}	3.76×10^{-2}	9.52×10^{-2}	2.47×10^{-1}	4.25×10^{-1}
Theory	0.5	5.42×10^{-3}	-	1.37×10^{-2}	3.44×10^{-2}	9.53×10^{-2}	2.50×10^{-1}	4.17×10^{-1}
Exp	0.314	-	1.42×10^{-2}	1.90×10^{-2}	3.89×10^{-2}	1.01×10^{-1}	2.55×10^{-1}	-
Theory	0.3	6.77×10^{-3}	-	1.65×10^{-2}	3.87×10^{-2}	1.03×10^{-1}	2.64×10^{-1}	-
Exp	0.109	-	-	9.48×10^{-3}	3.25×10^{-2}	-	-	-
Theory	0.1	9.53×10^{-3}	-	1.99×10^{-2}	4.43×10^{-2}	1.06×10^{-1}	-	-

¹ Experimental results adjusted by subtracting the fraction of energy escaping in the form of bremsstrahlung as determined by the TIGER code. To adjust the 16° experimental results, the average of the calculated 1° and 31° adjustments was used.

² Experimental values for 1° not obtained. Values obtained from calculated energy escape for energy calibration (reflected electrons only).

a. Comparison as a Function of Incident Energy

b. Comparison as a Function of Incident Angle

Figure V-A.2 Comparison of Experimental and Theoretical Number Backscatter in Beryllium

Table V-A.2

Fraction of Electrons Backscattered From Beryllium

	Energy (MeV)	Angle of Incidence						
		1°	16°	31°	46°	61°	76°	83.5°
Exp	1.033	1.20×10^{-2}	1.74×10^{-2}	3.06×10^{-2}	6.96×10^{-2}	1.70×10^{-1}	3.96×10^{-1}	5.84×10^{-1}
Theory	1.0	1.07×10^{-2}	-	2.91×10^{-2}	7.40×10^{-2}	1.85×10^{-1}	4.26×10^{-1}	6.20×10^{-1}
Exp	0.521	2.11×10^{-2}	2.17×10^{-2}	3.75×10^{-2}	7.89×10^{-2}	1.83×10^{-1}	3.87×10^{-1}	5.72×10^{-1}
Theory	0.5	1.40×10^{-2}	-	3.60×10^{-2}	8.29×10^{-2}	1.97×10^{-1}	4.20×10^{-1}	6.03×10^{-1}
Exp	0.314	2.10×10^{-2}	2.63×10^{-2}	4.10×10^{-2}	8.33×10^{-2}	1.84×10^{-1}	3.87×10^{-1}	-
Theory	0.3	1.63×10^{-2}	-	3.97×10^{-2}	8.67×10^{-2}	1.98×10^{-1}	4.23×10^{-1}	-
Exp	0.109	2.23×10^{-2}	2.68×10^{-2}	3.80×10^{-2}	8.39×10^{-2}	-	-	-
Theory	0.1	2.01×10^{-2}	-	4.25×10^{-2}	9.11×10^{-2}	1.96×10^{-1}	-	-

B. Electron Energy and Charge Albedos in Carbon

Energies (MeV): 1.0, 0.5, 0.3, 0.1, 0.075, 0.05, and 0.025

Angles ($^{\circ}$): 0, 15, 30, 45, 60, 75, and 82.5

Analysis Method: S

Angle Determination Method: Remote set

Calorimeter

Diameter: 5.08 cm

Thickness: 0.478 cm

Table V-B

Theoretically Calculated Fraction of the Incident Electron Energy
That Escapes From Carbon in the Form of Bremsstrahlung

Energy (MeV)	Angle of Incidence						
	0 $^{\circ}$	15 $^{\circ}$	30 $^{\circ}$	45 $^{\circ}$	60 $^{\circ}$	75 $^{\circ}$	82.5 $^{\circ}$
1.0	2.57×10^{-3}	-	2.84×10^{-3}	2.69×10^{-3}	2.70×10^{-3}	2.34×10^{-3}	2.35×10^{-3}
0.5	1.31×10^{-3}	-	1.29×10^{-3}	1.60×10^{-3}	1.43×10^{-3}	1.56×10^{-3}	8.35×10^{-4}
0.3	8.11×10^{-4}	-	7.97×10^{-4}	8.25×10^{-4}	6.65×10^{-4}	2.33×10^{-4}	8.77×10^{-4}
0.1	2.45×10^{-4}	-	2.67×10^{-4}	3.11×10^{-4}	1.55×10^{-4}	3.50×10^{-4}	-
0.075	1.94×10^{-4}	-	1.53×10^{-4}	1.79×10^{-4}	1.53×10^{-4}	3.84×10^{-4}	-
0.05	8.69×10^{-5}	-	1.10×10^{-4}	6.00×10^{-5}	6.09×10^{-5}	3.04×10^{-5}	-
0.025	4.21×10^{-5}	-	3.95×10^{-5}	2.50×10^{-5}	4.51×10^{-5}	6.57×10^{-5}	-

a. Comparison as a Function of Incident Energy

b. Comparison as a Function of Incident Angle

Figure V-3.1 Comparison of Experimental and Theoretical Energy Backscatter in Carbon

Table V-B.1
Fraction of Energy Backscattered From Carbon¹

		Angle of Incidence						
Energy (MeV)		0°	15°	30°	45°	60°	75°	82.5°
Exp	1.0	0.013	0.017	0.030	0.058	0.128	0.288	0.452
Theory	1.0	0.008	-	0.020	0.047	0.114	0.273	0.431
Exp	0.5	0.025	0.030	0.044	0.076	0.143	0.311	0.471
Theory	0.5	0.013	-	0.029	0.060	0.130	0.291	0.440
Exp	0.3	0.039	0.047	0.062	0.099	0.168	0.333	0.473
Theory	0.3	0.016	-	0.033	0.064	0.138	0.312	0.467
Exp	0.1	0.029	0.026	0.041	0.083	0.165	0.327	-
Theory	0.1	0.020	-	0.039	0.072	0.150	0.306	-
Exp	0.075	0.057	0.051	0.069	0.086	0.175	0.405	-
Theory	0.075	0.022	-	0.038	0.073	0.150	0.313	-
Exp	0.05	0.073	0.080	0.102	0.134	0.215	-	-
Theory	0.05	0.023	-	0.040	0.076	0.151	0.316	-
Exp	0.025	0.103	0.115	0.109	0.134	0.193	-	-
Theory	0.025	0.025	-	0.043	0.077	0.150	0.306	-

¹ Experimental results adjusted by subtracting the fraction of energy escaping in the form of bremsstrahlung as determined by the TIGER code. To adjust the 15° experimental results, the average of the calculated 0° and 30° adjustments was used.

a. Comparison as a Function of Incident Energy

b. Comparison as a Function of Incident Angle

Figure V-B.2 Comparison of Experimental and Theoretical Number Backscatter in Carbon

Table V-B.2

Fraction of Electrons Backscattered From Carbon

		Angle of Incidence						
Energy (MeV)		0°	15°	30°	45°	60°	75°	82.5°
Exp	1.0	0.028	0.032	0.056	0.114	0.203	0.453	0.631
Theory	1.0	0.024	-	0.054	0.112	0.236	0.457	0.627
Exp	0.5	0.031	0.042	0.068	0.130	0.247	0.458	0.626
Theory	0.5	0.032	-	0.066	0.127	0.241	0.456	0.612
Exp	0.3	0.038	0.041	0.076	0.132	0.246	0.451	0.610
Theory	0.3	0.037	-	0.071	0.130	0.244	0.469	0.636
Exp	0.1	0.045	0.052	0.083	0.136	0.249	0.447	-
Theory	0.1	0.042	-	0.077	0.135	0.252	0.451	-
Exp	0.075	0.046	0.052	0.079	0.135	0.255	0.433	-
Theory	0.075	0.043	-	0.075	0.134	0.252	0.458	-
Exp	0.05	0.054	0.064	0.087	0.159	0.258	-	-
Theory	0.05	0.045	-	0.077	0.139	0.251	0.460	-
Exp	0.025	0.063	0.087	0.080	0.127	0.215	-	-
Theory	0.025	0.047	-	0.080	0.136	0.247	0.447	-

C. Electron Energy and Charge Albedos in Aluminum

Energies (MeV): 1.033, 0.521, 0.314, 0.109, 0.084, 0.058, and 0.032

Angles ($^{\circ}$): 0, 15, 30, 45, 60, and 75

Analysis Method: t_d

Angle Determination Method: Hand set

Calorimeter

Diameter: 5.08 cm

Thickness: 0.264 cm

Table V-C(i)

A Comparison of Total Energy Deposited in Aluminum

Nominal Energy (MeV)	Angle (deg)	<u>Fraction of Energy Deposited</u>		
		<u>TIGER Calculation</u>	<u>Total Stopping Measurement</u>	<u>Integrated Differential Measurement</u>
1.0	0	0.954	0.940	0.939
1.0	60	0.785	0.800	0.735
0.5	0	0.942	0.948	0.919
0.5	60	0.764	0.709	0.750
0.3	0	0.933	0.946	0.908
0.3	60	0.760	0.750	0.732

Table V-C(ii)

Theoretically Calculated Fraction of the Incident Electron Energy
That Escapes From Aluminum in the Form of Bremsstrahlung

Energy (MeV)	Angle of Incidence					
	0°	15°	30°	45°	60°	75°
1.0	5.38×10^{-3}	5.57×10^{-3}	5.51×10^{-3}	5.24×10^{-3}	5.08×10^{-3}	4.73×10^{-3}
0.5	2.49×10^{-3}	2.55×10^{-3}	2.62×10^{-3}	2.82×10^{-3}	2.73×10^{-3}	2.14×10^{-3}
0.3	1.64×10^{-3}	1.69×10^{-3}	1.59×10^{-3}	1.50×10^{-3}	1.11×10^{-3}	1.14×10^{-3}
0.109	5.26×10^{-4}	5.43×10^{-4}	5.10×10^{-4}	4.97×10^{-4}	3.75×10^{-4}	5.03×10^{-4}
0.084	3.47×10^{-4}	3.21×10^{-4}	4.07×10^{-4}	3.64×10^{-4}	4.57×10^{-4}	1.72×10^{-4}
0.058	1.93×10^{-4}	2.08×10^{-4}	2.56×10^{-4}	2.65×10^{-4}	1.37×10^{-4}	2.33×10^{-4}
0.032	8.37×10^{-5}	9.85×10^{-5}	6.30×10^{-5}	9.26×10^{-5}	1.46×10^{-5}	1.43×10^{-4}

a. Comparison as a Function of Incident Energy

b. Comparison as a Function of Incident Angle

Figure V-C.1 Comparison of Experimental and Theoretical Energy Backscatter in Aluminum

Table V-C.1
 Fraction of Energy Backscattered From Aluminum¹

		Angle of Incidence					
	Energy (MeV)	0°	15°	30°	45°	60°	75°
Exp	1.033	0.046	0.040	0.062	0.110	0.195	0.368
Theory	1.0	0.042	0.047	0.071	0.118	0.202	0.375
Exp	0.521	0.050	0.060	0.085	0.133	0.228	0.396
Theory	0.5	0.056	0.063	0.087	0.143	0.233	0.396
Exp	0.314	0.052	0.056	0.082	0.139	0.249	0.411
Theory	0.3	0.065	0.072	0.098	0.151	0.244	0.409
Exp	0.109	0.074	0.084	0.111	0.170	0.266	0.430
Theory	0.109	0.074	0.080	0.108	0.159	0.251	0.417
Exp	0.084	0.079	0.086	0.113	0.161	0.260	0.428
Theory	0.084	0.075	0.084	0.110	0.164	0.257	0.418
Exp	0.058	0.074	0.080	0.103	0.158	0.249	0.410
Theory	0.058	0.079	0.085	0.112	0.164	0.261	0.417
Exp	0.032	0.088	0.098	0.117	0.152	0.272	-
Theory	0.032	0.082	0.086	0.114	0.165	0.256	0.418

¹ Experimental results adjusted by subtracting the fraction of energy escaping in the form of bremsstrahlung as determined by the TIGER code.

a. Comparison as a Function of Incident Energy

b. Comparison as a Function of Incident Angle

Figure V-C.2 Comparison of Experimental and Theoretical Number Backscatter in Aluminum

Table V-C. 2

Fraction of Electrons Backscattered From Aluminum

		Angle of Incidence					
Energy (MeV)		0°	15°	30°	45°	60°	75°
Exp	1.033	0.092	0.104	0.138	0.214	0.337	0.531
Theory	1.0	0.097	0.108	0.150	0.227	0.344	0.545
Exp	0.521	0.111	0.125	0.162	0.233	0.354	0.533
Theory	0.5	0.116	0.127	0.166	0.252	0.367	0.548
Exp	0.314	0.122	0.138	0.176	0.252	0.363	0.551
Theory	0.3	0.125	0.137	0.178	0.252	0.371	0.551
Exp	0.109	0.136	0.154	0.181	0.257	0.365	0.558
Theory	0.109	0.132	0.142	0.183	0.255	0.370	0.553
Exp	0.084	0.140	0.151	0.184	0.240	0.368	0.559
Theory	0.084	0.132	0.147	0.185	0.248	0.378	0.552
Exp	0.058	0.140	0.153	0.189	0.247	0.340	0.541
Theory	0.058	0.136	0.146	0.186	0.257	0.377	0.549
Exp	0.032	0.158	0.160	0.178	0.231	0.332	-
Theory	0.032	0.139	0.145	0.186	0.255	0.373	0.548

D. Electron Energy and Charge Albedos in Titanium

Energies (MeV): 1.033, 0.521, 0.314, and 0.109

Angles ($^{\circ}$): 0, 15, 30, 45, 60, and 75

Analysis Method: t_d

Angle Determination Method: Hand set

Calorimeter

Diameter: 5.08 cm

Thickness: 0.163 cm

Table V-D

Theoretically Calculated Fraction of the Incident Electron Energy
That Escapes From Titanium in the Form of Bremsstrahlung

Energy (MeV)	Angle of Incidence					
	0 $^{\circ}$	15 $^{\circ}$	30 $^{\circ}$	45 $^{\circ}$	60 $^{\circ}$	75 $^{\circ}$
1.0	8.85×10^{-3}	9.94×10^{-3}	9.95×10^{-3}	8.99×10^{-3}	7.79×10^{-3}	6.71×10^{-3}
0.5	4.75×10^{-3}	4.74×10^{-3}	4.39×10^{-3}	4.26×10^{-3}	4.15×10^{-3}	3.09×10^{-3}
0.3	2.73×10^{-3}	2.98×10^{-3}	2.56×10^{-3}	2.78×10^{-3}	2.16×10^{-3}	2.40×10^{-3}
0.1	6.32×10^{-4}	6.84×10^{-4}	9.37×10^{-4}	3.80×10^{-4}	5.65×10^{-4}	5.84×10^{-4}

a. Comparison as a Function of Incident Energy

b. Comparison as a Function of Incident Angle

Figure V-D.1 Comparison of Experimental and Theoretical Energy Backscatter in Titanium

Table V-D.1

Fraction of Energy Backscattered From Titanium¹

	Energy (MeV)	Angle of Incidence					
		0°	15°	30°	45°	60°	75°
Exp	1.033	0.091	0.103	0.119	0.177	0.280	0.461
Theory	1.0	0.091	0.099	0.129	0.193	0.280	0.443
Exp	0.521	0.156	0.160	0.182	0.238	0.329	0.483
Theory	0.5	0.116	0.124	0.158	0.214	0.314	0.472
Exp	0.314	0.139	0.161	0.181	0.236	0.338	0.502
Theory	0.3	0.132	0.139	0.174	0.233	0.331	0.481
Exp	0.109	0.167	0.174	0.201	0.262	0.359	-
Theory	0.1	0.140	0.150	0.186	0.235	0.330	0.487

¹ Experimental results adjusted by subtracting the fraction of energy escaping in the form of bremsstrahlung as determined by the TIGER code.

Figure V-D.2 Comparison of Experimental and Theoretical Number Backscatter in Titanium

Table V-D. 2

Fraction of Electrons Backscattered From Titanium

	Energy (MeV)	Angle of Incidence					
		0°	15°	30°	45°	60°	75°
Exp	1.033	0.180	0.190	0.230	0.309	0.430	0.600
Theory	1.0	0.178	0.193	0.240	0.326	0.431	0.612
Exp	0.521	0.203	0.221	0.257	0.331	0.443	0.597
Theory	0.5	0.207	0.218	0.266	0.337	0.452	0.614
Exp	0.314	0.217	0.231	0.274	0.348	0.459	0.617
Theory	0.3	0.224	0.232	0.279	0.353	0.463	0.619
Exp	0.109	0.226	0.239	0.273	0.343	0.441	-
Theory	0.1	0.223	0.235	0.284	0.345	0.453	0.611

E. Electron Energy and Charge Albedos in Molybdenum

Energies (MeV): 1.033, 0.521, 0.314, and 0.109

Angles ($^{\circ}$): 0, 15, 30, 45, 60, and 75

Analysis Method: t_d

Angle Determination Method: Hand set

Calorimeter

Diameter: 5.08 cm

Thickness: 0.091 cm

Table V-E(i)

A Comparison of Total Energy Deposited in Molybdenum

Nominal Energy (MeV)	Angle (deg)	Fraction of Energy Deposited		
		TIGER Calculation	Total Stopping Measurement	Integrated Differential Measurement
1.0	0	0.791	0.797	0.779
1.0	60	0.602	0.595	0.557
0.5	0	0.762	0.749	0.746
0.5	60	0.580	0.568	0.544
0.3	0	0.753	0.750	0.694
0.3	60	0.567	0.546	0.533
0.1	0	0.740	0.721	0.690

Table V-E(ii)

Theoretically Calculated Fraction of the Incident Electron Energy
That Escapes From Molybdenum in the Form of Bremsstrahlung

Energy (MeV)	Angle of Incidence					
	0°	15°	30°	45°	60°	75°
1.0	1.22×10^{-2}	1.25×10^{-2}	1.32×10^{-2}	1.10×10^{-2}	1.13×10^{-2}	8.18×10^{-3}
0.5	6.10×10^{-3}	5.57×10^{-3}	5.64×10^{-3}	5.34×10^{-3}	4.84×10^{-3}	3.84×10^{-3}
0.3	3.18×10^{-3}	3.36×10^{-3}	2.84×10^{-3}	2.71×10^{-3}	2.83×10^{-3}	2.21×10^{-3}
0.1	1.27×10^{-3}	1.49×10^{-3}	6.65×10^{-4}	1.11×10^{-3}	8.34×10^{-4}	8.21×10^{-4}

a. Comparison as a Function of Incident Energy

b. Comparison as a Function of Incident Angle

Figure V-E.1 Comparison of Experimental and Theoretical Energy Backscatter in Molybdenum

Table V-E. 1
 Fraction of Energy Backscattered From Molybdenum¹

		Angle of Incidence					
Energy (MeV)		0°	15°	30°	45°	60°	75°
Exp	1.033	0.191	0.200	0.235	0.297	0.394	0.554
Theory	1.0	0.194	0.205	0.239	0.300	0.392	0.538
Exp	0.521	0.245	0.251	0.278	0.337	0.427	0.568
Theory	0.5	0.231	0.241	0.271	0.328	0.427	0.559
Exp	0.314	0.247	0.266	0.299	0.365	0.452	0.594
Theory	0.3	0.244	0.252	0.288	0.352	0.428	0.571
Exp	0.109	0.278	0.284	0.325	0.383	0.464	-
Theory	0.1	0.254	0.269	0.296	0.355	0.444	0.572

¹ Experimental results adjusted by subtracting the fraction of energy escaping in the form of bremsstrahlung as determined by the TIGER code.

a. Comparison as a Function of Incident Energy

b. Comparison as a Function of Incident Angle

Figure V-E. 2 Comparison of Experimental and Theoretical Number Backscatter in Molybdenum

Table V-E.2

Fraction of Electrons Backscattered From Molybdenum

		Angle of Incidence					
		0°	15°	30°	45°	60°	75°
Exp	1.033	0.310	0.323	0.362	0.428	0.530	0.670
Theory	1.0	0.320	0.331	0.376	0.443	0.543	0.678
Exp	0.521	0.349	0.372	0.400	0.466	0.557	0.682
Theory	0.5	0.351	0.364	0.396	0.462	0.561	0.688
Exp	0.314	0.362	0.375	0.423	0.487	0.572	0.687
Theory	0.3	0.359	0.370	0.410	0.479	0.551	0.691
Exp	0.109	0.383	0.395	0.427	0.487	0.564	-
Theory	0.1	0.361	0.377	0.409	0.473	0.561	0.690

F. Electron Energy and Charge Albedos in Tantalum

Energies (MeV): 1.033, 0.521, 0.314, 0.109, 0.058, and 0.032

Angles (°): 0, 15, 30, 45, 60, and 75

Analysis Method: t_d

Angle Determination Method: Hand set

Calorimeter

Diameter: 5.08 cm

Thickness: 0.053 cm

Table V-F(i)

A Comparison of Total Energy Deposited in Tantalum

Nominal Energy (MeV)	Angle (deg)	Fraction of Energy Deposited			
		TIGER Calculation	Total Stopping Measurement	Integrated Differential Measurement*	
				A	B
1.0	0	0.670	0.668	0.640	0.631
1.0	60	0.495	0.484	0.472	-
0.5	0	0.634	0.635	0.632	0.585
0.5	30	0.596	0.593	0.590	-
0.5	60	0.470	0.458	0.454	-
0.3	0	0.630	0.617	0.613	0.564

* Two different methods were employed to make differential energy deposition measurements in Ta (see Reference 3 for discussion).

Table V-F(ii)

Theoretically Calculated Fraction of the Incident Electron Energy
That Escapes From Tantalum in the Form of Bremsstrahlung

Energy (MeV)	Angle of Incidence					
	0°	15°	30°	45°	60°	75°
1.0	1.63×10^{-2}	1.49×10^{-2}	1.53×10^{-2}	1.38×10^{-2}	1.21×10^{-2}	9.65×10^{-3}
0.5	9.13×10^{-3}	9.30×10^{-3}	9.54×10^{-3}	7.84×10^{-3}	8.18×10^{-3}	5.79×10^{-3}
0.3	5.87×10^{-3}	5.67×10^{-3}	6.13×10^{-3}	5.02×10^{-3}	5.85×10^{-3}	3.54×10^{-3}
0.1	1.80×10^{-3}	2.32×10^{-3}	1.87×10^{-3}	1.77×10^{-3}	1.51×10^{-3}	8.64×10^{-4}
0.05	7.57×10^{-4}	8.07×10^{-4}	1.01×10^{-3}	1.03×10^{-3}	9.06×10^{-4}	6.83×10^{-4}
0.025	3.18×10^{-4}	6.31×10^{-4}	5.14×10^{-4}	3.70×10^{-4}	5.21×10^{-4}	3.63×10^{-4}

a. Comparison as a Function of Incident Energy

b. Comparison as a Function of Incident Angle

Figure V-F.1 Comparison of Experimental and Theoretical Energy Backscatter in Tantalum

Table V-F.1

Fraction of Energy Backscattered From Tantalum¹

		Angle of Incidence					
Energy (MeV)		0°	15°	30°	45°	60°	75°
Exp	1.033	0.316	0.334	0.365	0.418	0.504	0.648
Theory	1.0	0.309	0.317	0.354	0.413	0.497	0.618
Exp	0.521	0.356	0.370	0.397	0.447	0.534	0.652
Theory	0.5	0.355	0.363	0.403	0.447	0.527	0.655
Exp	0.314	0.377	0.386	0.416	0.473	0.557	-
Theory	0.3	0.372	0.381	0.407	0.460	0.545	0.662
Exp	0.109	0.403	0.399	0.428	0.493	0.559	-
Theory	0.1	0.355	0.378	0.397	0.459	0.532	0.642
Exp	0.058	0.395	0.390	0.434	0.480	0.553	-
Theory	0.05	0.331	0.339	0.371	0.424	0.493	0.625
Exp	0.032	0.398	0.393	0.431	0.466	0.535	-
Theory	0.025	0.281	0.293	0.318	0.373	0.446	0.558

¹ Experimental results adjusted by subtracting the fraction of energy escaping in the form of bremsstrahlung as determined by the TIGER code.

a. Comparison as a Function of Incident Energy

b. Comparison as a Function of Incident Angle

Figure V-F. 2 Comparison of Experimental and Theoretical Number Backscatter in Tantalum

Table V-F. 2
Fraction of Electrons Backscattered From Tantalum

	Energy (MeV)	Angle of Incidence					
		0°	15°	30°	45°	60°	75°
Exp	1.033	0.440	0.452	0.483	0.540	0.621	0.739
Theory	1.0	0.449	0.457	0.498	0.557	0.635	0.747
Exp	0.521	0.486	0.495	0.526	0.578	0.657	0.752
Theory	0.5	0.486	0.490	0.533	0.580	0.657	0.775
Exp	0.314	0.497	0.512	0.539	0.595	0.668	-
Theory	0.3	0.496	0.505	0.533	0.587	0.672	0.773
Exp	0.109	0.506	0.518	0.550	0.600	0.662	-
Theory	0.1	0.472	0.496	0.512	0.583	0.659	0.758
Exp	0.058	0.497	0.508	0.539	0.589	0.662	-
Theory	0.05	0.450	0.457	0.494	0.549	0.624	0.757
Exp	0.032	0.494	0.501	0.526	0.554	0.576	-
Theory	0.025	0.400	0.412	0.444	0.507	0.588	0.705

a. Comparison at an Incident Angle of 0°

b. Comparison at an Incident Angle of 60°

Figure V-F.3 Comparison of Experiment and Theoretical Energy Backscatter in Tantalum as a Function of Incident Energy Using Standard and Improved Theoretical Cross Sections

Table V-F.3

Fraction of Energy Backscattered From Tantalum Calculated
With Standard and Improved Cross Sections¹

	Cross Sections	Energy (MeV)	Angle of Incidence	
			0°	60°
Theory	Standard	0.01	0.185	0.307
Theory	Improved	0.01	0.287	0.441
Theory	Standard	0.025	0.281	0.446
Theory	Improved	0.025	0.319	0.494
Experiment		0.032	0.398	0.535
Theory	Standard	0.05	0.331	0.493
Theory	Improved	0.05	0.352	0.517
Experiment		0.058	0.395	0.553
Theory	Standard	0.10	0.355	0.532
Theory	Improved	0.10	0.363	0.538
Experiment		0.109	0.403	0.559

¹ Experimental results adjusted by subtracting the fraction of energy escaping in the form of bremsstrahlung as determined by the TIGER code.

a. Comparison at an Incident Angle of 0°

b. Comparison at an Incident Angle of 60°

Figure V-F.4 Comparison of Experimental and Theoretical Number Backscatter in Tantalum as a Function of Incident Energy Using Standard and Improved Theoretical Cross Sections

Table V-F.4

Fraction of Electrons Backscattered From Tantalum Calculated
With Standard and Improved Cross Sections

	Cross Sections	Energy (MeV)	Angle of Incidence	
			0°	60°
Theory	Standard	0.01	0.285	0.446
Theory	Improved	0.01	0.391	0.570
Theory	Standard	0.025	0.400	0.588
Theory	Improved	0.025	0.420	0.612
Experiment		0.032	0.494	0.576
Theory	Standard	0.05	0.450	0.624
Theory	Improved	0.05	0.458	0.635
Experiment		0.058	0.497	0.662
Theory	Standard	0.10	0.472	0.659
Theory	Improved	0.10	0.476	0.651
Experiment		0.109	0.506	0.662

G. Electron Energy and Charge Albedos in Uranium

Energies (MeV): 1.033, 0.521, 0.314, 0.109, 0.084, 0.058, and 0.032

Angles (°): 0, 15, 30, 45, 60, and 75

Analysis Method: t_d

Angle Determination Method: Hand set

Calorimeter

Diameter: 5.08 cm

Thickness: 0.050 cm

Table V-G(i)

A Comparison of Total Energy Deposition in Uranium

Nominal Energy (MeV)	Angle (deg)	Fraction of Energy Deposited		
		TIGER Calculation	Total Stopping Measurement	Integrated Differential Measurement
1.0	0	0.615	0.555	0.584
1.0	60	0.427	0.394	0.413
0.5	0	0.582	0.528	0.554
0.3	0	0.553	0.505	0.550

Table V-G(ii)

Theoretically Calculated Fraction of the Incident Electron Energy
That Escapes From Uranium in the Form of Bremsstrahlung

Energy (MeV)	Angle of Incidence					
	0°	15°	30°	45°	60°	75°
1.0	2.36×10^{-2}	2.44×10^{-2}	2.30×10^{-2}	2.11×10^{-2}	1.70×10^{-2}	1.47×10^{-2}
0.5	9.69×10^{-3}	1.16×10^{-2}	9.97×10^{-3}	9.08×10^{-3}	9.51×10^{-3}	6.63×10^{-3}
0.3	6.23×10^{-3}	6.85×10^{-3}	5.95×10^{-3}	5.01×10^{-3}	5.52×10^{-3}	4.07×10^{-3}
0.109	2.54×10^{-3}	2.17×10^{-3}	1.83×10^{-3}	1.86×10^{-3}	1.74×10^{-3}	1.67×10^{-3}
0.084	1.69×10^{-3}	1.80×10^{-3}	2.01×10^{-3}	1.16×10^{-3}	1.75×10^{-3}	1.70×10^{-3}
0.058	1.46×10^{-3}	1.52×10^{-3}	1.33×10^{-3}	1.32×10^{-3}	1.32×10^{-3}	8.11×10^{-4}
0.032	1.15×10^{-3}	6.04×10^{-4}	4.89×10^{-4}	1.18×10^{-4}	2.86×10^{-4}	3.74×10^{-4}

a. Comparison as a Function of Incident Energy

b. Comparison as a Function of Incident Angle

Figure V-G.1 Comparison of Experimental and Theoretical Energy Backscatter in Uranium

Table V-G.1

Fraction of Energy Backscattered From Uranium¹

		Angle of Incidence					
	Energy (MeV)	0°	15°	30°	45°	60°	75°
Exp	1.033	0.421	0.431	0.463	0.513	0.589	0.698
Theory	1.0	0.368	0.378	0.411	0.458	0.548	0.654
Exp	0.521	0.464	0.477	0.509	0.546	0.613	0.714
Theory	0.5	0.415	0.419	0.450	0.504	0.563	0.678
Exp	0.314	0.489	0.491	0.521	0.568	0.631	0.718
Theory	0.3	0.421	0.431	0.464	0.517	0.581	0.676
Exp	0.109	0.483	0.488	0.522	0.572	0.635	0.702
Theory	0.109	0.402	0.419	0.449	0.495	0.560	0.661
Exp	0.084	0.485	0.497	0.516	0.555	0.615	0.696
Theory	0.084	0.389	0.410	0.435	0.481	0.547	0.648
Exp	0.058	0.461	0.473	0.505	0.544	0.608	-
Theory	0.058	0.372	0.383	0.416	0.454	0.535	0.648
Exp	0.032	0.429	0.453	0.488	0.506	0.563	-
Theory	0.032	0.330	0.343	0.366	0.406	0.496	0.597

¹ Experimental results adjusted by subtracting the fraction of energy escaping in the form of bremsstrahlung as determined by the TIGER code.

a. Comparison as a Function of Incident Energy

b. Comparison as a Function of Incident Angle

Figure V-G.2 Comparison of Experimental and Theoretical Number Backscatter in Uranium

Table V-G. 2

Fraction of Electrons Backscattered From Uranium

	Energy (MeV)	Angle of Incidence					
		0°	15°	30°	45°	60°	75°
Exp	1.033	0.491	0.503	0.531	0.582	0.649	0.750
Theory	1.0	0.508	0.518	0.554	0.600	0.689	0.778
Exp	0.521	0.534	0.540	0.568	0.613	0.677	0.768
Theory	0.5	0.543	0.547	0.577	0.632	0.683	0.791
Exp	0.314	0.548	0.556	0.586	0.634	0.701	0.778
Theory	0.3	0.545	0.557	0.581	0.641	0.700	0.787
Exp	0.109	0.543	0.555	0.583	0.630	0.690	0.747
Theory	0.109	0.526	0.538	0.576	0.620	0.683	0.777
Exp	0.084	0.545	0.547	0.577	0.620	0.678	0.740
Theory	0.084	0.509	0.534	0.559	0.607	0.672	0.773
Exp	0.058	0.518	0.537	0.562	0.598	0.654	-
Theory	0.058	0.498	0.507	0.544	0.586	0.675	0.786
Exp	0.032	0.496	0.494	0.516	0.541	0.574	-
Theory	0.032	0.459	0.476	0.502	0.554	0.648	0.754

a. Comparison at an Incident Angle of 0°

b. Comparison at an Incident Angle of 60°

Figure V-G.3 Comparison of Experimental and Theoretical Energy Backscatter in Uranium as a Function of Incident Energy Using Standard and Improved Theoretical Cross Sections

Table V-G. 3
 Fraction of Energy Backscattered From Uranium Calculated
 With Standard and Improved Cross Sections¹

	Cross Sections	Energy (MeV)	Angle of Incidence	
			0°	60°
Theory	Standard	0.01	0.167	0.266
Theory	Improved	0.01	0.317	0.470
Theory	Standard	0.025	0.303	0.466
Theory	Improved	0.025	0.358	0.515
Theory	Standard	0.032	0.330	0.496
Theory	Improved	0.032	0.363	0.518
Experiment		0.032	0.429	0.563
Theory	Standard	0.05	0.364	0.517
Theory	Improved	0.05	0.386	0.539
Theory	Standard	0.058	0.372	0.535
Theory	Improved	0.058	0.388	0.548
Experiment		0.058	0.461	0.608
Theory	Standard	0.084	0.389	0.547
Theory	Improved	0.084	0.403	0.565
Experiment		0.084	0.485	0.615
Theory	Standard	0.10	0.400	0.565
Theory	Improved	0.10	0.407	0.563
Theory	Standard	0.109	0.402	0.560
Theory	Improved	0.109	0.411	0.563
Experiment		0.109	0.483	0.635

¹ Experimental results adjusted by subtracting the fraction of energy escaping in the form of bremsstrahlung as determined by the TIGER code.

a. Comparison at an Incident Angle of 0°

b. Comparison at an Incident Angle of 60°

Figure V-G.4 Comparison of Experimental and Theoretical Number Backscatter in Uranium as a Function of Incident Energy Using Standard and Improved Theoretical Cross Sections

Table V-G. 4

Fraction of Electrons Backscattered From Uranium Calculated
With Standard and Improved Cross Sections

	Cross Sections	Energy (MeV)	Angle of Incidence	
			0°	60°
Theory	Standard	0.01	0.263	0.407
Theory	Improved	0.01	0.433	0.609
Theory	Standard	0.025	0.437	0.630
Theory	Improved	0.025	0.467	0.636
Theory	Standard	0.032	0.459	0.648
Theory	Improved	0.032	0.470	0.638
Experiment		0.032	0.496	0.574
Theory	Standard	0.05	0.486	0.659
Theory	Improved	0.05	0.497	0.652
Theory	Standard	0.058	0.498	0.675
Theory	Improved	0.058	0.499	0.660
Experiment		0.058	0.518	0.654
Theory	Standard	0.084	0.509	0.672
Theory	Improved	0.084	0.513	0.676
Experiment		0.084	0.545	0.678
Theory	Standard	0.10	0.521	0.693
Theory	Improved	0.10	0.521	0.674
Theory	Standard	0.109	0.526	0.683
Theory	Improved	0.109	0.523	0.671
Experiment		0.109	0.543	0.690

H. Electron Energy and Charge Albedos in Uranium Dioxide

Energies (MeV): 1.0, 0.5, 0.3, and 0.1

Angles (°): 0, 15, 30, 45, 60, and 75

Analysis Method: S

Angle Determination Method: Remote set

Calorimeter

Diameter: 4.85 cm

Thickness: 0.083 cm

Table V-H

Theoretically Calculated Fraction of the Incident Electron Energy
That Escapes From Uranium Dioxide in the Form of Bremsstrahlung

Energy (MeV)	Angle of Incidence					
	0°	15°	30°	45°	60°	75°
1.0	2.14×10^{-2}	2.11×10^{-2}	1.95×10^{-2}	1.93×10^{-2}	1.54×10^{-2}	1.27×10^{-2}
0.5	9.90×10^{-3}	8.95×10^{-3}	9.47×10^{-3}	8.14×10^{-3}	7.11×10^{-3}	6.22×10^{-3}
0.3	4.97×10^{-3}	3.96×10^{-3}	5.23×10^{-3}	4.16×10^{-3}	3.35×10^{-3}	3.37×10^{-3}
0.1	1.41×10^{-3}	1.57×10^{-3}	1.62×10^{-3}	1.61×10^{-3}	1.33×10^{-3}	7.87×10^{-4}

a. Comparison as a Function of Incident Energy

b. Comparison as a Function of Incident Angle

Figure V-H.1 Comparison of Experimental and Theoretical Energy Backscatter in Uranium Dioxide

Table V-H. 1

Fraction of Energy Backscattered From Uranium Dioxide¹

		Angle of Incidence					
Energy (MeV)		0°	15°	30°	45°	60°	75°
Exp	1.0	0.315	0.334	0.361	0.431	0.514	0.664
Theory	1.0	0.328	0.342	0.378	0.426	0.516	0.629
Exp	0.5	0.371	0.384	0.410	0.470	0.548	0.689
Theory	0.5	0.370	0.378	0.412	0.470	0.546	0.651
Exp	0.3	0.384	0.402	0.413	0.482	0.566	0.699
Theory	0.3	0.384	0.395	0.425	0.476	0.555	0.663
Exp	0.1	0.375	0.407	0.413	0.465	0.573	0.652
Theory	0.1	0.362	0.381	0.404	0.449	0.532	0.647

¹ Experimental results adjusted by subtracting the fraction of energy escaping in the form of bremsstrahlung as determined by the TIGER code.

a. Comparison as a Function of Incident Energy

b. Comparison as a Function of Incident Angle

Figure V-H.2 Comparison of Experimental and Theoretical Number Backscatter in Uranium Dioxide

Table V-H.2

Fraction of Electrons Backscattered From Uranium Dioxide

		Angle of Incidence					
		0°	15°	30°	45°	60°	75°
Exp	1.0	0.451	0.471	0.498	0.556	0.631	0.746
Theory	1.0	0.463	0.480	0.516	0.566	0.655	0.759
Exp	0.5	0.490	0.501	0.535	0.585	0.658	0.750
Theory	0.5	0.500	0.507	0.540	0.603	0.677	0.762
Exp	0.3	0.510	0.519	0.545	0.600	0.670	0.757
Theory	0.3	0.506	0.515	0.545	0.602	0.674	0.775
Exp	0.1	0.494	0.508	0.539	0.583	0.643	0.718
Theory	0.1	0.479	0.500	0.521	0.571	0.656	0.765

VI. Conclusions

Using a new calorimetric method, we have carried out systematic measurements of saturated integral electron energy albedos as a function of target atomic number and incidence angle for source electrons with kinetic energies ranging from 0.025 to 1.0 MeV. Saturated integral electron number albedos were obtained simultaneously. In each case, state-of-the-art predictions were obtained from a Monte Carlo model. The generally good agreement between theory and experiment over this extensive parameter space strongly validates both the theoretical model and the new experimental technique. The new technique offers important advantages over more traditional methods. The following addresses four specific problem areas:

- A. For the most part the experimental and theoretical energy albedos agree quite well. There is an obvious disagreement in Ta and U at low incident energies. This is probably due to the elastic scattering cross sections employed in the standard calculations. As shown in Sections V-F and V-G, results that use improved cross sections¹² are in better agreement with experiment, but there are still significant discrepancies.
- B. Even more difficult to understand is the situation with the U energy albedos at higher energies where the theoretical data fall approximately 10% below the measured results. This is especially disturbing in light of the excellent agreement for UO_2 where the magnitudes clearly indicate that transport is dominated by the U constituent. Indeed, these UO_2 results lessen our concern over a possible problem with the U cross sections in the transport code, and strongly suggest the presence of a systematic error in the present total-stopping calorimeter data for U. This possibility is further reinforced by the relatively poor agreement between the total-stopping deposition data for U and the integrated differential data listed in subsection V-G.
- C. Except for small incident angles and low atomic numbers where differencing leads to large uncertainties, the present method for obtaining number albedos appears to be competitive with techniques that measure backscatter directly. Otherwise, agreement between theory and experiment is very good except at low incident energies. In the case of Ta and U, some of this low-energy disagreement can probably be attributed to the elastic scattering cross sections employed in the calculations. We do not understand those cases in U and Al at low energies where the experimental results fall below the theoretical predictions.
- D. Finally, there appears to be some tendency of our experimental number albedos to fall below the theoretical predictions. Even though the measurements were made at high vacuum, there is the possibility that the +55-V bias on the calorimeter may have resulted in the collection of a significant number of ionization electrons in the large-volume chamber, as well as secondaries emitted from surrounding structures.

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