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Optical Measurement of Free-Electron Polarization

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The spin polarization of photoelectrons emitted by an activated gallium arsenide photocathode excited with circularly polarized light has been measured by an optical method: A crossed-beam experiment has been performed in which polarized electrons transfer spin angular momentum to zinc atoms in inelastic exchange collisions. The polarized atoms emit circularly polarized light in the direction of the spin transfer. The degree of circular polarization is directly related to the electron polarization.

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We have performed the first experiment where spin polarization of free electrons is detected by an optical method. The method used was discussed theoretically a few years ago.[1-3] Polarized electrons can transfer spin angular momentum to atoms by inelastic exchange collisions. In such a collision, the electrons polarize the atoms and the information about the polarization of the electron beam is contained in the emitted light. This light, observed in the direction of the spin transfer, is circularly polarized. For two-electron atoms, when there is no orbital angular momentum transferred, the degree of light polarization is very simply related to the polarization of the incident electrons. The Pauli principle plays a dominant role in the polarization of these atoms; this is to be distinguished from situations where atomic polarization arises because of magnetic interaction.

In our experiment, excitation from the $ns^2\,{}^1S_0$ ground state to the triplet $ns(n+1)s\;{}^3S_1$ states has been considered. For a collision where opposite-spin electrons are exchanged, a spin up (down) electron transfers a unit of angular momentum to the atom and the substate $|{}^3S;1-1\rangle$ ($|{}^3S;1+1\rangle$) cannot be populated. Therefore with polarized electrons the population of the ${}^3S_1$ state is not equally distributed among the magnetic sublevels. More precisely if n_+ (n_-) represents the number of electrons with spin parallel (antiparallel) to the quantization axis Z, the polarization of the electron beam being $P_e=(n_+-n_-)/(n_++n_-)$, the relative populations $N(M)$ of excited atoms in the $|{}^3S;1M\rangle$ substates are

$$N(M=0)=\tfrac{1}{3},\quad N(M=\pm 1)=\tfrac{1}{3}(1\pm P_e).$$

The light polarization from the transition to the $nsnp\;{}^3P_J$ states which is observed is therefore connected to the population $N(M)$. In fact, light emission involves orbital variables and any optical effect related to the spin appears only through spin-orbit interaction. It is therefore essential to have the fine structure well resolved in order to observe separately the circular polarization of the three lines ($J=0, 1, 2$). The total emitted light intensity $I=I_++I_-$, where I_+ (I_-) is the intensity of the light with σ_+ (σ_-) polarization, is proportional to $2J+1$. The polarization $P=(I_+-I_-)/(I_+$

$+I_-$) is equal to $+P_e$, $+P_e/2$, and $-P_e$-2 for $J=0$, 1, and 2, respectively. Therefore a measurement of the circular polarization of any of the three $^3S_1$-^3P_J lines yields the value of the electron-beam polarization.

To be significant such a measurement must fulfill three conditions: (i) The $^3S_1$ state must be excited directly by the incident electrons and any contribution to the population of this level by cascading from higher states must be avoided. (ii) Any magnetic interaction of the free electron which could cause its spin to flip must be negligible in the excitation process. In fact such interactions would be significant only for heavy atoms, such as mercury, at high incident energies[4] and would affect mostly the minima of the differential cross section.[5] (iii) Spin-orbit coupling within the excited atom must be large enough to allow the fine-structure splitting of the atomic ^3P_J levels to be easily resolved spectroscopically and yet not so large as to lead to a breakdown of LS coupling.

Condition (i) limits the useful beam energy to a range between the $^3S_1$ threshold and the energy of the first states able to cascade, whereas conditions (ii) and (iii) imply that the chosen atom should be neither too light nor too heavy. Examination of the periodic table shows that, among two-electron atoms, zinc is the lightest element suitable for atomic-beam experiments in which the fine structure is easily resolved. It has also been confirmed experimentally[6] for this atom that exchange scattering is the dominant process for triplet excitation and furthermore that the $4p\,^3P_J$ states are pure Russel-Saunders states.

Optical measurements in the vicinity of the threshold are difficult because of the weak signal, and the experiment was possible thanks to a stable and intense source of polarized electrons. The negative-electron-affinity gallium arsenide source which has been developed in our laboratory following the ideas of Lampel and Weisbuch[7] and the work of Pierce and Meier[8] fulfills these conditions. Such a source, very attractive for novel investigations in various fields of physics,[5,9,10] gives an intense beam of polarized electrons at low energy. It is a p-type GaAs sample (Zn doping 4×10^{19} cm^{-3}) activated to negative electron affinity by covering its surface with monolayers of cesium and oxygen under ultrahigh-vacuum (UHV) conditions. Polarized electrons are created by absorption of circularly polarized light with energy $h\nu=1.55$ eV close to the band-gap energy ($E_G=1.42$ eV at room temperature). Typical characteristics of the source are a photoemitted current of 10 μA for a laser output power of 1.5 mW at λ = 799.3 nm and electron polarization of ~30%. Its stability is described by a yield which decays less than 1% per hour in UHV (pressure $\leq1.5\times10^{-10}$ Torr) and an electron optical transmission of ~40% at 8 eV.

The experimental arrangement is illustrated schematically in Fig. 1. Light from a krypton laser is circularly polarized by a quarter-wave plate and is reflected from a polished electrode before striking the activated GaAs[100] surface[11] in an UHV chamber. The GaAs sample, at room temperature, is biased negatively and the first

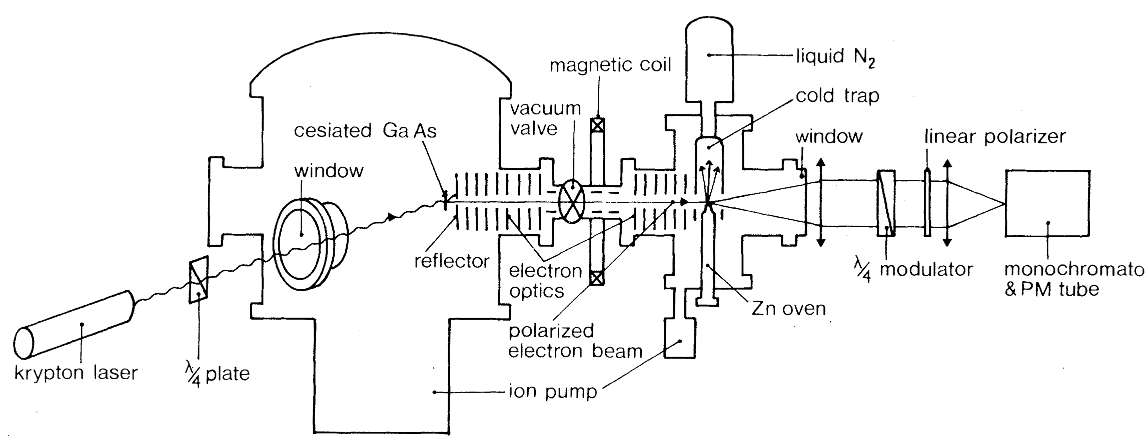

FIG. 1. Experimental setup (not to scale). The polarized electrons from the illuminated GaAs source cross the zinc-atom beam and the emitted light is analyzed along the direction of propagation of the electrons (Z axis).

electrode is kept at a small positive voltage to extract the longitudinally polarized photoelectrons. Electron optics focus the beam into the interaction region at the required energy. A coaxial magnetic coil maintains the beam focus through the valve which links the UHV chamber to the collision chamber. The well-collimated zinc-atom beam emerges from an oven heated to a temperature of about 580 °C.[12] The light emitted from the interaction region along the Z axis is focused by optical lenses through a quarter-wave-plate modulator into a monochromator. The electron spin polarization can be easily reversed by switching the polarization of the exciting light from σ_+ to σ_-.

The multiplet zinc lines $5s\,^3S_1-4p\,^3P_J$ have been observed.[13] Figure 2 shows the total intensity $I_+ + I_-$ and the intensity difference $I_+ - I_-$ when the electron spin polarization is reversed by rotating the excitation quarter-wave plate. The data shown were obtained in a 30-min scan and indicate the time scale required to obtained significant results.

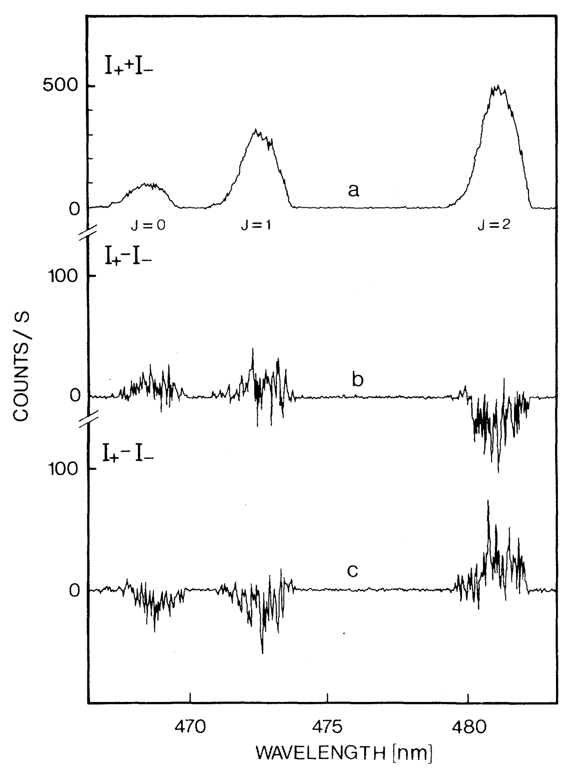

FIG. 2. Raw data for a 30-min scan obtained at an electron energy of 10 eV vs the wavelength of the emitted light. This illustrates the fine structure of the ^3P_J states and their respective polarizations. (a) Total intensity $I_+ + I_-$; (b) and (c) difference spectra $I_+ - I_-$ measured for σ_+ and σ_- excitations. Because of the rotation of the $\lambda/4$ plate analyzer $(I_+ - I_-)/(I_+ + I_-)$ should be multiplied by $\pi/2$ to yield the light polarization P.

Figure 3 shows a measurement of the onset of light emission from the $5s\,^3S_1-4p\,^3P_2$ line at $\lambda = 481.2$ nm, together with the light circular polarization plotted versus electron energy. The electron-beam energy was obtained from the threshold (at 6.65 eV) of the light intensity curve. In an energy range of about 1 eV above threshold, the polarization is constant within the statistical uncertainties. No significant structure has been observed in any of the numerous runs we have performed. For higher energies, the circular polarization starts to decrease, as expected, when the electron energy is large enough to excite the first states ($5p\,^3P_J$ at 7.6 eV) able to cascade on the $5s\,^3S_1$ level.

The electron beam polarization P_e can be deduced from the straight line fitted to the data obtained at low energy. It is related to the circular polarization P by the relation $P = -KP_e/2$, where $K = 0.97$ is a coefficient which takes into account the depolarization due to the hyperfine structure occurring in the natural isotope mixture of zinc

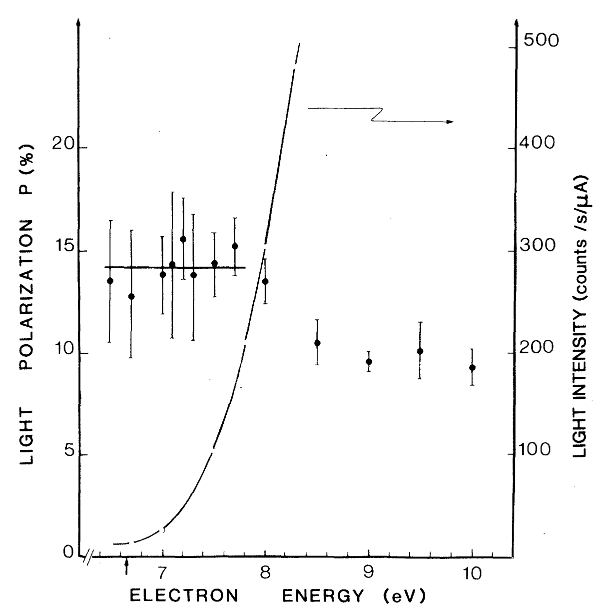

FIG. 3. Plots of the light intensity and the light polarization for the $5s\,^3S_1-4p\,^3P_2$ transition, vs the electron energy. The arrow indicates the threshold and the horizontal line represents the mean value of the experimental points in the energy range of 0.92 eV above threshold. The error bars represent two standard deviations.

with nonzero nuclear spins.[2] One obtains $P_e = (28 \pm 2)\%$, a value consistent with other measurements on the GaAs source at room temperature.[8,14,15]

As a new method for measuring the spin polarization of free electrons, the optical detection of spin-dependent effects has the simplicity inherent in most optical methods. In the experiment performed, elementary angular momentum algebra relates P to P_e and thus this method does not require any calibration procedure. Furthermore, it may also be used for transverse polarized electrons. For the observed process, each collision gives rise to a photon but the small fraction of electrons interacting with the atomic vapor makes this technique less sensitive than Mott detection. An improvement of the optical method may be considered by having the electrons interact with condensed matter. Further work in this direction is in progress.

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