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Coulomb Scattering of Electrons in Aluminum without Atomic Excitation

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The differential cross sections for Coulomb scattering of electrons without atomic excitation from thin aluminum targets were measured for incident energies of 0.1, 0.2, 0.5, 0.7, 1.0, 1.25, 1.5, 2.0, 2.5, and 3.0 MeV. The electron spectra were obtained with lithium-ion-drifted silicon detectors at scattering angles from 30 to 150 deg. The experimental cross sections above 0.1 MeV agree within the experimental error with the Mott cross section.

INTRODUCTION

THE experimental investigation of Coulomb scattering of electrons without atomic excitation by the atom as a function of angle has been continued. Previous measurements at 1 MeV for aluminum have been reported by the present authors[1] The reported experimental cross sections were compared to the Mott cross section calculated by Doggett and Spencer[2] and to the experimental cross sections reported by Spiegel *et al.*[3] The present experiment includes similar measurements for aluminum at incident electron energies of 0.1, 0.2, 0.5, 0.7, 1.0, 1.25, 1.5, 2.0, 2.5, and 3.0 MeV at scattering angles from 30 to 150 deg. The cross sections for these energies and angles have also been compared to the Mott cross section calculated by Spencer and Doggett[2] The Mott cross-section calculations were carried out for a point, unscreened nucleus. In the energy range from 0.1 to 3.0 MeV for scattering angles from 30 to 150 deg, the effects of finite nuclear size and atomic electron screening are assumed to be negligible for aluminum. The criteria for this judgment are based on the range of momentum-transfer values q of 0.34 to 13 (in units of m_0c) for which measurements have been made. It is predicted that screening effects become important in aluminum for $q<0.1$. This has been verified by the calculations of Lin[4] for Cu ($Z=29$) which predict only about a 1% reduction of the cross section at 0.1 MeV and a scattering angle of 30 deg ($q=0.34$). On the other hand, finite nuclear size is not expected to be significant except at large values of momentum transfer. In the present experiment the largest value of momentum transfer occurs at an incident energy of 3 MeV and a scattering angle of 150 deg. Here the value of $q=13$ is still considered to be small enough for aluminum that the effect on the cross section due to the nuclear charge distribution is small.

EXPERIMENTAL PROCEDURE

A diagram of the scattering geometry is shown in Fig. 1. The vacuum chamber provided for the accurate positioning of two electron detectors at any angle with respect to the incoming electron beam as shown in the drawing. A well-focused beam of monoenergetic electrons in the energy range from 0.5 to 3 MeV was obtained from the LTV 3-MeV Van de Graaff accelerator. In the energy range from 0.1 to 0.3 MeV the electrons were accelerated by a 300-kV Texas Nuclear accelerator. Measurements of electron yields were made at scattering angles from 30 to 150 deg. In most instances measurements were made in 15-deg intervals. As in the previously reported measurements, energy spectra of the scattered electrons were determined by means of solid state detectors. Since the range of incident energy has been varied from 0.1 to 3 MeV, however, in the present work, it was necessary to employ different thicknesses of detectors to obtain usable pulse-height spectra. Lithium-ion-drift silicon wafers of 1-, 2-, and 3-mm thicknesses were used to measure spectra for incident energies up to 2 MeV. The appropriate thickness was chosen to maximize the signal to background while stopping the electron completely for incident

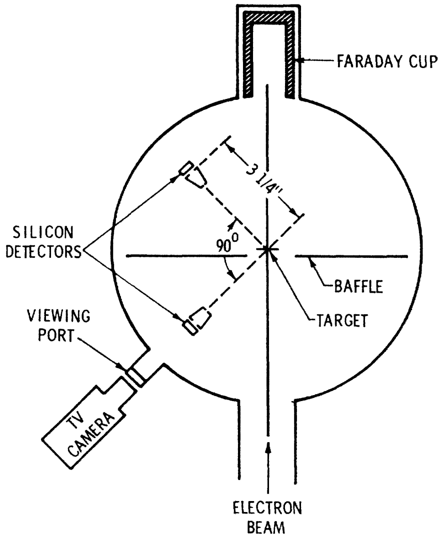

FIG. 1. Experimental arrangement.

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[1] D. H. Rester and W. J. Rainwater, Jr., Phys. Rev. **138**, A12 (1965).

[2] J. A. Doggett and L. V. Spencer, Phys. Rev. **103**, 1597 (1956).

[3] V. Spiegel, Jr., T. F. Ruane, D. J. Anthony, B. Waldman, and W. C. Miller, Ann. Phys. (N. Y.) **6**, 70 (1959).

[4] Shin-R Lin, Phys. Rev. **133**, A965 (1964).

energies up to 1.5 MeV. In order to reduce detector penetration effects at higher energies, single wafers of various thicknesses were stacked to obtain thicknesses greater than the range of the incident electron. As examples of the differences in pulse-height distributions obtained for various stacked-wafer configurations, pulse-height distributions are shown in Figs. 2 and 3. Figure 2 illustrates the response obtained with a stacked configuration of a 1-mm and a 3-mm wafer while Fig. 3 shows a response obtained with a stacked configuration of a 2-mm and a 3-mm wafer, both for 2.5-MeV incident electrons. The range in silicon predicted for 2.5-MeV electrons is less than 4.9 mm. In the case of the stacked-wafer configuration of 4 mm, the effect of electron penetration can be seen by a reduction of the full energy peak and by a sizeable broad peak between the full energy peak and the electron-electron peak. In the case of the 5-mm configuration it can be seen that the full energy peak is relatively larger with a reduction in the number of pulses between it and the electron-electron peak. Its response is more nearly like that of a single-wafer detector. A diagram of the detector-collimator system showing the typical arrangement of the stacked wafers is shown in Fig. 4.

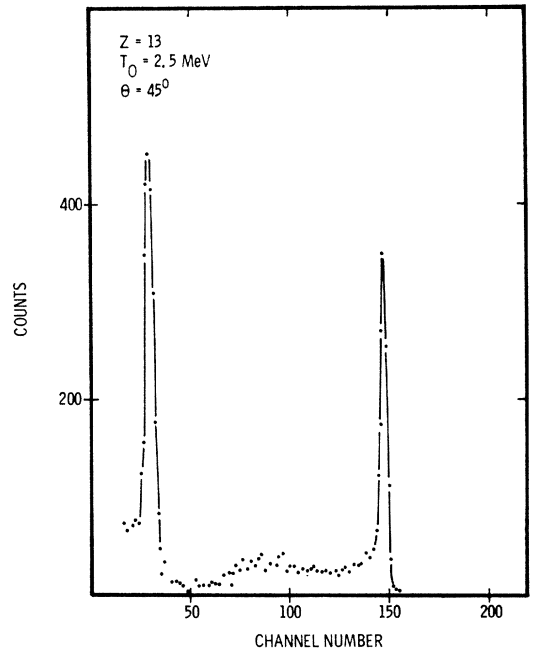

Fig. 2. Pulse-height distribution obtained with a stacked configuration of a 1- and a 3-mm silicon wafer. This spectrum was accumulated at a scattering angle of 45 deg for an incident-electron energy of 2.5 MeV. The pronounced hump between the Coulomb-scattered electron peak at 2.5 MeV and the electron-electron peak is due to the 2.5-MeV electrons which have escaped from the sensitive volume of the detector.

At each energy, spectra were accumulated with the detectors at room temperature except at 100 keV. At this energy 1-mm detectors were employed which exhibited room temperature full width at half-maximum of 22 keV. A resolution of 22% at 100 keV rendered the electron-electron peak unresolvable at the smaller forward angles. By cooling the wafer to −25°C energy resolutions were obtained down to 6%, and the electron-electron peak could be resolved and its energy

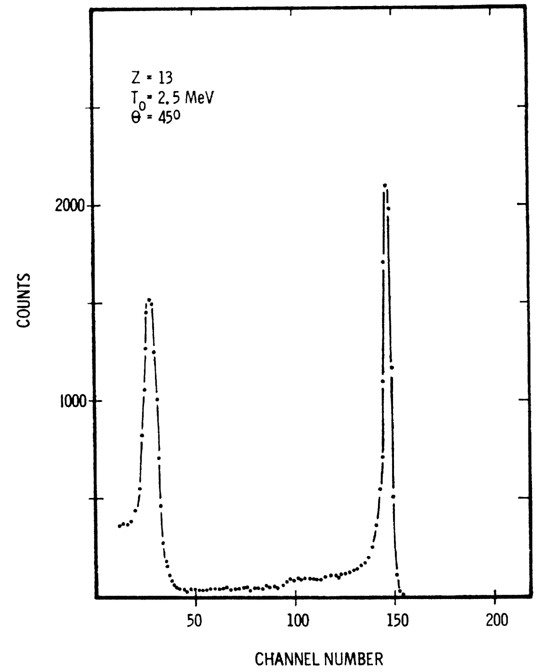

Fig. 3. Same as Fig. 2 except that the spectrum was obtained with a stacked configuration of a 2- and a 3-mm silicon wafer. This 5-mm configuration reduced the number 2.5-MeV electrons which escaped from the sensitive volume of the detector by eliminating straight-through penetration. The reduced hump (relative to that shown in Fig. 2) is due to those 2.5-MeV electrons which escaped through the sides of the detector.

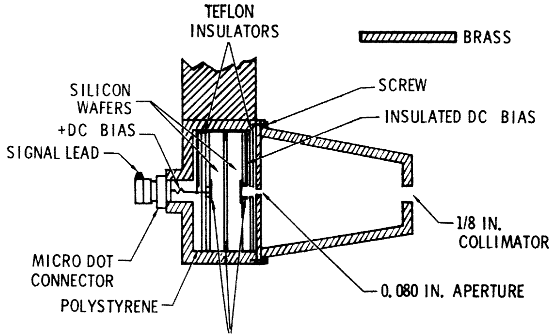

Fig. 4. Diagram of the detector-collimator system. The brass housing for the 0.75-in.-diam silicon wafers allowed for detector configurations up to 5 mm in thickness. For lesser thicknesses the void behind the wafers was filled with Teflon insulation and polystyrene. Positive bias voltages were applied to the lithium (*n*-type material) sides of the wafers through pressure contacts. The adjacent sides of the detectors, which are of the gold-surface-barrier type, were separated by a thin brass ring. This ring was wedged into the brass housing, making the ground contact for the wafers.

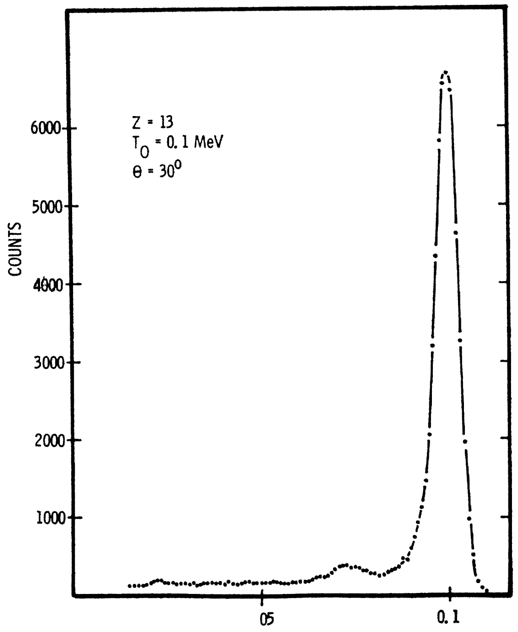

FIG. 5. Pulse-height distribution obtained with a 1-mm lithium-ion-drift silicon detector at a scattering angle of 30 deg for 100-keV incident electrons. This spectrum was accumulated with the detector cooled to $-25°C$. The energy resolution for the 100-keV Columb-scattered electron peak is less than 7%.

determined. A spectrum accumulated at a scattering angle of 30 deg for an incident energy of 100 keV is shown in Fig. 5.

Thin, self-supporting aluminum scattering foils were fabricated by vacuum evaporation techniques with thicknesses ranging from 11 to 371 $\mu g/cm^2$. Thickness determinations were made by weighing a known area of aluminum deposited during evaporation and by

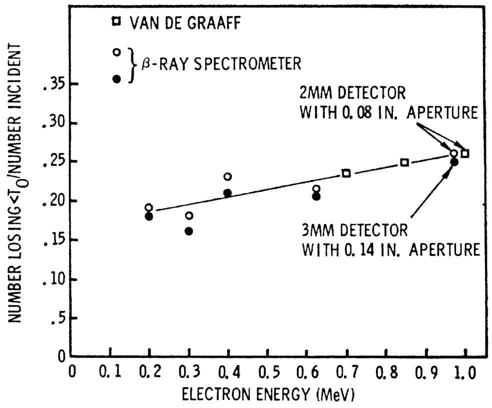

FIG. 6. Fraction of incident monoenergetic electrons losing less than the incident energy in the detector plotted as a function of incident-electron energy. The data points at 0.7, 0.85, and 1.0 MeV were determined from spectra of electrons scattered from the Van de Graaff beam. The other points were obtained using a 180-deg magnetic beta-ray spectrometer, which provided monoenergetic electrons with normal incidence on the detectors.

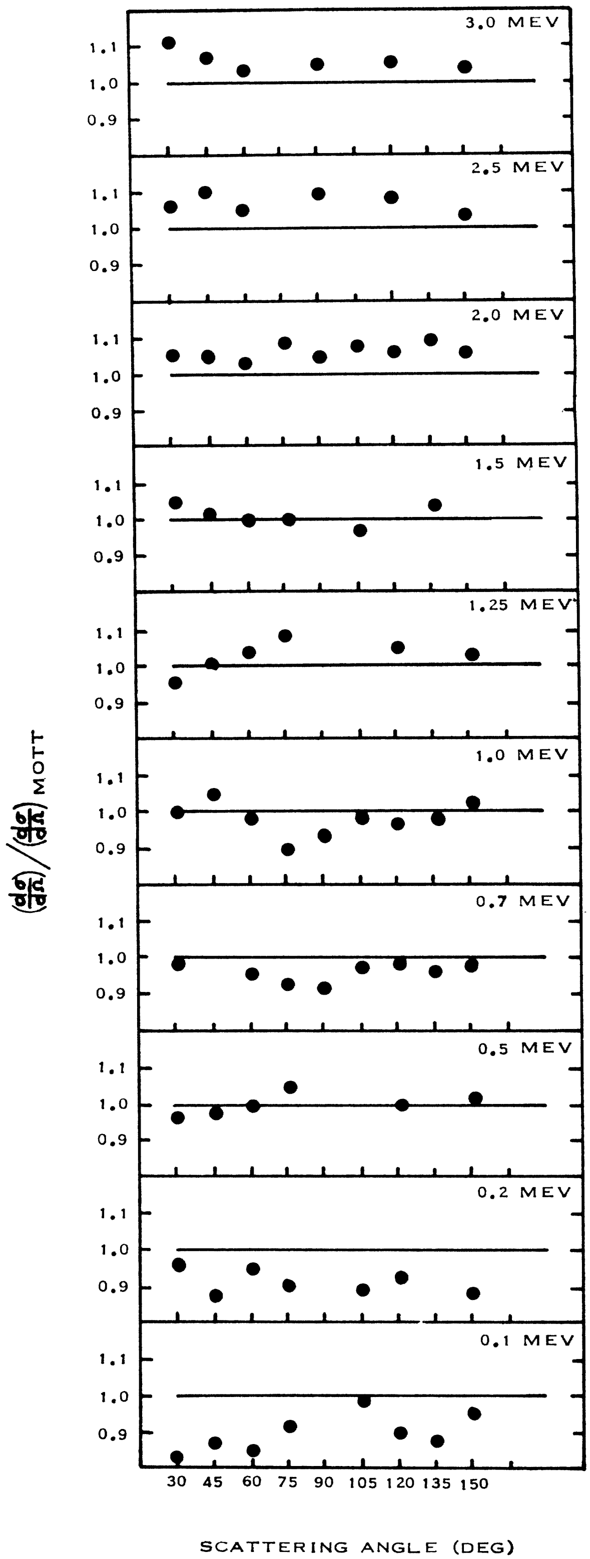

FIG. 7. A plot of the experimental cross sections normalized to the Mott cross section as a function of scattering angle.

measuring the energy loss of 5.3-MeV alpha particles from a Po-210 source.

The solid-state detector spectrometers were energy-calibrated by measurements of the internal conversion electron lines from the Th $(B+C+C'')$ emanating source, Cs-137, and Bi-207. These sources provide well-resolved electron lines of energies from 0.148 to 1.68 MeV and allow the energy calibration of the spectrometer to be carried out to within 1%.

A conservative extimated error in the experimental values of the cross sections is 10%. The largest contribution to the estimated error is in the target-thickness determination, which has an average estimated error of 4% for the various thicknesses used in this experiment. Since the cross section is very dependent on scattering angle, considerable error can be introduced by uncertainties in setting the scattering angle.
However, in the region of scattering angle from 20 to 60 deg at all energies it was possible to monitor the energy of the electron-electron peak. The energy of this peak is a very sensitive measure of the angle and thus provides a precise means of setting the scattering angle. Additional uncertainties arose from current integration, detector response, energy calibration, and the effective solid angle.

EXPERIMENTAL RESULTS

The yields of scattered electrons at each scattering angle and incident energy were obtained by removing the response of the electron spectrometer to monoenergetic electrons from the pulse-height distributions. The responses of the lithium-ion-drift single-wafer detectors to monoenergetic electrons were found by two methods. One method was to extract the responses from the pulse-height distributions obtained by observing the electrons scattered from the scattering foil at a forward scattering angle such as 30 deg. Below 1.5 MeV the contribution to the spectrum from "inelastic" electrons at less than the full pulse-height peak is very small In addition the electron-electron peak is well resolved and can be easily removed from the distribution. The other method was by use of a 180-deg magnetic beta-ray spectrometer, which provided monoenergetic electrons with normal incidence at the detector position in the spectrometer. Detectors used in the experiment were placed in the magnetic spectrometer and their responses were obtained for incident energies from 0.2 to 1.0 MeV. These responses were found to agree with the responses reduced from the pulse-height distributions due to scattered electrons. Figure 6 shows quantitatively the results of the response measurements from 0.2 to 1 MeV for a 2-mm and a 3-mm detector by both of these methods. In the figure the fraction of the response corresponding to pulse height resulting from less than the full energy deposition in the detector is plotted as a function of incident energy. In the determination of the yields of scattered electrons, from which cross-section values were obtained, the number of electrons corresponding to the full energy pulse-height was obtained and corrected for the number of electrons registering less than the pulse height corresponding to the full energy. At energies above 1.0 MeV all corrections of this type were obtained from the pulse height distributions of the scattered electron spectrum at 30 deg. Thus, the correction to the yield in the full-energy line above 1.0 MeV has been obtained by integrating the pulse-height spectrum after removing the peak due to electron-electron scattering at 30 deg and applying this correction to the peaks at all scattering angles.

The experimental cross sections were compared with the Mott cross section for a point, unscreened nucleus which has been calculated by Doggett and Spencer.[2] These comparisons are shown in Fig. 7. The figure consists of a plot of the experimental cross sections normalized to the Mott cross section as a function of scattering angle. While the experimental results agree within the experimental error at all energies except at 0.1 MeV for the forward angles, it is apparent that the experiment is closer to the theory at energies from 0.5 to 1.5 MeV. The experimental values at 0.1 and 0.2 MeV are below the theoretical predictions while the experimental values at 2.0, 2.5, and 3.0 are above the theoretical predictions. The results reported by Spiegel *et al.*[3], at 1.0, 1.75, and 2.50 MeV are generally below the Mott cross section.