Spin-Orbit and Exchange Effects in Elastic Scattering of Spin-Polarized Electrons from Spin-Polarized Na Atoms

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We report the first measurements of elastic scattering of spin-polarized electrons from spin-polarized Na atoms as a function of scattering angle. The incident energy is 54.4 eV, and the angular range is 20°–135°. Data are presented as an exchange asymmetry and a spin-orbit asymmetry. Each asymmetry has a magnitude of 3% to 4%, indicating that both the exchange and spin-orbit interactions must be taken into account to predict our experimental results.

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The scattering of spin-polarized electrons from atomic targets has been the subject of a great deal of work in recent years.[1] In general, investigations have concentrated on either spin-orbit effects, using closed-shell, high-Z targets,[2] or exchange effects, using light, spin-polarized one-electron targets and low incident energies.[3-6] To date, there have been no experimental studies in which spin-orbit and exchange effects were both investigated. In addition, studies of exchange effects have been very sparse. The only angular dependence in the literature is the measurement of the exchange cross section for potassium by Collins, Bederson, and Goldstein[3]; other recent work[4-6] has concentrated on energy dependence at fixed scattering angles.

The present study was undertaken with the main purpose of obtaining the first measured angular dependence of the exchange spin asymmetry for elastic scattering of spin-polarized electrons from a spin-polarized atomic target. In conducting this work, we found that it was possible to measure, for the first time in the same atomic system, the spin asymmetries due to both the exchange and spin-orbit interactions. The existence of the spin-orbit interaction is frequently neglected in discussions of low-energy electron-sodium scattering because the atomic charge ($Z=11$) is so small.[1]

The data presented here were obtained from an apparatus developed for general polarized-electron–polarized-atom collision studies.[6] A sketch of the experimental geometry is shown in Fig. 1. Polarized electrons are produced in a NEA GaAs source by photoemission with circularly polarized light at 810 nm from a diode laser.[7] The electrons are brought into the scattering region through a set of transport optics with polarization perpendicular to the scattering plane. The present results were obtained with an electron energy of 54.4 eV, electron beam currents between 2 and 8 μA, and an electron polarization of 0.25, as measured by Mott scattering at 30 keV.[8]

The atomic beam, of density 10^9–10^{10} cm^{-3}, is produced in an effusive recirculating sodium oven. It is spin polarized perpendicular to the scattering plane by optical pumping[9] with circularly polarized light from a stabilized, single-frequency ring dye laser locked to the $3S_{1/2}(F=2) \rightarrow 3P_{3/2}(F=3)$ transition. The laser beam intersects the atom beam approximately 1 cm before the electron beam. Detailed investigations of the particular experimental setup used for the present work show that the atomic polarization obtained is 0.61 ± 0.02.[10]

Electrons are detected with a channel electron multiplier equipped with a retarding-field analyzer to reject inelastically scattered and background electrons. The detector is mounted on a rotary turntable and can be positioned from $+70°$ to $-135°$. Suitably placed apertures ensure that the entire scattering volume is viewed by the detector at all angles. The angular resolution is estimated to be $\pm 3°$. At each scattering angle, four signal counting rates were measured. The electron spin was modulated at 200 Hz by the application of a high-voltage square wave to a Pockels cell, thereby periodically reversing the helicity of the circularly polarized diode laser light. Gated scalers collected counts separately for the two electron spin orientations. At 2-s intervals, the atomic polarization was inverted by a change of the helicity of the optical pumping light. Thus intensities for "parallel up," $I^{\uparrow\uparrow}$, "parallel down," $I^{\downarrow\downarrow}$, "antiparallel up," $I^{\uparrow\downarrow}$, and "antiparallel down," $I^{\downarrow\uparrow}$, were obtained (we use the first superscript arrow to refer to the electron

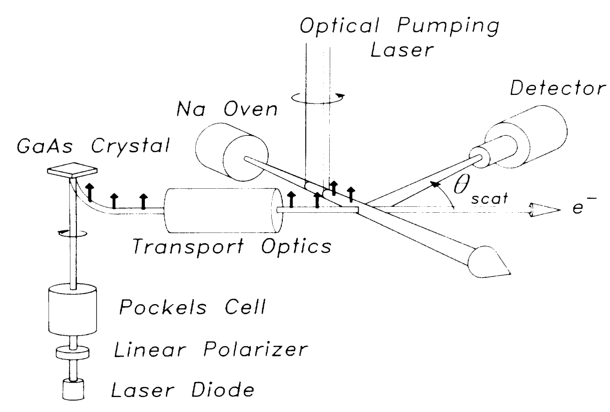

FIG. 1. Sketch of the experimental geometry.

spin and the second to indicate the atomic spin). Periodically, the atom beam was blocked and a background signal was measured and subtracted from each intensity. Typical signal rates (after background subtraction) ranged from 1500 Hz at the smallest angles to 15 Hz at the cross-section minimum. Background rates ranged from 400 to 3 Hz. Measurements were made at positive and negative angles as a check on overall apparatus symmetry and consistency, and the results were appropriately averaged. In addition, tests were made in the region of the cross-section minimum with the atom beam off to determine that no spurious background asymmetries were present. The data shown here are a result of approximately $\frac{1}{2}$ to 2 h of collection time per point.

The four intensities $I^{\uparrow\uparrow}$, $I^{\downarrow\downarrow}$, $I^{\uparrow\downarrow}$, and $I^{\downarrow\uparrow}$ represent all the information one can obtain in an elastic-scattering experiment without spin analysis of the scattered electron or atom after collision. Since they are all measured on the same relative scale, it is useful to generate asymmetries, because then the common scale factor in each intensity is cancelled.

If exchange and spin-orbit effects both contribute significantly to the scattering, it is not in general possible to define asymmetries whose values are strictly determined by either effect alone. One can, however, construct an asymmetry that is completely analogous to the exchange asymmetry which has been used in describing pure exchange experiments.[4-6] Similarly, one can define a spin-orbit asymmetry that corresponds to the asymmetry used in discussing spin-orbit scattering.[1] Though each asymmetry may contain contributions from both exchange and spin-orbit, the "exchange" asymmetry is nonzero only if exchange is significant, and similarly for the spin-orbit asymmetry.

We define

$$A^{\mathrm{exch}}=\frac{1}{P_e P_a}\frac{(I^{\uparrow\downarrow}+I^{\downarrow\uparrow})-(I^{\uparrow\uparrow}+I^{\downarrow\downarrow})}{(I^{\uparrow\downarrow}+I^{\downarrow\uparrow})+(I^{\uparrow\uparrow}+I^{\downarrow\downarrow})} \tag{1}$$

as the normalized difference between antiparallel and parallel intensities, averaged over "up" and "down" incident electron spins, and

$$A^{\mathrm{s.o.}}=\frac{1}{P_e}\frac{(I^{\uparrow\uparrow}+I^{\uparrow\downarrow})-(I^{\downarrow\uparrow}+I^{\downarrow\downarrow})}{(I^{\uparrow\uparrow}+I^{\uparrow\downarrow})+(I^{\downarrow\uparrow}+I^{\downarrow\downarrow})} \tag{2}$$

as the normalized difference between incident spin-up and incident spin-down intensities, averaged over atomic spin orientation. P_e and P_a are the degrees of polarization of the electron and atom beams, respectively.

In Fig. 2, we show the exchange asymmetry A^{exch}, as calculated from Eq. (1). The most notable features in the measured asymmetry are a broad negative peak of about −4% in the angular range from 30° to 60°, and fairly sharp positive and negative excursions centered around 108° (the location of a deep minimum in the cross section).[11] The broad feature can be attributed to a slight triplet dominance in that angular range, which then becomes less pronounced after 70°. The positive

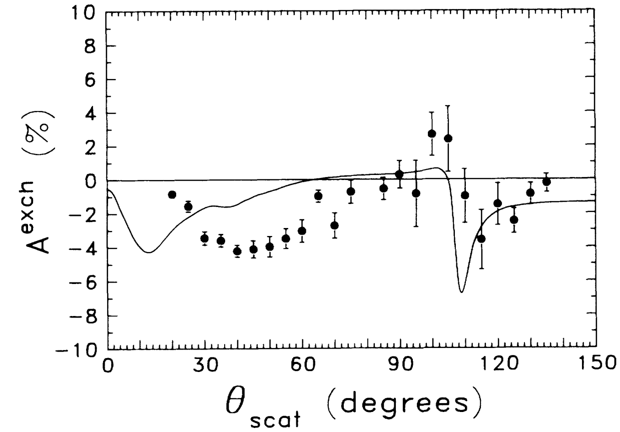

FIG. 2. Exchange asymmetry A^{exch}, as defined in Eq. (1), vs scattering angle θ_{scat}. Theory (solid line) is the two-state close-coupling calculation of Ref. 10. Error bars are 1 standard deviation derived from counting statistics, and do not include an overall scale uncertainty of ±6% of the asymmetry value.

and negative peaks near the cross-section minimum can be interpreted by consideration of what happens when the singlet and triplet cross sections have minima at slightly different angles. A difference between the two cross sections will then show a rapid change in sign near the minimum, as observed in the data.

Two-state close-coupling theoretical results of Mitroy, McCarthy, and Stelbovics[12] are also shown in Fig. 2, indicated by the solid line. Quite significant discrepancies are seen between theory and experiment, though in a qualitative sense there is similar behavior. Both theory and experiment are negative at smaller angles, and have roughly the same magnitude. The small-angle peaks are at very different locations, however, and the structures at the cross-section minimum are not very similar. Whether the discrepancies shown here are caused simply by inadequate treatment of exchange in the calculation, or by combined effects of spin-orbit and exchange (which would not appear in this nonrelativistic calculation), is a question whose answer will hopefully be forthcoming in the near future.

The spin asymmetry $A^{\mathrm{s.o.}}$, defined in Eq. (2), is shown in Fig. 3. Here we see that the asymmetry has a positive and a negative peak surrounding the cross-section minimum, just as A^{exch} did in the same region. In fact, the same basic explanation for this behavior can be invoked, i.e., that the spin-up and spin-down cross sections have minima slightly offset from each other. Once again, a difference between the two will change sign rapidly in the region of the minima, causing the observed structure.

For a theoretical comparison, we show in Fig. 3 an asymmetry from the fully relativistic static-potential calculation of Gregory and Fink.[13] This shows quite good qualitative agreement with the data, although the mea-

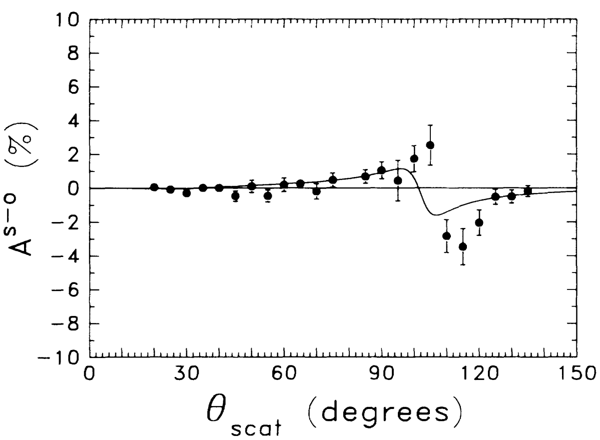

FIG. 3. Spin-orbit asymmetry $A^{s.o.}$, as defined in Eq. (2), vs scattering angle θ_{scat}. Theory (solid line) is the relativistic static-potential calculation of Ref. 11. Error bars are as in Fig. 2.

sured spin asymmetry is somewhat larger in magnitude at the extreme values, and the angular position of the zero crossing is somewhat different.

Though theoretical results are shown for comparison with both A^{exch} and $A^{s.o.}$, we note that neither theory is complete, because the two-state close-coupling calculation will predict a value of zero for $A^{s.o.}$, as will the relativistic calculation for A^{exch}. Each theory gives only four complex scattering amplitudes, while it has been shown that six amplitudes are necessary when spin-orbit and exchange are both significant.[14] A more detailed analysis of the present experimental results in terms of the amplitudes of Ref. 13 will be discussed in a forthcoming publication.

By performing these spin-dependent studies, we have increased the number of experimentally observable variables, and hence have provided significantly more ground for comparison with theory. These results will hopefully stimulate more realistic calculations which simultaneously incorporate exchange and spin-orbit interactions. Future experiments of this type at other energies for Na and on other alkalis (as polarization methods permit) should provide a wealth of new information.

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