"Triple" Scattering Experiment for Obtaining the Maximum Possible Information on Elastic Electron Scattering from Mercury

O. Berger, J. Kessler, K. J. Kollath, R. Möllenkamp, and W. Wübker
Physikalisches Institut der Universität Münster, D-4400 Münster, Germany
(Received 1 December 1980)

Experimental results on the change of electron spin polarization due to elastic scattering are reported. Measurements with a mercury target have been made at electron energies between 30 and 350 eV at a scattering angle of 90°. In conjunction with results for the differential cross section and the Sherman function, such measurements yield the maximum possible information on the scattering process.

PACS numbers: 34.80.Bm

Elastic scattering of electrons from unpolarized atomic targets can theoretically be described by the direct scattering amplitude $f=|f|\exp(i\gamma_1)$ and the spin-flip amplitude $g=|g|\exp(i\gamma_2)$ originating from spin-orbit interaction. These amplitudes, which depend on electron energy E, atomic number Z, and scattering angle θ, have been calculated by applying various approximations for the electron-atom interaction. The results tend to become less reliable as the electron energy decreases.[1]

Experimental studies of elastic electron scattering have so far been restricted to the determination of two observables: Single-scattering experiments yielded cross sections $d\sigma/d\Omega=|f|^2+|g|^2$ while double-scattering experiments yielded the polarization after the scattering of an initially unpolarized electron beam, which is given by the Sherman function

$$S=-2\frac{|f||g|\sin(\gamma_1-\gamma_2)}{|f|^2+|g|^2}.$$

Obviously the measurement of these two observables does not suffice to obtain all the information about the process which requires three parameters, namely $|f|$, $|g|$, and the relative phase $(\gamma_1-\gamma_2)$, to be determined.

The missing information can be gained by observing the change of polarization of a polarized electron beam by the scattering. Here, two more observables T and U [see Eq. (1) below] can be determined; they describe the change of the polarization vector in the scattering plane. Conventionally this requires a triple-scattering experiment: The first scattering produces the initial polarization $\vec{P}$ and the third scattering analyzes the polarization $\vec{P}'$ resulting from the second scattering process. The difficulty of such measurements becomes evident by the fact that so far only one pioneer experiment of this kind has been made in electron scattering.[2] However, in this experiment no independent measurement of T and U has been made, because not all polarization components could be observed. Also, the scattering energy was 261 keV, where electron scattering is well understood, since it takes place in the weakly screened Coulomb field of the nucleus. In the more interesting range of much lower energies where electron-atom scattering is usually studied no such experiments with reasonable reliability were feasible in the past. This has changed because of the development of better sources of polarized electrons in the past few years.

The experiment described in the present paper uses a Fano-effect source instead of scattering for producing the primary polarization $\vec{P}$ and thus reduces the number of consecutive scattering processes to two. It allows an independent determination of the observables T and U at low electron energies and yields, as a by-product, a remeasurement of S. The method is based on the fact that the electron polarization $\vec{P}'$ after scattering and the polarization $\vec{P}$ before scattering are connected by [see Ref. 1, Eq. (3.89)]

$$\vec{P}'=\frac{1}{1+\vec{P}\cdot\hat{n}S}\{\hat{n}(\vec{P}\cdot\hat{n}+S)+\hat{k}_2[(\vec{P}\cdot\hat{k}_1)(T\cos\theta+U\sin\theta)+\vec{P}\cdot(\hat{k}_1\times\hat{n})(U\cos\theta-T\sin\theta)] + (\hat{k}_2\times\hat{n})[(\vec{P}\cdot\hat{k}_1)(T\sin\theta-U\cos\theta)+\vec{P}\cdot(\hat{k}_1\times\hat{n})(T\cos\theta+U\sin\theta)]\}, \quad (1)$$

where $\hat{k}_1$ and $\hat{k}_2$ are unit vectors along the directions of incidence and observation, respectively, $\hat{n}=\hat{k}_1\times\hat{k}_2/|\hat{k}_1\times\hat{k}_2|$, $T=(|f|^2-|g|^2)/(|f|^2+|g|^2)$, and $U=2|f||g|\cos(\gamma_1-\gamma_2)/(|f|^2+|g|^2)$. $\vec{P}'$ is thus resolved into components along the directions $\hat{n}$, $\hat{k}_2$, and $\hat{k}_2\times n$ (see Fig. 1). The formulas show that $d\sigma/d\Omega$, S, T, and U are needed to determine $|f|$, $|g|$, and $\gamma_1-\gamma_2$ (though S and U are not independent of each other, both are required for an unambiguous determination of the relative phase).

In our experiments the polarization $\vec{P}$ of the primary electron beam has been chosen to be parallel or antiparallel to $\hat{k}_1 \times \hat{n}$, so that we have $\vec{P} \cdot \hat{n} = \vec{P} \cdot \hat{k}_1 = 0$, and Eq. (1) simplifies to

$$\vec{P}' = S\hat{n} \pm P(U\cos\theta - T\sin\theta)\hat{k}_2 \pm P(T\cos\theta + U\sin\theta)\hat{k}_2 \times \hat{n}, \tag{2}$$

with $P = |\vec{P}|$. Measurement of the latter two components of $\vec{P}'$ therefore yields T and U.

A schematic diagram of the apparatus is shown in Fig. 2. The experimental setup for producing the polarized electrons is similar to that described by Heinzmann, Kessler, and Lorenz,[3] though an extraction system like that described by Heinzmann[4] has been used and measures to increase the intensity have been taken.[5] Usually a beam of 3 nA current with a cross section of approximately 1 cm^2, an energy spread ≤ 1.5 eV, and a polarization of 80% has been extracted.

The electrons which are elastically scattered from a Hg beam are transmitted through a filter lens and a Wien filter and enter a Mott detector for polarization analysis. Two pairs of counters in the Mott analyzer, which detects only transverse polarization components, allow simultaneous analysis of the polarization components $\vec{P}_1' \cdot \hat{n}$ and $\vec{P}_1' \cdot \hat{k}_2 \times \hat{n}$ if the Wien filter is off. If the Wien filter is on, the two polarization components perpendicular to the magnetic field $\vec{B}$ are rotated through 90° ($\vec{P}_1' \rightarrow \vec{P}_2'$) so that the longitudinal component $\vec{P}_1' \cdot \hat{k}_2$ can be measured also.

The experimental procedure has been as follows:

(i) With use of an electrostatic deflector[6] at the position of the Hg target for diffuse deflection of the primary beam, the electron-optical components are adjusted and the primary polarization is measured. (The Wien filter must be on here to obtain transverse polarization.)

(ii) The polarization components $\vec{P}' \cdot \hat{k}_2$ and $\vec{P}' \cdot \hat{k}_2 \times \hat{n}$ resulting from scattering by the Hg beam are measured simultaneously with the Wien filter on. To check the results the experiments are sometimes run with the Wien filter off. The results for $\vec{P}' \cdot \hat{k}_2 \times \hat{n}$ of this measurement (which is free of possible stray magnetic fields originating from the Wien filter) agreed within the error limits with those found with the Wien filter on.

(iii) P is remeasured to make certain that there are no long-term drifts.

The signal count rate for the measurements of T and U varied between 3 and 0.3 s^{-1}, compared with 0.1 s^{-1} background counts. On average, five counts were collected in a single measuring interval under the control of a microcomputer (Rockwell International AIM-65) which automatically replaced such data by a new measurement which were disturbed by excessive pickup of unknown origin (more than fifteen counts per interval).

In order to eliminate instrumental asymmetries, the primary polarization was reversed by using left- and right-circularly polarized light in the Fano-effect source. After about fifty measuring intervals for each of the two directions of the primary polarization, the counts were added, the value of the observed polarization component was computed, and ten to twenty of these data were averaged to give the final result. The scatter of these results was generally in good agreement with that expected from counting statistics.

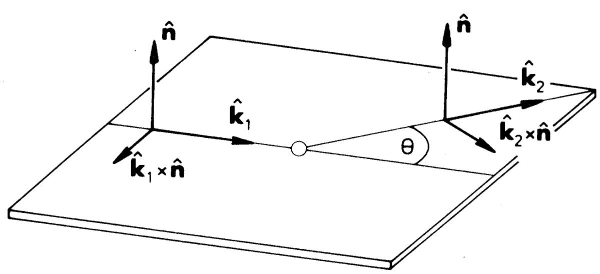

FIG. 1. Definition of scattering geometry.

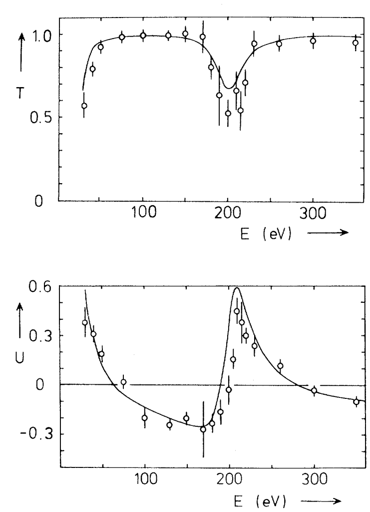

FIG. 2. Schematic diagram of the apparatus.

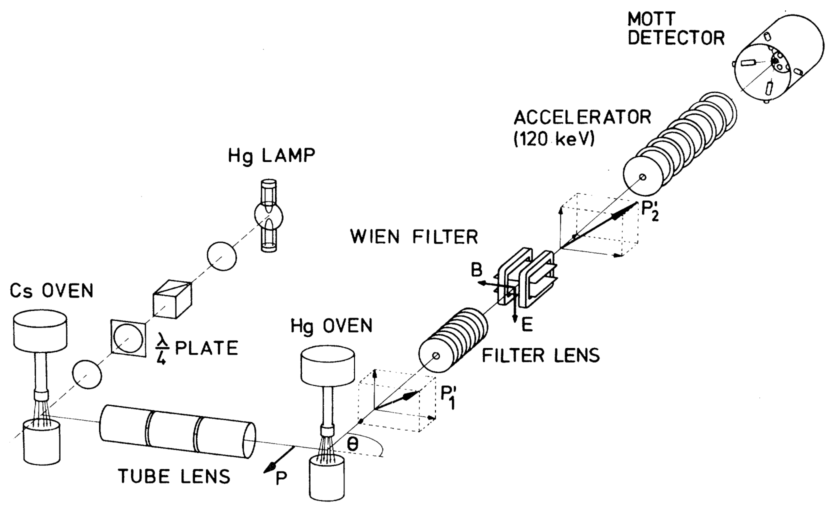

FIG. 3. Results for the observables T and U vs scattering energy at $\theta = 90°$. Experimental points with single statistical error and theoretical curve based on Walker's calculations.

The values for the component $S\hat{n}$ obtained when the Wien filter was off have not been used to evaluate S because elimination of instrumental asymmetries by reversal of $\vec{P}$ is not possible with this component, as is clearly seen from Eq. (2). As an additional check of the apparatus, S has, however, been measured in the conventional way by using a rotatable gun of unpolarized electrons. The data are not presented here because they agree completely with earlier results.[7]

The results for T and U obtained from the components $\vec{P}' \cdot \hat{k}_2$ and $\vec{P}' \cdot \hat{k}_2 \times \hat{n}$ according to Eq. (2) are shown in Fig. 3. The full lines are theoretical curves based on relativistic scattering calculations by Walker[8] including exchange: Walker's data have been convoluted with the instrumental angular resolution $\Delta\theta = \pm 4^0$, which takes into account a theoretical angular acceptance of the filter lens of $\pm 2^0$ and an angular spread of the primary beam of less than $\pm 3.5^0$ as measured by means of a Faraday cup. (Convolution with $\Delta\theta = \pm 3^0$ as a check showed that the curves do not depend essentially on the exact value of $\Delta\theta$.)

Apart from a slight shift between the theoretical and experimental results for U near 200 eV the agreement is good. This is not too surprising since from earlier measurements of the Sherman function and the differential cross section we did not expect severe discrepancies at the energies and the angle chosen here for the first runs of this new type of polarization experiment. The experiments will be extended to other angles and elements where, from earlier measurements of S and $d\sigma/d\Omega$, we anticipate deviations from theory.

In conjunction with measurements of S and $d\sigma/d\Omega$, the results for T and U presented here yield the maximum possible information on the scattering process for the values of Z, E, and θ at which the experiment has been performed.

We gratefully acknowledge a grant by the Deutsch Forschungsgemeinschaft for a three-week stay of Dr. D. W. Walker at our institute, which enabled us to adapt his program for computation of numerical data on the basis of his theory. We also thank Dr. U. Heinzmann for his assistance in developing the Fano-effect source.

[1]J. Kessler, *Polarized Electrons* (Springer, Berlin, 1976), Chap. 3.

[2]R. J. van Duinen and J. W. G. Aalders, Nucl. Phys. A115, 353 (1968). Another triple-scattering experiment with a different goal [G. F. Hanne and J. Kessler, J. Phys. B 9, 791 (1976)] will be excluded from our considerations.

[3]U. Heinzmann, J. Kessler, and J. Lorenz, Z. Phys. 240, 42 (1970).

[4]U. Heinzmann, J. Phys. B 11, 399 (1978).

[5]A source of this type is described in the literature by P. F. Wainwright, M. J. Alguard, C. Baum, and M. S. Lubell, Rev. Sci. Instrum. 49, 571 (1978). We are grateful to Dr. M. S. Lubell for preliminary information about this source.

[6]K. Jost, private communication.

[7]W. Eitel, K. Jost, and J. Kessler, Phys. Rev. 159, 47 (1967).

[8]D. W. Walker, Adv. Phys. 20, 257 (1971), and private communication.