Inelastic-Electron-Scattering Cross-Section Measurements at 0.2-, 1.0-, and 2.0-MeV Incident Electron Energies*

D. H. Rester
Advanced Technology Center, Incorporated, Dallas, Texas 75222

and

N. Edmonson
George C. Marshall Space Flight Center,
National Aeronautics and Space Administration, Huntsville, Alabama 35800
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Spectra of inelastically scattered electrons from Al and Au targets are shown for scattering angles of 45 and 135 deg at incident electron energies of 0.2, 1.0, and 2.0 MeV, and for an angle of 60 deg at an energy of 1.0 MeV. Theoretical values from the Bethe-Heitler theory, calculated from the formulas of McCormick, Keiffer, and Parzen, are compared to the measured values.

I. INTRODUCTION

At intermediate electron energies, the spectra of electrons scattered with measurable energy loss by thin target foils have been reported in three experimental studies. In the first of these, by Motz and Placious,[1] a sector-field magnetic analyzer was used to observe inelastically scattered electrons emerging from the target at 100 deg. Targets of Al and Au were used for an incident electron energy of 0.5 MeV. In the second study, by Dick and Motz,[2] a solid-state surface-barrier detector was employed to measure the total spectrum of scattered electrons, including the line due to Mott (elastic) scattering, at the incident energies of 0.2 and 0.4 MeV. Measurements were reported for angles from 40 to 140 deg. The third study, by Missoni, Dick, Placious, and Motz,[3] combined the use of a magnetic spectrometer of a new design and a high-resolution solid-state detector to study the very low-energy region of the inelastic electron spectrum, from 10 to 400 keV, for incident electron energies of 0.1, 0.2, 0.4, and 3.0 MeV. Targets of C, Cu, and Au were bombarded.

The study of inelastic electron scattering reported in the present paper was motivated primarily by the very large discrepancy between the results of the measurements reported in the second study listed above and previous measurements of Mott scattering with solid-state detectors,[4] in which the region of the scattered-electron spectrum was measured from the Mott peak at the incident energy down to less than 10% of the incident energy. In the latter measurements, no discernible yield of scattered electrons with energies below the Mott peak was observed, except at angles less than 90 deg where the Møller line was observed. Present in each pulse-height distribution was the continuum of counts which characterizes the response of a Si detector to a monoenergetic group at the incident energy (and, where significant, the additional contribution to the continuum of pulses due to the Møller line). However, the fraction of pulses in the energy region below the full energy peak in the continuum was less than 25% of the yield in the peak at incident energies below 1.0 MeV. This small yield, primarily the result of the detector response, is in contrast with the inelastic cross sections obtained in the second study listed above which were reported to be as high as 15 times the elastic cross section at 150 deg for Al for a bombarding energy of 0.4 MeV.

In the study reported here, a magnetic analyzer was used in conjunction with a high-resolution Si(Li) detector. The magnetic analyzer was used to remove the very intense line at the incident energy so that the Si(Li) detector could detect the relatively small yield of inelastically scattered electrons. The inelastic electrons would otherwise have been masked by the detector response in the same pulse-height region due to the detection of the line at the incident energy. Comparisons of the experimental spectra are made with the predicted yield of inelastic electrons from the Bethe-Heitler theory integrated over photon energy as given by the formulas of McCormick, Keiffer, and Parzen.[5] Comparison of the experimental values with the theoretical predictions of the inelastic electron spectra from bremsstrahlung emission is valid in the region of the distribution greater than about 25% of the incident energy, since multiple scattering effects for targets of the thicknesses used in the present measurements and the contribution from collisions resulting in atomic excitation are expected to be significant only at much lower electron energy. The effects of multiple scattering in the low-energy region are shown in Ref. 3. In addition to the continuum of electrons in the energy region of interest in the present measurements, however, the Møller line is observed at 45 and 60 deg. The effect of Møller scattering on the yield in the continuum at higher energy may be significant.

II. EXPERIMENTAL PROCEDURE

Scattered electrons from thin targets of Al and Au were detected by a Si(Li) detector positioned at the focal point of a sector-field magnetic spectrometer. The entrance to the magnetic spectrometer was well collimated so that electrons from an area on the target foil slightly larger than the beam spot of 1 mm would be accepted by the spectrometer. An electron baffle was arranged in the chamber on the opposite side of the target from the spectrometer entrance aperture to prevent particles scattered by the target from backscattering from the chamber wall into the spectrometer acceptance angle. Except for the presence of the strong line from elastic scattering and the resulting continuum of pulses due to the detector response, the magnetic spectrometer would not have been required. This is illustrated by several of the spectra of Fig. 1. Solid circles are used to plot the response of a Si(Li) detector to the scattered beam from an Au target at a bombarding energy of 0.2 MeV (without magnetic analysis). Also shown, plotted with triangles, is the response of the same detector exposed to electrons in the 0.2-MeV line only, i.e., with the magnetic spectrometer set to bend 0.2-MeV electrons into the detector. It is apparent that the dominant contribution to the yield in the energy region of the inelastic electrons is that of the detector response to the 0.2-MeV electron group. The difference between the two curves is the spectrum of inelastically scattered electrons from the target. Solid triangles are used to show the spectrum of electrons from measurements obtained by scanning the energy region with the magnetic spectrometer at 135 deg. The magnetic spectrometer measurements agree in magnitude with the difference between the two curves above. However, the accuracy of the relatively weak spectrum of inelastically scattered electrons obtained by measurement is significantly increased by use of the magnetic spectrometer. This is especially true at higher incident electron energies for Al targets where the yield of inelastic electrons is lower.

The momentum resolution of the magnetic spectrometer was 2%. Si(Li) detectors of thicknesses of 2–5 mm were used in the measurements to provide more than an adequate active detector volume to capture the incident electrons. The response of the detector to the electron group at each magnetic field setting was such as to allow the greatest sensitivity in detecting the low yield of particles. The

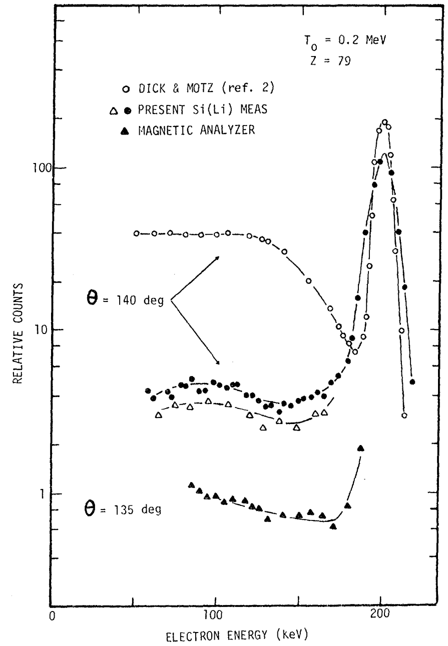

FIG. 1. Comparison of measurements reported by Dick and Motz (Ref. 2) with similar recent measurements on an Au target for 0.2-MeV incident energy. The data plotted with circles were taken from a figure of the paper by Dick and Motz. They correspond to the present measurements of electrons scattered by the target at 140 deg plotted with solid circles. The response of the Si(Li) detector to 0.2 MeV electrons is shown in the inelastic region with triangles. If the difference between the curves plotted with solid circles and triangles were taken, it would be the yield of inelastically scattered electrons obtained from the measurements with a Si(Li) detector. This difference compares in magnitude with the yield obtained with magnetic analysis at 135 deg, plotted with solid triangles. The yield of inelastic electrons from the present measurements is more than an order of magnitude less than that reported from the earlier measurements.

Si(Li) detector could be operated at reduced temperature with the Gaussian part of the response to monoenergetic electrons having a full width at half-maximum of 5 keV.

Au targets were fabricated by evaporation of the metal to a thickness of 20 $\mu g/cm^2$ onto 10-$\mu g/cm^2$ polycarbonate foils. Although the beam spot was about 1 mm in diameter, target foils of 4-cm diameter were used to avoid possible sources of background scattering at the target position from very weak direct beam components, or scattered beam striking thick materials in the view of the spectrometer. Self-supporting Al targets of thicknesses in the range of 20–50 $\mu g/cm^2$ were used.

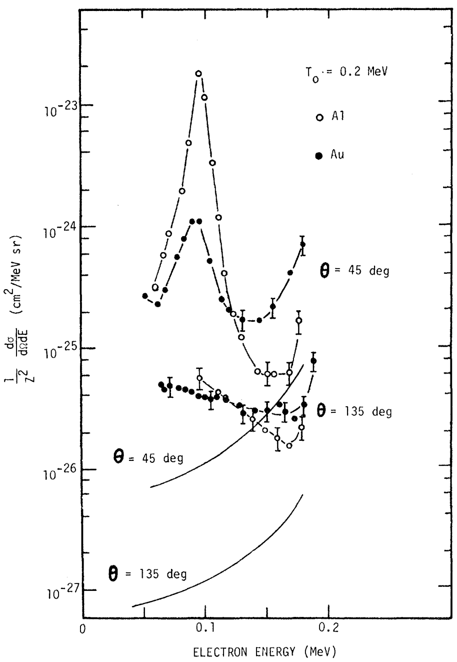

FIG. 2. Spectra of inelastically scattered electrons from Al and Au targets for scattering angles of 45 and 135 deg and an incident electron energy of 0.2 MeV. The Møller peak is prominent at 45 deg for each element at this bombarding energy and also at bombarding energies of 1.0 and 2.0 MeV. The theoretical reduced cross-section values from the formulas of McCormick *et al.* (Ref. 5) are shown as continuous lines for 45 and 135 deg. The error bars on the experimental points represent an experimental error of 20% at 45 deg and 30% at 135 deg.

III. EXPERIMENTAL RESULTS

The results of Dick and Motz[2] are shown in Fig. 1 at 0.2-MeV bombarding energy for an Au target and a scattering angle of 140 deg. In the same figure is the spectrum taken by the present authors to duplicate Dick and Motz's measurement for the same target material and scattering angle at 0.2 MeV. The comparison was made by equating the yield of elastically scattered electrons. In the energy region of the inelastically scattered electrons, the comparison shows that the data of Dick and Motz are about an order of magnitude higher than the data from the present measurement. Since the yields of elastically and inelastically scattered electrons are recorded concurrently in measurements such as these, it is impossible to measure a ratio of inelastically scattered to elastically scattered electrons less than the actual value. In the case of the data reported by Dick and Motz, the spectrum of true inelastics from the target has been lost in a spectrum of electrons from other sources. On the other hand, most of the yield in the more recent measurements with the Si(Li) detector in the inelastic electron energy region is due to the response of the detector to the elastic line as discussed above.

The masking of the inelastically scattered electrons by the response to the elastic line, which occurs when a solid-state detector alone is used to measure the spectrum of scattered electrons from the target, was avoided in the measurements reported below by use of a magnetic spectrometer. Spectra were measured at 45 and 135 deg for Al and Au targets for bombarding energies of 0.2, 1.0, and 2.0 MeV and at 60 deg for 1.0 MeV. The Møller peak was observed as an intense component of the spectrum at forward angles for each target at each bombarding energy and appears to influence the electron yield over a large region of the spectrum. At an incident electron energy of 0.2 MeV, the Møller peak in the Au spectrum is somewhat distorted and is about twice the width at half-maximum above the continuum as the peak in the Al spectrum. At the higher bombarding energies the Møller lines for both elements are very similar in shape and width. However, the linewidths observed at 1.0- and 2.0-MeV incident electron energies as well as at 0.2 MeV cannot be accounted for entirely by the

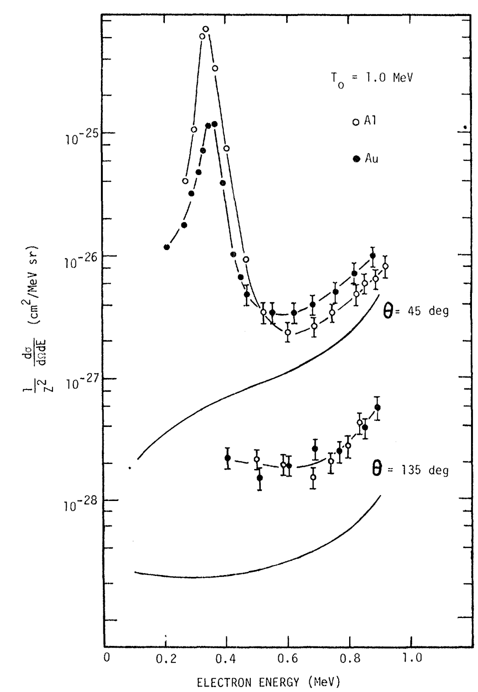

FIG. 3. Spectra of inelastically scattered electrons from Al and Au targets for an incident electron energy of 1.0 MeV. Comparisons are made with the theoretical reduced cross-section values for electrons scattered by bremsstrahlung emission evaluated in the Born approximation.

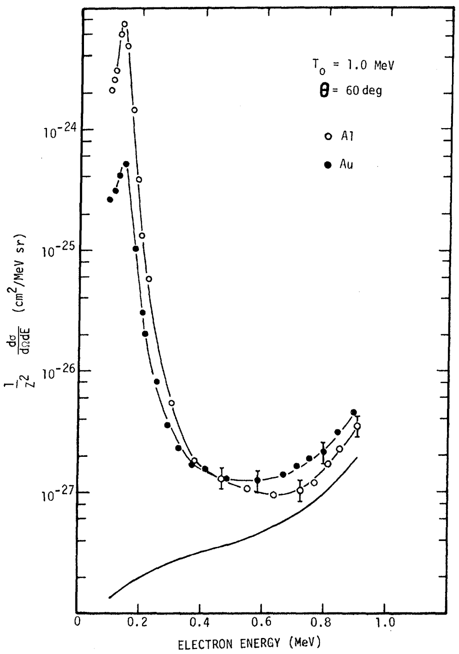

FIG. 4. Reduced cross-section values at 60 deg for Al and Au targets for an incident energy of 1.0 MeV.

finite solid angle of the spectrometer entrance aperture and the resolution of the magnet-detector system.

Reduced cross-section values obtained from the measurements for an incident electron energy of 0.2 MeV are shown in Fig. 2. The Born-approximation values of the reduced inelastic-scattering cross section from integration of the Bethe-Heitler theory over photon angle are also shown in Fig. 2. The values were obtained from the formulas of McCormick, Keiffer, and Parzen.[5] From measurements on the Au target at both angles, inelastic-scattering cross-section values were obtained which are an order of magnitude greater than the theoretical values for the interaction in which bremsstrahlung is produced. However, the value for Al at 45 deg approaches the theoretical value in magnitude at an electron energy of 0.17 MeV, in the region between the Møller and elastic lines. At 135 deg for Al the experimental values cross the values measured for Au. An experimental error of 20% at 45 deg and 30% at 135 deg has been assigned to the cross-section values.

The comparisons of the theoretical and experimental cross-section values for bombarding energy of 1.0 MeV are shown in Figs. 3 and 4. For the case of Al at 45 deg, the comparison is similar to that at an incident electron energy of 0.2 MeV. However, the energy region above the Møller line is greater at 1.0 MeV. In this region the shape of the curve through the experimental points is similar to the shape of the theoretical curve, but the theoretical values average about 50% below the experimental values. At a scattering angle of 135 deg, the experimental values for both Al and Au targets are about 5 times greater than the theoretical predictions. For the case of Au at 45 deg, the measured cross-section values are closer to the theory than at 0.2-MeV bombarding energy. To increase the energy region of the spectrum between the Møller and elastic lines, spectra for both Al and Au targets were taken at 60 deg. Reduced cross-section values for 60 deg are shown in Fig. 4. Although the Møller line energy is decreased, the increased intensity of the line at larger angle results in a discernible contribution to the continuum up to about 0.6 MeV. Above 0.6 MeV, the comparison at 60 deg is similar to that at 45 deg.

The results of the measurements for an incident electron energy of 2.0 MeV are shown in Fig. 5. The theoretical values for Al at 45 deg are about 30% lower than the experimental values in the energy region above the Møller line. As at 1.0 MeV, the shape of the experimental curve in this region is similar to the theoretical shape. The very low yield at 135 deg limited the accuracy of cross-section values of this angle. Here the yield per energy increment was observed to be two orders of mag-

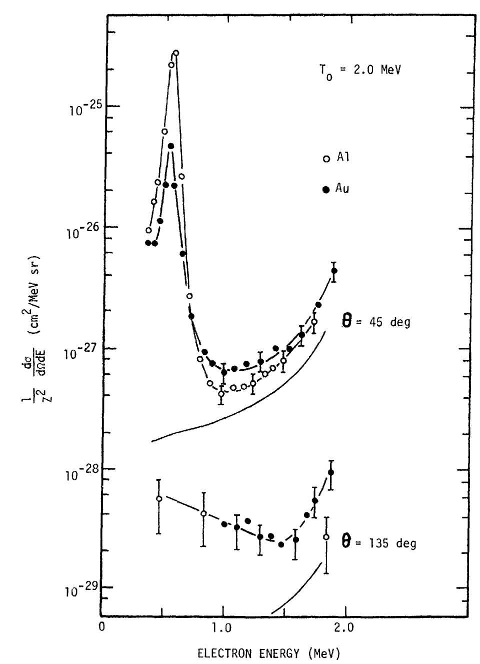

FIG. 5. Comparison of experimental inelastic electron spectra for Al and Au targets with the Born-approximation predictions of the spectra of inelastic electrons scattered by bremsstrahlung emission for an incident electron energy of 2.0 MeV. An experimental error of 50% is assigned to the values at 135 deg for Al.

nitude less than at 0.2 MeV and 135 deg for the same target. At the higher bombarding energy, increased x-ray background and the low yield resulted in an experimental error of nearly twice the error of 30% assigned for the other measurements at 135 deg. The observed yield at the backward angle reached a minimum as a function of electron energy. It was possible to obtain resolvable electron yields only in the regions above and below the minimum. The experimental values for Au for 2.0-MeV bombarding energy continue the trend seen between 0.2 and 1.0 MeV and are closer to the theoretical values than at the lower energies.

IV. CONCLUSIONS

The experimental values reported here are significantly smaller than the values of Dick and Motz.[2] A comparison of the cross-section values at 0.2 and 1.0 MeV from the present measurements with the values of Motz and Placious[1] at 0.5 MeV indicates that the present values are consistent with the earlier values for Au, while the earlier values for Al appear to be somewhat higher than the present values. Although it is not possible to make a direct comparison to the values reported by Missoni *et al.*,[3] the present values appear to be consistent with their values at lower electron energies. Comparisons[6] of experimental bremsstrahlung cross sections to the values from the Bethe-Heitler theory revealed agreement at 1.7- and 2.5-MeV incident electron energies for Al. From the latter comparisons, it can be inferred that there are other significant contributions to the yield of inelastic electrons in the region of the spectrum measured in the present experiment, since differences between the experimental values and theoretical values from the Bethe-Heitler theory outside the experimental error were observed. Coincidence measurements will be required to resolve the inelastic spectrum into its components. Analysis of the predicted coincidence rates indicates that accurate coincidence measurements are feasible for incident energies below 1.0 MeV.

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Sensitivity of Rainbow Structure in Proton-Helium Elastic Scattering to Small Changes in the Potential Surface*

Merle E. Riley
Sandia Laboratories, Albuquerque, New Mexico 87115
(Received 22 January 1971)

The proton-on-helium elastic-scattering differential cross section is computed through the rainbow region for two different potential surfaces, each of high accuracy, for center-of-mass energies 92.7 and 15.4 eV (115.8 and 19.3 eV in the lab frame) to test an assumption that the semiclassical approximation would give adequate information at the rainbow angle to distinguish experimentally the better of the theoretical potentials.

INTRODUCTION

Helbig *et al.*[1] proposed that high-resolution differential-cross-section (σ) measurements would be able to distinguish between the ground-state Born-Oppenheimer potential-energy surfaces of Michels[2] and Wolniewicz[3] for the HeH^+ system. This has since been done by Doverspike *et al.*[4] by examining the rainbow region at a collision energy of 4 eV center of mass (c.m.), and comparing with differential cross sections calculated by partial-wave analysis using JWKB phase shifts, of which about 400 were needed for convergence throughout the rainbow structure. Helbig *et al.* found that a