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SLOW ELECTRON POLARIZATION IN ELASTIC SCATTERING BY ALKALI METAL IONS

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Polarization of an electron beam as a result of exchange scattering by polarized alkali metal atoms is considered. At low energies the degree of polarization depends on the relation between the scattering lengths in the singlet and triplet states. Owing to a favorable relation between the scattering lengths, almost complete polarization is achieved for Li and Na atoms. With increasing energy, when the angular distribution becomes anisotropic, almost complete polarization (≈ 100%) is attained for electron energies and scattering angles that correspond to a minimum of the elastic scattering differential cross section. For all alkali metal atoms numerical values are presented for regions of considerable polarization at collision energies up to 2 eV.

METHODS of producing polarized electron beams and of detecting the polarization are being sought at the present time. Polarization effects can be produced in electron scattering by atoms as the results of 1) spin-orbit interaction and 2) exchange interaction between a scattered electron and atomic electrons.

At low velocities and in scattering by light atoms the spin-orbit interaction is very small, as a general rule. However, in some special cases the spin-orbit interaction even at low energies can induce appreciable effects, such as the polarization of electrons ejected from atoms through photoionization by circularly polarized light near the minimum of the cross section.[1] The main source of polarization effects at low velocities is the exchange interaction. When an unpolarized beam of electrons is scattered by polarized atoms, then as a result of the exchange interaction the spin orientation of the atomic electrons is partially transferred to the scattered electrons. On the other hand, when a beam of polarized electrons is scattered by an unpolarized atomic target the exchange interaction leads to depolarization of the electron beam and the target becomes polarized to some degree. The question arises whether this effect can be used as an effective experimental method of producing polarized beams.

Electron polarization in exchange scattering on polarized hydrogen atoms was first studied theoretically in[2]. The equations derived in[2] contain no characteristic parameters that would enable a general prediction of the degree of expected polarization. Therefore without a numerical evaluation of the polarization, based on the scattering phase shifts, the efficiency of the exchange mechanism of polarization remains an open question. A calculation for H atoms utilizing the equations in[2] shows that at low energies ($E \lesssim 1$ eV) the polarization is of the order 0.1–0.2 and does not attain unity at any elastic scattering energy ($E < 10.2$ eV). However, we shall show here that the H atom is not a typical example, but rather an unfavorable exception, with regard to electron polarization.

We have investigated the scattering of unpolarized electrons by alkali metal atoms on the assumption that interaction with a valence electron plays the principal role in the exchange interaction. We discovered that almost complete polarization is achieved at some collision energies E and scattering angles θ.

Before determining the desired regions of E and θ we shall elucidate the general conditions for achieving a considerable degree of polarization. Since the entire polarization effect is associated with the domination of the exchange interaction over the direct interaction, it is obvious at the start that appreciable polarization can be expected at low energies. Moreover, when particles having identical spins are scattered it is natural to expect that maximum polarization will be achieved through pure exchange scattering, when the initial polarization of the atoms is transferred completely to the scattered electron beam. According to[2] the polarization $P_i^{(e)\prime}$ of an initially unpolarized electron beam will after scattering be given by

$$P_i^{(e)\prime} = \frac{2FF^* - FG^* - F^*G}{3FF^* + GG^*} P_i^{(a)} \equiv p(k, \theta) P_i^{(a)}, \tag{1}$$

where $F = F(k, \theta)$ and $G = G(k, \theta)$ are the amplitudes of triplet ($S = 1$) and singlet ($S = 0$) scattering, $P_i^{(a)}$ is the component of the atomic polarization vector before the collisions. We easily note that $p(k, \theta) \leq 1$ at all times. Therefore complete polarization of scattered electrons ($P_i^{(e)\prime} = P_i^{(a)}$) is achieved when

$$F(k, \theta) + G(k, \theta) = 0. \tag{2}$$

Under this condition the direct scattering amplitude $f = \frac{1}{2}(F + G)$ vanishes and pure exchange scattering occurs, as was assumed. However, we also note that Eq. (2), when fulfilled, determines a fixed pair of k and θ values, whereas we are really interested in the energy and angular regions within which appreciable polarization occurs. For the latter result it is required that the sum $|F + G|$ be minimal in some region of k and θ. In this case the exchange interaction will be dominant over the direct interaction and considerable polarization will result.

We shall first consider the region of small k, when the scattering is isotropic. In this case we have

$$p(k) = 2\frac{\sin^2\delta_- - \sin\delta_- \sin\delta_+ \cos(\delta_- - \delta_+)}{3\sin^2\delta_- + \sin^2\delta_+} \tag{3}$$

(δ_- and δ_+ are the phase shifts for S = 1 and S = 0). We note that in accordance with (2) complete polarization of the electron beam occurs when

$$\frac{1}{k^2}[\sin^2\delta_- + \sin^2\delta_+ + 2\sin\delta_-\sin\delta_+\cos(\delta_- - \delta_+)] = 0, \qquad (4)$$

which is obviously not fulfilled for phase shifts different from 0 or $n\pi$.

We shall present values of p(k) in the limit k → 0 for Li, Na, K, and Cs atoms on the basis of scattering lengths obtained in[3]. In the approximation of strong $n_0s - n_0p$ coupling with exchange the singlet and triplet scattering lengths are 3.65 and −5.66 for Li, 4.23 and −5.91 for Na, 0.45 and −15.0 for K, −4.04 and −25.3 for Cs. Accordingly, for the degrees of polarization we obtain: Li—0.97, Na—0.98, K—0.69, and Cs—0.56. We obtain approximately 0.70 for Rb in the isotropic scattering region in accordance with the phase shifts calculated in[4]. We thus see that practically complete polarization of electron beams occurs in the region of isotropic scattering by Li and Na. We also note that, according to[5], the ratio of the direct and exchange cross sections is 0.05 for Li and 0.03 for Na. Considerable polarization also results for K and Rb in the isotropic scattering region.

With increasing energy, when the polarization becomes a function of the energy and the angle, the minimum of $|F + G|$ in a certain region of k and θ corresponds to the highest value of p in this region. To determine these regions of k and θ we note that $|F + G| \to 0$ when we have $4\sigma(k, \theta) = 3FF^* + GG^* \to 0$ for the differential cross section. Therefore, if at some fixed value of k the differential cross section vanishes or has a sharp minimum in the vicinity of some angle θ, the corresponding values of k and θ are associated with the greatest polarization. It follows from calculations in[3] that the differential cross sections $\sigma(k, \theta)$ of e-A elastic scattering (A = Li, Na, K, Cs) have characteristic minima in the intervals E ≈ 0.1–0.2 eV, $\theta \approx 85^\circ - 100^\circ$ and E ≈ 0.8–1.8 eV, $\theta \approx 100^\circ - 115^\circ$. Therefore considerable polarization should be observed in these regions of E and θ.

We have calculated the polarization $p(k, \theta)$ and the cross section $\sigma(k, \theta)$ for electron scattering by polarized Rb atoms, using the phase shifts $\delta_l^{\pm}$ $(0 \le l \le 8)$[4] and have found that the lowest values of $\sigma(k, \theta)$ correspond to $p(k, \theta) \approx 1$. For example, when E = 0.150 Ry the polarization $p(k, \theta)$ increases from 0.6 to 1 as $x = \cos\theta$ changes from 0.0 to −0.1, and in this interval of x the cross section σ is diminished by an order of magnitude.

We note in conclusion that atomic ions having spin ½ (such as He^+) can also be used as targets. In this case it follows from general considerations that at low energies $k \ll 1$ the polarization should be small because of the dominance of Coulomb scattering. The optimal energy region corresponds to k ≈ 0.5–1.0.

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