Coulomb Scattering without Atomic Excitation for 50-, 100-, 200-, and 400-keV Electrons

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Cross sections for the single scattering without atomic excitation of 50-, 100-, 200-, and 400-keV electrons from thin targets of gold, tin, and copper are experimentally determined at angles ranging from 20 to 110 deg. These experimental cross sections show good agreement with the Lin, Sherman, and Percus phase-shift calculations for the Mott exact cross section, which was evaluated with an approximate Hartree screening potential for gold and copper. On the other hand, the experimental results show appreciable differences from Born cross section calculations containing Molière screening, particularly for the lowest electron kinetic energy (50 keV) and the largest atomic number (79) and for the region where the momentum transfer to the nucleus (in m_0c units) is less than unity.

1. INTRODUCTION

THE most accurate cross section estimates for the process of electron-atom scattering without atomic excitation are obtained from the Mott[1] phase-shift calculations. With this phase-shift method, Mott has derived an exact formula[2] which applies to electron Coulomb scattering for an *unscreened, point* nucleus and which neglects radiation effects. The problem of including atomic screening effects (or nuclear size effects[3]) in phase-shift calculations is complicated, and only with the advent of fast computers has it become possible to evaluate the exact cross section with screening. Such phase-shift calculations of the screened cross section have been carried out by Bartlett and Welton,[4] Mohr,[5] Mohr and Tassie,[6] and most recently with a more accurate procedure by Lin, Sherman, and Percus.[7] Other simpler methods for estimating the screened cross section are based on Born-approximation calculations[8] which include screening effects as a multiplicative factor to the unscreened cross section and which require a central screening potential. At present, there is considerable uncertainty in the accuracy of the cross sections given by the above calculations.

The purpose of the present investigation is to provide experimental data that can be compared with the theoretical estimates for the screened cross section which are given both by the Born approximation and the phase-shift calculations. Screening effects for the above process become important if the impact parameter is larger than the K-shell radius which roughly corresponds to the region where the momentum transfer (in m_0c units) to the atom is less than $Z/137$. The present measurements are carried out with 50-, 100-, 200-, and 400-keV electrons scattered from thin gold, tin, and copper targets at scattering angles where the momentum transfer (in m_0c units) to the atom is in the region from approximately 0.2 to 1.6. Previous measurements in this energy and momentum transfer region are not consistent with each other and are summarized for example by Spiegel *et al.*[9] and by Kessler.[10] None of these earlier results clearly establish the accuracy of the screened cross section given by either the phase-shift or the Born-approximation calculations which are discussed above.

2. EXPERIMENTAL PROCEDURE

In these measurements, a $\frac{1}{8}$-in.-diam beam of monoenergetic electrons at 50, 100, 200, and 400 keV from the NBS constant potential accelerator is directed at thin targets of gold, tin, and copper. The transmitted electron beam enters an electron trap in the target chamber, and the total electron charge incident on the target is measured with a current integrator.

The electrons that are scattered at a given angle from the target pass through an aperture which is used with additional scattering baffles and which subtends a solid angle of 3.2×10^{-4} sr from the center of the target. Measurements are made at 10-deg intervals from 20 to 110 deg, and the beam directions for the incident and scattered electrons were experimentally checked in order to determine the scattering angle with an absolute accuracy better than 0.1 deg. The energy distribution of the scattered electrons is determined with a scintillation spectrometer employing a $\frac{1}{8}$-in.-thick plastic crystal and a multichannel pulse-height analyzer. This energy distribution has the form of an "elastic" line with a shape that depends on the spectrometer resolution, plus a low-energy tail. The experimental cross sections are determined from measurements of the

[1] N. F. Mott and H. S. W. Massey, *The Theory of Atomic Collisions* (Oxford University Press, London, 1949), 2nd ed.
[2] N. Sherman, Phys. Rev. **103**, 1601 (1956), Eq. (1). This formula is evaluated for a wide range of parameters by Sherman in the above reference and also by J. A. Doggett and L. V. Spencer, *ibid.* 1597 (1956).
[3] Phase-shift calculations that include nuclear-size effects have been carried out by D. R. Yennie, D. G. Ravenhall, and R. N. Wilson, Phys. Rev. **95**, 500 (1954).
[4] J. H. Bartlett, Jr., and T. A. Welton, Phys. Rev. **59**, 281 (1941).
[5] C. B. O. Mohr, Proc. Roy. Soc. (London) **A182**, 189 (1943).
[6] C. B. O. Mohr and L. J. Tassie, Proc. Phys. Soc. (London) **A67**, 711 (1954).
[7] Shin-R Lin, N. Sherman, and J. Percus, Nucl. Phys. **45**, 492 (1963).
[8] See Chap. IX, Eqs. (11) and (13) of Ref. 1.
[9] V. Spiegel, Jr., T. F. Ruane, D. J. Anthony, B. Waldman, and W. C. Miller, Ann. Phys. (N.Y.) **6**, 70 (1959).
[10] J. Kessler, Z. Physik **155**, 350 (1959).

total number of electrons contained in the "elastic" line. For a given electron energy, the number of electrons in the "elastic" line is experimentally determined by integrating the pulse-height distribution curve above a minimum pulse height which is equal to 0.75 P_0, 0.67 P_0, and 0.25 P_0 (where P_0 is the pulse height corresponding to the peak intensity of the line shape) for 400-, 200- or 100-, and 50-keV electrons respectively, and which corresponds to a counting rate that is approximately 2 orders of magnitude smaller than the peak counting rate. Additional measurements of the electrons contained in the elastic line were made at the smaller angles with a magnetic spectrometer and the cross sections determined with both types of spectrometers showed good agreement. The magnetic spectrometer, which has much better energy resolution than the scintillation spectrometer, was not used exclusively because its stray magnetic field at the large scattering angles changes the incident electron direction and thereby introduces a very important systematic error in the scattering angle. For scattering angles less than 90 deg, an additional peak due to Møller scattering is superimposed on the low-energy tail. This Møller peak could not be resolved from the elastic peak for scattering angles less than 50 deg, and for these cases the number of electrons measured in the elastic peak required a small correction (less than a few percent) which was derived from the Møller cross section[11] in order to account for the contribution of the Møller scattered electrons. Other corrections relating to radiative and nuclear-size effects are negligible in this energy region.

The targets consist of evaporated films of gold, tin, and copper, with thicknesses in the region from 10 to 50 $\mu g/cm^2$. These films are evaporated on collodion backings approximately 5 $\mu g/cm^2$ thick. The small contribution (less than 10%) of the collodion backings is determined from measurements at each angle with a separate collodion target which was calibrated in terms of the target collodion backings before evaporation. For each scattering angle, the target surface is inclined at various angles ranging from 0 to 60 deg with respect to the surface that is normal to the incident beam direction, in order to permit all measurements to be made in the transmission position where the scattered electron emerges from the target surface opposite to that of the incident electron. This latter precaution is necessary in order to have negligible multiple scattering effects for these targets. For a given atomic number, measurements were made with different effective target thicknesses and, within the experimental errors, the cross sections determined from the measurements were found to be independent of the target thickness.

The experimental values for the cross section have a maximum fractional standard deviation of 2%. In addition, the following estimates are given for the uncertainties in the experimental cross sections introduced by the important systematic errors: (1) effective target thickness ±4%; (2) electron scattering angle ±1%; (3) total electron charge incident on target ±1%; (4) corrections involving the spectrometer resolution ±2%; (5) detector efficiency ±1%; (6) solid angle of detector ±1%. On the basis of the above estimates, the accuracy of the experimental cross sections are expected to be better than 10%. In addition, the systematic errors are expected to have a negligible effect on the shape of the experimental cross section curves that are compared with theoretical curves in Figs. 1–3.

[11] C. Møller, Ann. Physik **14**, 568 (1932).

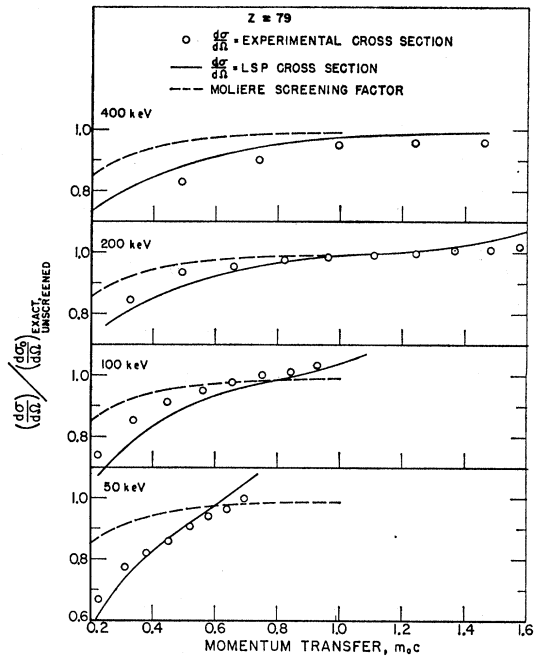

FIG. 1. Dependence of the cross section for electron scattering without atomic excitation on the momentum transfer $[2p_0 \sin(\varphi/2)]$ to the atom in the collision. These results apply to a gold target for initial electron kinetic energies of 50, 100, 200, and 400 keV. The open circles give the ratio of the experimental cross section to the unscreened Mott exact cross section obtained from Eq. (1) in Ref. 9. The dashed lines give the ratio of the screened to the unscreened Mott-Born cross section (Ref. 12), which is equal to the Molière screening factor $[1-F(q_0)]^2$, where $F(q_0)$ is the Molière atomic-form factor given by Eq. (II–12) in Ref. 13. The solid lines give the ratio of the screened to the unscreened Mott exact cross section, where the screened cross section is evaluated by Lin, Sherman, and Percus (Ref. 7) with an approximate Hartree screening potential. (See Ref. 14).

3. RESULTS

The cross-section results for electron single scattering without atomic excitation from gold, tin, and copper targets are shown in Figs. 1–3, respectively, for electron kinetic energies of 50, 100, 200, and 400 keV. These results show the dependence of experimental and theoretical cross section ratios on the momemtum q_0, which is transferred to the atom in the collision. For this low-energy region, the momentum transfer q_0 is equal to

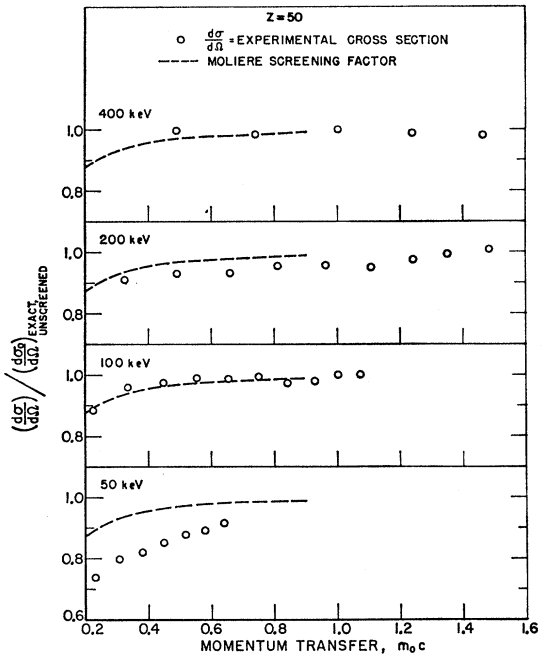

FIG. 2. Same as caption in Fig. 1 except that gold is replaced by tin and no theoretical values (solid line) are given for the screened Mott exact cross section.

$2p_0 \sin(\varphi/2)$, where p_0 is the inital electron momentum (in m_0c units) and φ is the electron scattering angle. The open circles in Figs. 1–3 give the ratio of the experimental cross section (without systematic error limits) to the unscreened Mott exact cross section shown in Eq. (1) of Ref. 2, which was evaluated for the above parameters with an IBM 7090 computer. The dashed lines in Figs. 1–3 give the theoretical values for the ratio of the screened to the unscreened Mott-Born cross section,[12] which is equal to the factor $[1-F(q_0)]^2$, where $F(q_0)$ is the Molière atomic form factor.[13] The solid lines in Figs. 1 and 3 give the theoretical values for the ratio of the screened to the unscreened Mott exact cross section, where the screened cross section is evaluated from the phase-shift calculations of Lin, Sherman, and Percus[7] with an approximate Hartree screening potential given by Byatt[14] and the unscreened cross section is evaluated as above from Eq. (1) in Ref. 2.

The experimental results for gold in Fig. 1 show that atomic screening effects which are expressed by the departure from unity of the ratio of the screened to the unscreened cross section are important in the region where the momentum transfer (in m_0c units) is less than unity. Also, screening effects are appreciable even at 400 keV and become more important as the electron kinetic energy decreases to 50 keV. For small q_0 values, the ratio of the screened to the unscreened cross sections becomes smaller than unity. On the other hand, for large q_0 values and particularly at the lower energies, this ratio becomes larger than unity which indicates that the probability of collisions with small impact parameters becomes larger with a screened than with an unscreened nuclear charge. The experimental results for tin and copper do not reveal any large screening effects except at 50 keV, and indicate that as Z decreases, the screening effects become important at smaller values of the mometum transfer and the electron kinetic energy.

The theoretical results show that in the region where q_0 is less than unity there is a considerable difference (which is as large as 50% at 50 keV for gold) in the screening effects predicted by the Born-approximation calculations and by the phase-shift calculations. Such differences, which are considerably smaller for copper than for gold, may be attributed both to the breakdown of the Born approximation for these energies and to the

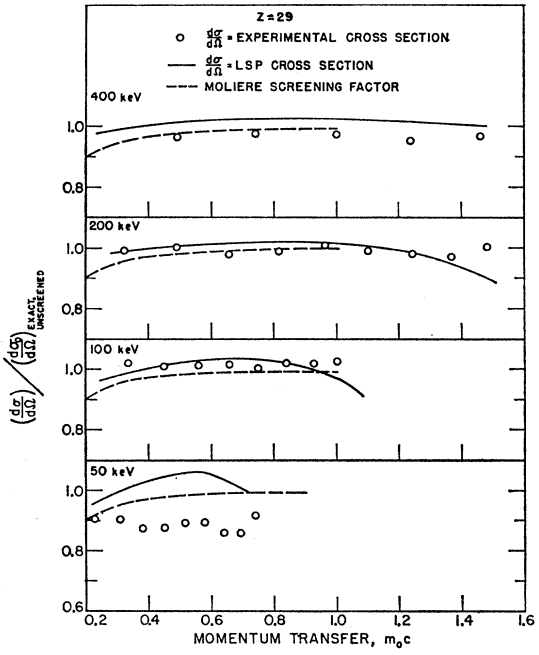

FIG. 3. Same as caption in Fig. 1 except that gold is replaced by copper.

[12] The screened Mott-Born cross section is simply equal to the product of the unscreened Born cross section [given by Mott in formula (42), p. 80 of Ref. 1] and the atomic screening factor $[1-F(q_0)]^2$.

[13] G. Molière, Z. Naturforsch **2a**, 133 (1947). The analytical expression for the Molière form factor used in these calculations is given, for example, in Eq. (II–12) by H. W. Koch and J. W. Motz, Rev. Mod. Phys. **31**, 920 (1959).

[14] W. J. Byatt, Phys. Rev. **104**, 1298 (1956). Byatt approximates the Hartree screening potential of many different neutral atoms including mercury ($Z=80$) and zinc ($Z=30$) [but not including gold ($Z=79$), tin ($Z=50$), or copper ($Z=29$)] with analytical expressions which are a function of the atomic number. In the calculations which give the results shown by the solid lines in Figs. 1 and 3, the atomic numbers for gold and copper were substituted in the Byatt expressions for mercury and zinc, respectively, and the differences in the potentials introduced by these substitutions is estimated to be less than 5%.

inadequacy of the simple analytical Molière screening factor.[13] The experimental cross sections and particularly the shapes of the experimental cross-section curves in Figs. 1 and 3 show good agreement within the experimental errors (except for copper at 50 keV where the discrepancies are not understood) with the theoretical curves for gold and copper given by the phase-shift calculations of Lin, Sherman, and Percus.[7] The results for tin in Fig. 2 show that the Born approximation calculations with Molière screening break down at 50 keV, but give reasonably accurate results at the higher energies.

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Polarization of He^3 Gas by Optical Pumping

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The process of He^3 nuclear polarization by metastability exchange with optically pumped metastable He^3 atoms is described and experimental details given. Phenomenological theories are presented which explain the optical signals and the time variation of the polarization. The polarization is measured both optically and by nuclear magnetic resonance. Relaxation of the nuclear spins by diffusion through magnetic field gradients is discussed. When gradients are small, nuclear relaxation times as long as 4000 sec have been measured. The maximum polarization achieved was $40\pm5\%$ in He^3 gas at a pressure of one mm Hg.

I. INTRODUCTION

OPTICAL pumping techniques have been successfully applied to produce orientation of the magnetic moments of a number of atomic species. In particular, the alkali metals, mercury, and the helium isotope of mass four have been investigated in considerable detail by this method.

Colegrove and Franken first reported the alignment by optical pumping of He^4 atoms in the $2\,^3S_1$ metastable state.[1] These studies were later extended by Schearer.[2] In their experiments, metastable atoms were produced by an rf discharge in a Pyrex bulb containing He^4 gas at low pressure. In the steady state, approximately one millionth of the He^4 atoms were in the desired $2\,^3S_1$ state. Orientation of the magnetic moments of the metastable atoms was accomplished by $2\,^3S-2\,^3P$ pumping light from a helium lamp. Transitions between the three equally spaced magnetic sublevels of the $^3S_1$ state were induced by an rf magnetic field at the resonant frequency and detected by monitoring the transmitted pumping light.

Consider now the differences one must expect in attempting to polarize He^3 metastables by the same procedure. As in the case of He^4, the pumping light will tend to produce unequal populations of the $^3S_1$ magnetic sublevels, and the equilibrium polarization reached will depend on the rate at which these atoms are removed from a particular sublevel by various collision processes. For both He^4 and He^3 the most rapid pertinent collision process is the transfer of metastability from atom to atom, and it is this mechanism that plays a fundamentally different role in the two gases. He^4 has nuclear spin zero and a nondegenerate ground state; thus, metastability exchange collisions cannot alter the magnetic quantum number of the metastable atom, since angular momentum must be conserved. In contrast, He^3 has a nuclear spin $I=\frac{1}{2}$ and a ground-state Zeeman doublet; metastability exchange can in this case result in a ±1 change in the metastable magnetic quantum number, with a corresponding ∓1 change in the ground-state nuclear magnetic quantum number. Since exchange collisions occur more rapidly than the metastables can absorb photons, the He^3 metastables will be rapidly mixed among their available Zeeman levels, with simultaneous loss of angular momentum to ground-state atoms. It was first thought that this exchange process would

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[1] F. D. Colegrove and P. A. Franken, Phys. Rev. **119**, 680 (1960).
[2] L. D. Schearer, *Advances in Quantum Electronics* (Columbia University Press, New York, 1961), pp. 239–251.