Observation of polarized electrons by Davisson and Germer

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Early attempts to observe electron polarization in the scattering of low-energy electrons from solids are reviewed. It is found that results published by Davisson and Germer in 1929 were analyzed incorrectly, and that they had in fact observed significant electron polarizations in the diffraction of low-energy electrons from single-crystal nickel.

In a recent Letter,[1] O'Neill, Kalisvaart, Dunning, and Walters report the observation and measurement of electron-spin polarization in low-energy-electron diffraction (LEED) from a clean tungsten (100) surface. The purpose of this Comment is to point out the surprising fact that electron-spin polarization in LEED from single-crystal nickel was observed by Davisson and Germer in 1929.

In 1927, Davisson and Germer[2] published their well-known work on the diffraction of low-energy electrons from nickel single crystals. In 1929 they published[3] a lesser known work in which they attempted to detect polarization of electrons diffracted from a nickel crystal in a double-scattering experiment. Figure 1 shows the geometry of the double-crystal measurement. Electrons scattered from the first crystal, if polarized, were expected to show an asymmetry in the scattering from the second crystal as this crystal was rotated around an axis coincident with the electron beam between the two crystals. Davisson and Germer[3] reported that no electron polarization was observed in their measurements.

Negative results were also reported by Joffé and Arsénieva[4] in 1929 for scattering of 80 eV to 6.4 keV electrons from steel and by Langstroth[5] in 1932 for scattering of 1- to 10-keV electrons from tungsten. Several theories, which showed the impossibility of polarizing electrons in scattering by fields which vary on a macroscopic scale, appeared to offer explanations of the negative experimental results.[6] In 1929 Mott[7] showed that electron polarization is expected when high-energy electrons are scattered in the Coulomb field of the nucleus.[8] The combination of these results seems to have caused the neglect of polarization measurements of *low-energy* electrons scattered from solids for over 30 years.[9]

In 1966, Maison[10] noted the recent successes in observing polarization of slow electrons scattered from atoms,[11] and gave plausibility arguments as to why a polarization effect should also be observed in low-energy-electron scattering from solids. Indeed, subsequent measurements by Eckstein[12] of the polarization of 300- to 900-eV electrons scattered from solid Hg gave a maximum value of 23%. For scattering of 900 eV electrons from foils of W, Pt, and Au, Loth[13] measured polarizations up to 15%, even though the vacuum was poor and it was necessary to heat the metals to observe a significant polarization.

A careful analysis of the paper of Davisson and Germer[3] reveals the surprising fact that their data analysis was incorrect, and that they had observed significant polarizations in the diffraction of low-energy electrons from nickel. Davisson and Germer used the polarization of light as the model for their data analysis, and therefore expected[14] that the scattering of polarized electrons from the second crystal would give two maxima and two minima as the crystal is rotated through 360°. They therefore looked for a second harmonic in the variation of electron scattering with the angle of rotation of

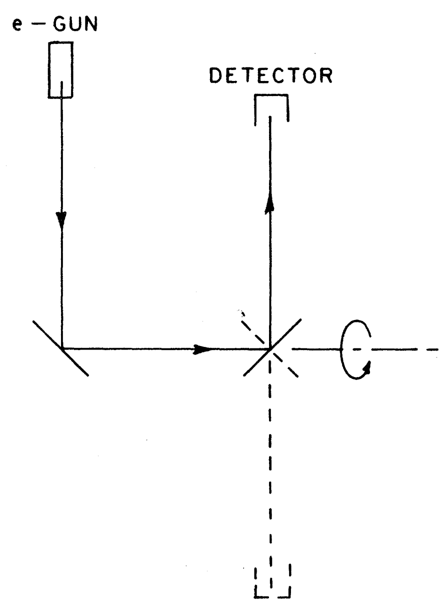

FIG. 1. An unpolarized electron beam incident at 45° on the first crystal is specularly diffracted and is then incident at 45° on the second crystal. The second crystal and the detector are rotated about an axis coincident with the electron beam between the two crystals.

TABLE I. Reanalysis of Davisson and Germer data.

Energy (eV)	Coefficient of first harmonic[a]	Polarization minimum	Polarization maximum
20	0.013 ± 0.012	0.03	0.16
55	0.015 ± 0.013	0.04	0.17
77	0.017 ± 0.008	0.09	0.16
103[b]	0.065 ± 0.011	0.23	0.27
120	0.021 ± 0.004	0.13	0.16

[a]From Ref. 3. Polarization is the square root of this coefficient.

[b]Davisson and Germer express reservations about the data at 103 eV.

the second crystal. To within experimental error this second harmonic was found to be zero. However, for spin polarization, one expects only one maximum and one minimum[15] as the second crystal is rotated through 360°, and therefore it is the first harmonic in crystal rotation which should show spin polarization. In fact, Davisson and Germer did find nonzero amplitudes for the first harmonic in crystal rotation, and consequently *did* observe spin polarization.

The variation of the scattering intensity I with angle of rotation ϕ of the second crystal is given by[6,11]

$$I = I_0[1 + PS(\theta)\cos\phi],$$

where $P=[N(\uparrow) - N(\downarrow)]/[N(\uparrow) + N(\downarrow)]$ is the polarization of the incident electron beam, S is the polarization function of the detector (the polarization of an unpolarized beam after scattering), θ is the scattering angle, and ϕ is the angle between the polarization direction and the normal to the plane of scattering. For two identical crystals, $P=S$, and the amplitude of the first harmonic depends on P^2. From the data of Davisson and Germer for the first harmonic, one finds, for example, a polarization of $(14.5 \pm 1.5)\%$ for the 90° scattering of 120-eV electrons from the (111) face of nickel. Table I gives the reanalysis of the original data.

It is interesting that the experimental results remained misinterpreted for so long. In their brief note, Joffé and Arsénieva[4] also reported an asymmetry with a period of 2π but dismissed it following the interpretation of Davisson and Germer. Langstroth[5] was correctly looking for the 2π asymmetry but found none. A large number of workers[4] looking for the correct polarization effect in the double scattering of high-energy electrons as well as a number of later reviews appear not to have noticed the incorrect analysis of Davisson and Germer.

The properly-interpreted results of Davisson and Germer, which represent the first published measurements of the polarization of low-energy diffraction from single crystals, have important implications for experiments today.[16] Low-energy electron diffraction can be used as a *source* of polarized electrons. Moreover, when calibrated, scattering from a known surface provides a low-energy, highly sensitive, ultrahigh vacuum polarization *detector*, a welcome alternative to the conventional high-energy (~100 keV) Mott detector. Recent theoretical work on spin-polarized electron scattering from[17] W and[18] Cu single-crystal surfaces pointed out that the spin polarization is very sensitive to the form of the scattering potential. Thus the spin of the electron adds a new dimension in scattering experiments like LEED and provides a promising new technique for the study of clean and adsorbate-covered surfaces.

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[8]The polarization is produced by an $\vec{L}\cdot\vec{S}$ interaction, where $\vec{L}$ is the angular momentum of a partial wave being scattered and $\vec{S}$ is the spin of the electron.

[9]In retrospect, it is surprising that it took so long to realize that the $\vec{L}\cdot\vec{S}$ interaction could produce polarization in low-energy scattering.

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[11]J. Kessler, Rev. Mod. Phys. 41, 3 (1969), and references therein.

[12]W. Eckstein, Z. Phys. 203, 59 (1967).

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[14]Since the polarization of light is actually an alignment, in this model the amount of scattering should be invari-

ant to a 180° rotation of the crystal.

[15]Since spin has a direction, and the scattering depends on $\vec{L} \cdot \vec{S}$, a 180° rotation of the crystal reverses the sign of the effect.

[16]To our knowledge, polarized low-energy electron scattering from solids is being investigated experimentally at Rice University [M. Kalisvaart, M. R. O'Neill, F. B. Dunning, and G. K. Walters, Bull. Am. Phys. Soc. 20, 407 (1975) and Ref. 1], the University of New South Wales, and the National Bureau of Standards.

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