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†Alfred P. Sloan Research Fellow.

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SPIN POLARIZATION OF SLOW ELECTRONS BY ELASTIC RESONANCE SCATTERING FROM NEON*

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The generation of intense beams of polarized electrons is of considerable interest at the present time. Two significant advances have recently been made in this field, namely, the ejection of polarized photoelectrons from a polarized atomic beam,[1,2] and Mott scattering of electrons from the screened Coulomb charges of beams of mercury and gold atoms in the keV energy range,[3,4] based on the theory of Mohr,[5] Bunyan,[6] and others.[7] We wish to point out here that a perhaps even more powerful method for the production of intense beams of polarized electrons is a direct consequence of the recent discovery by Simpson and his co-workers[8] of a doublet structure in the resonance for elastic scattering of electrons by neon atoms at 16 eV (0.6 eV below the first excitation level), based on earlier work by Schulz,[9] Simpson,[10] and others,[11] and interpreted by Fano.[12] The questions raised by these experiments are also of more general interest in connection with the nature of autoionizing atomic energy states.[13-15]

The resonance observed by Simpson[8] in the total cross section for the scattering of electrons from neon consists of a small decrease in cross section, followed by two successive peaks, of which the first is approximately twice as pronounced at the second. The two peaks are separated by 0.095 eV, corresponding closely to the $P_{1/2}$-$P_{3/2}$ fine-structure splitting in the ground state of Ne^+. In view of these facts, the resonances have been interpreted by Simpson and Fano[12] as corresponding to the formation of metastable compound states with the configuration $(1s^2 2s^2 2p^5 3s^2)P_{1/2,3/2}$, that is, states of the Ne^- ion formed by adding a $3s$ electron to the lowest excited state of neon. There is little doubt that this interpretation is correct in view of the energy location, separation, and relative statistical weights of the two states. Under these circumstances, interference between resonance and potential scattering in the presence of fine-structure splitting will give rise to almost complete polarization of electrons scattered through 90° at certain energies, as in the polarization of neutrons and protons by scattering from helium,[16] as we shall now demonstrate.

If the incident electron beam is described as an unpolarized plane wave advancing in the z direction, the spin state of electrons scattered in a direction specified by the polar angles θ, φ is defined[17] by a 2×2 density matrix with off-diagonal elements ρ_{ab}, ρ_{ba}:

$$\rho_{ab} = \rho_{ba}^{\;*} = \tfrac{1}{2}(hg^* - gh^*)e^{-i\varphi}/(|g|^2 + |h|^2), \tag{1}$$

where for $l = 0$, 1, and 2 scattering only (see below) and two adjacent p-wave resonances of identical widths Γ at energies $E_0 - \Delta E/2$ and $E_0 + \Delta E/2$, respectively,

$$g(\theta) = k^{-1}\left[g_0 - \left(\frac{q_1 - i}{q_1 + i}\right)\left(\frac{2}{\epsilon + x + i} + \frac{1}{\epsilon - x + i} + \frac{3}{q_1 - i}\right)\cos\theta + g_2\right], \tag{2}$$

$$h(\theta) = k^{-1}\left(\frac{q_1 - i}{q_1 + i}\right)\left(\frac{1}{\epsilon - x + i} - \frac{1}{\epsilon + x + i}\right)\sin\theta. \tag{3}$$

Here $q_1 = -\cot\xi_1$, where ξ_1 is the $l = 1$ phase shift in the absence of resonance; $\epsilon = (E - E_0)/\tfrac{1}{2}\Gamma$; $x = \Delta E/\Gamma$; and $g_{0,2}$ are given by $g_l = k^{-1}(2l+1)\exp(i\delta_l)\sin\delta_l P_l(\cos\theta)$, as usual. We have used the line-shape function predicted by Fano,[18] which follows from the relations $\delta_{1\pm} = \xi_1 - \cot^{-1}(\epsilon \pm x)$ between the total $P_{3/2}$ and $P_{1/2}$ phase shifts δ_{1_+} and δ_{1_-}, respectively, and the potential-scattering phase shift ξ_1. The x and y components of the polarization vector of the scattered electron beam are then given by twice the real, and twice the imaginary, parts of ρ_{ba}, respectively.

The total cross section $\sigma = \int(|g|^2 + |h|^2)d\Omega$ has a resonant part

$$\sigma_{\text{res}}(\epsilon) = \frac{4\pi}{k^2}\left(\frac{1}{1 + q_1^{\,2}}\right)\left[2\frac{(\epsilon + q_1 + x)^2}{1 + (\epsilon + x)^2} + \frac{(\epsilon + q_1 - x)^2}{1 + (\epsilon - x)^2}\right], \tag{4}$$

which in principle could be fitted to the experimental resonance curve to obtain the parameters q_1, x, and Γ. However, in Simpson's experiment the transmitted electron current was measured in a region of very large (exponential) absorption, so that the relative amplitudes of the extrema of $\sigma_{\text{res}}(\epsilon)$ cannot be interpreted quantitatively. For this reason, we have deduced q_1 from other data (see below) and then computed the remaining parameters from the observed energy locations of the extrema of $\sigma_{\text{res}}(\epsilon)$, in conjunction with (4).

The phase shift ξ_1 can be deduced from the differential-scattering cross section just below resonance. Of the early experimenters[19-21] studying elastic scattering of low-energy electrons by neon, only Ramsauer and Kollath[21] measured absolute cross sections, in particular at 15.9 eV, as shown in Fig. 1. Westin[22] made a phase-shift analysis of the Ramsauer

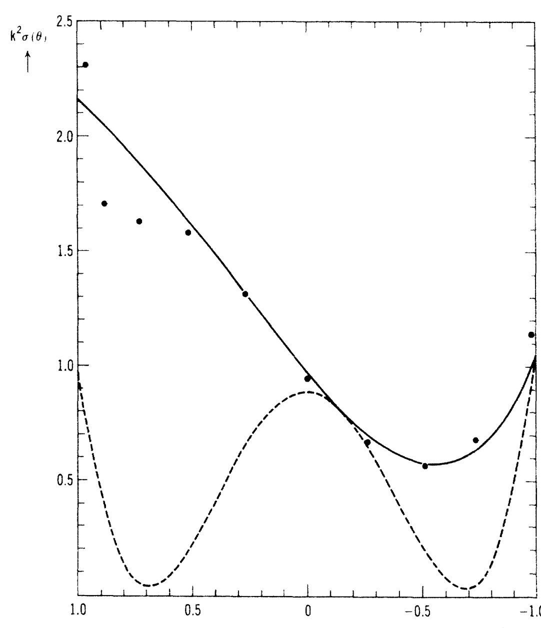

FIG. 1. Comparison of Ramsauer and Kollath's experimental points[21] for the scattering of 15.9-eV electrons by neon (solid circles) with the angular distribution (solid curve) predicted with the set of three phase shifts $\delta_0 = 289.0°$, $\xi_1 = -17.1°$, and $\delta_2 = 2.9°$, derived by a least-squares analysis of Ramsauer's data. In this analysis, the experimental points for forward scattering with $\cos\theta > 0.51$ have been disregarded, inasmuch as the forward scattering is distorted by polarizability effects.[25] The dashed curve is an angular distribution calculated from Westin's phase shifts[22] ($\delta_0 = 340°$, $\delta_1 = 180°$, $\delta_2 = 15°$) for this electron energy.

data on the assumption that the phase shifts are smoothly varying functions of energy, the existence of scattering resonances then not having been suspected. An anomalous consequence of this assumption was that the δ_1 phase shift did not go to zero, but instead approached 200° at zero energy. On the other hand, Simpson's data (drop in total cross section followed by rise) implies that $-q_1 = \cot\xi_1$ is negative, so that ξ_1 must lie either in the second or the fourth quadrant. This observation can be reconciled with Westin's analysis, which fits the high-energy data, and other physical requirements by assuming that δ_1 decreases from zero at zero energy to −17° just below resonance, at which point there is a sudden increase by 180°, thus linking up with Westin's values above the resonance. In other words, at low energies (large impact parameters), the p-wave experiences a repulsive interaction, which becomes attractive at smaller impact parameters, sufficiently so as to give rise to a virtual state. This description is consistent with an exchange interaction of relatively long range.[23]

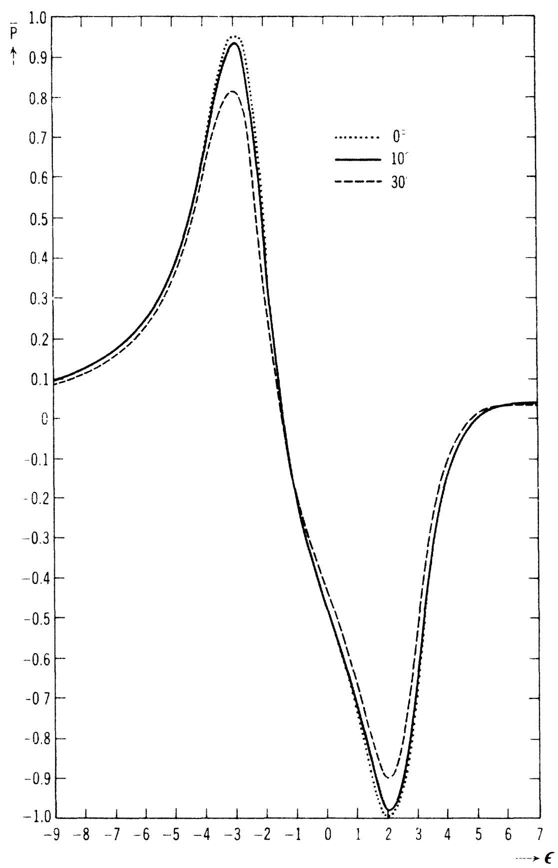

FIG. 2. Electron polarization ($\bar{P}$), averaged over three different solid angles, as a function of electron energy for electrons scattered by neon in the vicinity of the scattering resonance at $E_0 = 16.079$ eV. Here $\epsilon = (E-E_0)/\frac{1}{2}\Gamma$, where $\Gamma = 0.038$ eV. The electrons are assumed to be incident along the z axis, and to be scattered into the solid angle subtended by a pyramid of square cross section, the y axis passing through the center of the pyramid, and the faces of the pyramid making the indicated angles with the y axis. (The average polarization vector under these circumstances is parallel to the x axis).

On this basis, we have fitted a set of three phase shifts δ_0, ξ_1, and δ_2 to Ramsauer's 15.9-eV data by the method of least squares, with the result shown in Fig. 1. The analysis suggests that $\sin\delta_0$ and $\sin\xi_1$ have the same sign, but that $\sin\delta_2$ and $\sin\xi_1$ have opposite signs. Therefore, δ_2 must be positive. δ_0 must lie in the fourth quadrant, and for physical reasons[24] we prefer a positive angle less than 360°. Combination of these results with Simpson's data [assuming the line-shape function given by (4)] then leads to the following values: $\delta_0 = 289.0°$; $\xi_1 = -17.1°$; $\delta_2 = 2.9°$; $\Gamma = 0.038$ eV; $\Delta E = 0.094$ eV; and $E_0 = 16.079$ eV.

Using these values, we have computed the expected electron polarization for scattering into a finite solid angle centered around $\theta = 90°$, with the result shown in Fig. 2. It will be seen that the average polarization depends only slightly on the solid angle, so that with suitable electron optics it should be possible to collect a substantial fraction of all scattered electrons in a highly polarized condition. It should also be noted that the maximum resonance differential cross section at 16 eV in neon is much larger than the Coulomb (Rutherford) cross section at several hundred eV, the energy at which the Mott-scattering experiments are now performed.[4] On the other hand, resonance scattering requires a much higher degree of energy resolution than does Mott scattering.

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MAGNETIC DICHROISM IN EuSe

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Magnetic dichroism is the magnetic-field-induced difference in optical absorption coefficients for light with different senses of polarization. Magnetic circular dichroism, which occurs for light propagating along the direction of magnetization, is well known and produces the ellipticity associated with the Faraday effect (magnetic circular birefringence). Similarly, magnetic linear dichroism, which occurs for light propagating at right angles to the magnetization, must coexist with the Cotton-Mouton effect (magnetic linear birefringence), although both of these effects are usually so small as to escape observation. This paper describes a remarkably large magnetic circular and linear dichroism exhibited by a single crystal of EuSe at 4.2°K. These effects reflect not only the wavelength dependence and magnetic shift of the broad-band absorption but also the various spin structures exhibited by EuSe.

EuSe is unusual in that the antiferromagnetic spin configuration of Eu^{++} ions at temperatures below the ordering temperature (~6°K) can be readily altered by a magnetic field. Combined measurements of magnetization[1] and powder neutron diffraction[2] suggest the following picture: In zero field the spins in each (111) plane are ferromagnetically aligned, but angles between spins of successive (111) planes are approximately 90°, 180°, −90°, 180°, 90°, ⋯. At intermediate applied fields (1-2 kOe for powder specimens), the spins of two of the four sets of (111) planes flop into parallel alignment with the other two and yield a nonoscillatory ferromagnetic component. Above ~8 kOe pure ferromagnetic alignment remains. The other europium chalcogenides exhibit either ferromagnetic order (EuO and EuS) where the near-