Coulomb Scattering in Aluminum without Atomic Excitation for 1-MeV Electrons*

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(Received 9 November 1964)

The cross sections for Coulomb scattering of 1-MeV electrons without atomic excitation from thin aluminum targets were measured at scattering angles from 20 to 150 deg. The electron spectra were obtained by use of lithium-ion-drift silicon detectors. The experimental cross sections are compared with the theoretical values of Doggett and Spencer. Agreement is within the experimental error.

INTRODUCTION

THE experimental measurements of the Coulomb scattering of electrons without atomic excitation by the atom as a function of angle for incident energies of 500 keV to several MeV have not generally yielded consistent results. The most systematic study of atomic scattering in this energy range, including measurements for targets of Al, Ni, Ag, and Au, has been reported by Spiegel *et al.*[1] Recently, accurate measurements of the cross sections for Coulomb scattering of electrons without atomic excitation from targets of Au, Sn, and Cu at energies below 500 keV were reported by Motz, Placious, and Dick.[2] Good agreement with the cross sections calculated by Lin, Sherman, and Percus[3] was obtained at several incident electron energies at angles for which the main interest was a comparison of the experimental and calculated values of the cross section where screening effects due to the atomic electrons were included. The present paper reports the experimental determination of the cross section for Coulomb scattering of electrons without atomic excitation for an incident electron energy of 1.00 MeV on thin aluminum foils. Measurements were made at scattering angles from 20 to 150 deg. At 1.00 MeV and for angles greater than 15 deg the screening effect is negligible in aluminum ($Z=13$). A comparison of the experimental values of the cross section has been made to the calculated values reported by Doggett and Spencer.[4]

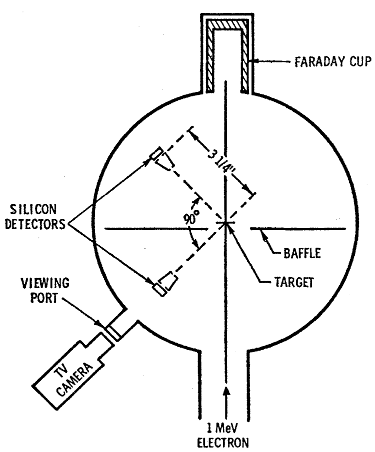


FIG. 1. Experimental arrangement.

EXPERIMENTAL PROCEDURE

The arrangement of the experimental apparatus is shown in Fig. 1. The scattering chamber was made of aluminum with an inside diameter of 10 in. The detectors were mounted on cooling manifolds suspended from the top of the chamber and could be rotated 360 deg. A target holder for remotely positioning a viewing quartz and the target foil was provided. The LTV 3-MeV Van de Graaff accelerator provided the beam of monoenergetic electrons which was focused at the center of the scattering chamber. The total number of electrons entering the chamber was determined by use of a current integrator.

The electrons scattered from the target at a given angle passed through a detector collimator-aperture system which subtends a solid angle of 5.15×10^{-4} sr from the target center. Measurements of electron yields were made at scattering angles of 20 and 30 deg and at angles thereafter corresponding to 15-deg intervals up to 150 deg. Alignment checks throughout the experiment ensured repositioning of the detectors to within 0.2 deg. The energy spectra of the scattered electrons were determined by means of solid-state detector spectrometers employing 2-mm-thick lithium-ion-drift silicon crystals, low-noise amplifier systems, and a multichannel pulse-height analyzer. Typical pulse-height distributions obtained are shown in Figs. 2 and 3.

Thin self-supporting aluminum targets of 27 and 35 μg/cm^2 were used in this experiment. These targets were fabricated by vacuum evaporation of aluminum onto glass slides which had been previously coated with a thin film of soap. The glass slides were placed in a tray into which distilled water was slowly introduced until the entire perimeter of the slide was in contact with the water. At this point the aluminum foil is gradually separated from the slide as the soap film dissolves. Aluminum rings were used to lift the foils from the water and to provide supporting frames for placement in the scattering chamber. Target thicknesses were

* Work done under National Aeronautics and Space Administration Contract No. NASw-948.

[1] V. Spiegel, Jr., T. F. Ruane, D. J. Anthony, B. Waldman, and W. C. Miller, Ann. Phys. (N.Y.) **6**, 70 (1959).
[2] J. W. Motz, R. C. Placious, and C. E. Dick, Phys. Rev. **132**, 2558 (1963).
[3] S. Lin, N. Sherman, and J. Percus, Nucl. Phys. **45**, 492 (1963).
[4] J. A. Doggett and L. V. Spencer, Phys. Rev. **103**, 1597 (1956).

determined by weighing a known area of aluminum deposited on a surface adjacent to the target slides. Additional determinations of the target thickness were made by measuring the energy loss of the 5.3-MeV alpha particles from a Po^{210} source. Relative thicknesses of the foils could also be obtained by comparing their measured yields of Coulomb scattered electrons. Good agreement was found between the various types of determinations.

In order to reduce multiple scattering effects, the target was rotated 15, 30, and 15 deg for the scattering angles 75, 90, and 105 deg, respectively. The contribution from electrons which were scattered from the

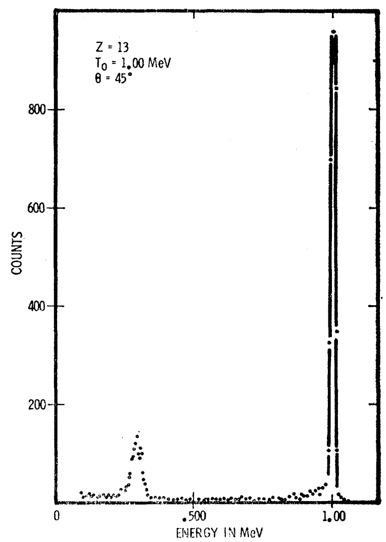
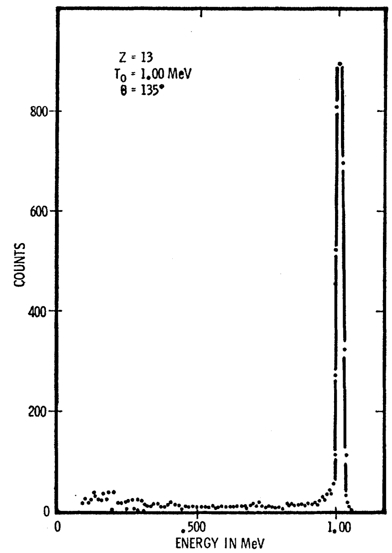


FIG. 2. Pulse-height spectrum of 1-MeV electrons scattered at 45 deg from a 27-μg/cm^2 aluminum target. The peak at 1 MeV is due to Coulomb scattered electrons without atomic excitation. Well resolved from this peak at about 340 keV is the peak due to electron-electron scattering. This spectrum was obtained with a 2-mm lithium-ion-drift silicon detector which was cooled to -25°C. The line at 1 MeV due to Coulomb scattered electrons has a full width at half-maximum of 15 keV due to the energy spread of the incident electron beam and the detector–amplifier noise. The detector was shown to be essentially windowless to electrons by investigating its response to 5.3-MeV α particles.

chamber walls into the detectors was reduced to negligible levels by means of a thick aluminum baffle placed across the center of the chamber parallel to the plane of the target. X-ray backgrounds were significantly reduced through optimally placed shielding at each scattering angle. These backgrounds were determined by removing the target from the beam and accumulating spectra at each angle.

The estimated error in the measured values of the cross sections is about 10%, with the largest contributions being due to the uncertainties in the target thicknesses, the scattering angles, and the detector solid angles.

FIG. 3. Pulse-height spectrum of 1-MeV electrons scattered at 135° from a 27-μg/cm^2 aluminum target. This spectrum shows the electron line at 1 MeV due to Coulomb scattering without atomic excitation. At angles greater than 90° the electron-electron peak is not present.



EXPERIMENTAL RESULTS

In order to extract the yields at each scattering angle, due to Coulomb scattering of electrons without atomic excitation, it was necessary to determine the detector response to monoenergetic electrons. This was done by analyzing the pulse-height spectrum at 30 deg where the Møller peak is resolvable and other inelastic events are negligible. The response to monoenergetic electrons could be reduced to two components: a Gaussian distribution and a low-energy tail. This tail was expected to be due mainly to electrons which backscatter out of the silicon crystal before losing their total energy and to aperture effects. The calculation of reflection coefficients for normal incidence predicts about a 15% contribution from the low-energy tail due to backscatter. The yield in the low-energy tail was measured

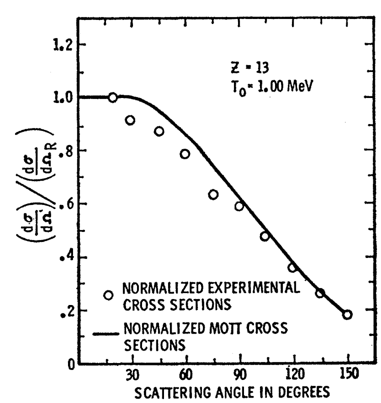


FIG. 4. Dependence of the differential cross section for electron scattering without atomic excitation on the scattering angle. The circles are the ratio of the experimentally determined cross section to the Rutherford cross section. The solid line gives the ratio of the Mott cross section (calculated by Doggett and Spencer) to the Rutherford cross section.

to be 26% of the total yield at 1 MeV for a 2-mm-thick silicon crystal. The yields due to Coulomb scattering were determined by integrating the Gaussian peak and correcting for the yield in the low-energy tail.

The experimental cross sections $d\sigma/d\Omega$ were reduced from the measured yields by use of the following relation:

$$d\sigma/d\Omega = N/\Delta\Omega qt.$$

The quantity N is the yield of electrons measured in a known solid angle $\Delta\Omega$ at a given scattering angle. The quantity t is the number of target atoms per cm^2 normal to the beam direction and is determined from the target thickness. The quantity q is the number of electrons incident on the target.

The measured cross sections were compared to the Mott cross sections which were calculated by Doggett and Spencer.[2] These comparisons are shown in Fig. 4 where the differential cross section $d\sigma/d\Omega$ for Coulomb scattering without atomic excitation, normalized to the Rutherford cross section $d\sigma/d\Omega_R$, is plotted as a function of scattering angle. The calculations of Doggett and Spencer have neglected finite nuclear size and atomic electron screening, since they have negligible effect for aluminum at the values of momentum transfer for which the cross sections were determined. The present experimental values are, on the average, 8% lower than the theoretical values at scattering angles 90 deg and smaller, while the experimental values for angles greater than 90 deg are on the average less than 3% lower. The results reported by Spiegel *et al.*,[1] using a magnetic spectrometer and a 1.5-mg/cm^2 Al target at 1 MeV, on the other hand, are lower than the Mott cross section values by an average of 3% at the forward angles, while the values at backward angles are about 10% below the Mott cross sections. Although the apparent shape of each of the experimental cross-section curves differs from the shape of the Mott cross-section curve, both measurements confirm the Mott cross sections within the estimated experimental errors.

PHYSICAL REVIEW VOLUME 138, NUMBER 1A 5 APRIL 1965

Absolute Total Electron–Helium-Atom Scattering Cross Sections for Low Electron Energies*

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(Received 6 November 1964)

The Ramsauer technique has been used to measure the absolute total electron–helium-atom scattering cross section as a function of electron energy from 0.30 to 28 eV with an estimated probable error of ±3%. No "fine structure" has been observed at the lower electron energies studied. The variation of the cross section with energy for energies less than 3 eV is in reasonable agreement with the modified effective-range formula given by O'Malley, using a scattering length of $1.15a_0$. The cross section first increases with decreasing electron energy from 2.2 Å^2 at 28.0 eV to a maximum of 5.6 Å^2 at about 1.2 eV and then decreases to 5.4 Å^2 at 0.300 eV. The cross section has been found to decrease sharply with increasing energy at about 0.5 eV below the first excitation energy. This resonance, predicted by Baranger and Gerjuoy and originally observed by Schulz, first decreases with increasing energy to a minimum of about 10% below the background at 19.285±0.025 eV and then increases to a gentle maximum of about 3% above the background at 19.65±0.05 eV. The resolution of this resonance as well as the 10% decrease in the cross section at the minimum is determined by the half-width of the electron beam at this energy which is about 0.1 eV.

INTRODUCTION

THE earliest direct measurements of the total electron–rare-gas atom scattering cross section which attempted to use electrons of well-defined energy were made by Ramsauer[1] in 1921. These measurements were extended by Brode[2] in 1925, who used a slightly different technique.

For helium,[3] Brode's results[2] are in general about 25% lower than Ramsauer's.[1,4] The total cross section was calculated by Allis and Morse[5] in 1931 by using a simple atomic model. McDougall,[6] shortly thereafter, calculated the cross section by considering a Hartree field due to the atom and making a partial-wave analysis for the (l=0, 1, 2,) partial waves. McDougall's calculation yielded a cross section which is about 17% lower than Brode's measurement at 25 eV. The two results agree at about 17 eV and McDougall's results are considerably higher, even than Ramsauer's at lower energies. By

* Supported by the Lockheed Independent Research Program.
[1] C. Ramsauer, Ann. Physik **66**, 546 (1921), measured the total cross section in helium for electron energies from about 1 to 50 eV.
[2] R. B. Brode, Phys. Rev. **25**, 636 (1925).
[3] Throughout this paper, the discussion will always be about helium, except where specifically mentioned otherwise.
[4] However, Brode's and Ramsauer's results are approximately the same at about 3.75 eV.
[5] W. P. Allis and P. M. Morse, Z. Physik **70**, 567 (1931).
[6] J. McDougall, Proc. Roy. Soc. (London) **A136**, 549 (1932).