Spin-Resolved Elastic Scattering of Electrons from Sodium below the Inelastic Threshold

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A very stringent test of low-energy electron-atom collision theory is made in the most favorable energy regime for the close-coupling approximation. Data are presented as exchange asymmetries in angle-resolved elastic scattering of spin-polarized electrons from spin-polarized sodium atoms. Data are reported for two incident energies, 1.0 and 1.6 eV, both of which are below the first excited-state threshold. The angular range is 20°–142.5°. The close-coupling approximation is found to give excellent agreement with experiment at both energies.

In electron-atom scattering, alkali metals have been the focus of substantial theoretical and experimental efforts for some time. Theoretically, the alkali metals present a simple system with only one electron outside of a closed shell, therefore approximating a hydrogenic system. The favored theoretical approach for such systems at low energies has been to employ the close-coupling approximation, in which the wave function of the system is expanded in terms of a few low-lying states of the atom. Sodium is particularly well suited to this approach since the large dipole polarizability of the atom is almost entirely accounted for by including only the ground and first excited states. It is reasonable to predict, then, that a close-coupling expansion with only a few states should be accurate at low energies, especially below the first excited-state threshold.

Despite the substantial amount of experimental work on electron-sodium scattering, a stringent test of this prediction has not been satisfactorily carried out. Differential, i.e., angle-resolved, cross sections have been measured at low energies [1], but since the results are normalized to theory, they provide only a semiquantitative test.

In general, measurements of cross sections can suffer from difficulties with normalization and systematic corrections. Problems often encountered include corrections for a changing scattering volume as a function of angle, changes in detector efficiency when the scattered intensity changes by as much as six magnitudes, and changes in the overlap of the electron and atom beams as functions of time and scattering angle.

Such problems preclude a stringent test of theory. These errors can be eliminated from the experimental-theoretical comparison by the use of spin-polarized projectiles. In this case, the quantities determined are asymmetries, which are formed by taking a ratio of the difference and sum of two spin-resolved cross sections [2,3]. All normalization factors cancel, making asymmetries experimentally robust. Furthermore, asymmetries provide a more demanding test of theoretical performance than total or differential cross sections since they probe the relative behavior of separate spin channels rather than their sum.

Earlier spin-resolved low-energy elastic electron-alkali scattering investigations have involved scattering from potassium using the recoil method [4], scattering from hydrogen at a fixed angle [5], and scattering from lithium at three fixed angles [6]. These pioneering experiments had either low angular resolution, large error estimates, or only a few data points below the inelastic threshold. Because of the limited scope of these studies, comparison with theory was instructive, but not conclusive.

In this Letter we report the measurement of exchange asymmetries for electron scattering below the inelastic threshold for sodium, and compare them with the results of a well-known close-coupling calculation [7]. High-precision data are presented at 1.0 and 1.6 eV over the wide angular range of 20°–142.5° at 5° intervals. This represents the first detailed comparison with theory, at an energy and in a system where the close-coupling approximation should be completely applicable.

Four spin-dependent intensities are measured, corresponding to the possible arrangements of projectile and target spins: parallel up $I^{\uparrow\uparrow}$, parallel down $I^{\downarrow\downarrow}$, antiparallel up $I^{\uparrow\downarrow}$, and antiparallel down $I^{\downarrow\uparrow}$. The first superscript arrow indicates electron spin and the second the atomic spin. The intensities are then combined to form the spin-exchange asymmetry

$$A_{\text{ex}} = \frac{1}{P_e P_a} \frac{(I^{\uparrow\downarrow} + I^{\downarrow\uparrow}) - (I^{\uparrow\uparrow} + I^{\downarrow\downarrow})}{(I^{\uparrow\downarrow} + I^{\downarrow\uparrow}) + (I^{\uparrow\uparrow} + I^{\downarrow\downarrow})} \tag{1}$$

$$= \frac{|S|^2 - |T|^2}{|S|^2 + 3|T|^2}, \tag{2}$$

where P_e and P_a are the polarizations of the electron and atom beams, respectively. In Eq. (2), the exchange asymmetry is expressed in terms of the magnitudes of the singlet (S) and triplet (T) complex scattering amplitudes [3]. Its value can range from $+1$ in the case of pure singlet scattering to $-\frac{1}{3}$ for pure triplet scattering. The exchange asymmetry can also be expressed as

$$A_{\text{ex}} = (1 - r)/(1 + 3r), \tag{3}$$

where r is the ratio of triplet to singlet cross sections,

$$r = |T|^2/|S|^2. \tag{4}$$

The present results were obtained using a crossed-beam, polarized-electron–polarized-atom scattering apparatus, described in detail elsewhere [8]. A schematic of the experimental arrangement is shown in Fig. 1. The electron beam is produced by photoemission from a negative-electron-affinity GaAs crystal. The electron polarization P_e is determined with a 100-keV cylindrical Mott analyzer [9]. Measurements of the electron polarization were carried out regularly during the experiments presented here, resulting in a value for P_e of 0.32 ± 0.02. The uncertainty in the electron polarization is due primarily to the inherent calibration uncertainties associated with Mott polarimetry measurements [10]. The energy calibration and the energy width of the electron beam were determined using two distinct methods. First, the $1s2s^2$, ^2S resonance in He at 19.36 eV [11] was measured at a 90° scattering angle by flooding the scattering chamber to 1.6×10^{-5} Pa (1.2×10^{-7} Torr). Second, to confirm that the energy calibration had not shifted when the energy was lowered to 1.6 eV, the 2.1-eV threshold of the $3S$-$3P$ optical excitation function of sodium was measured. The observed energy width of the electron beam was 250 ± 50 meV (FWHM). These two tests agree in both the energy calibration and the energy width of the electron beam to within 50 meV.

A sodium beam of density 10^{15}-10^{16} atoms/m^3 is produced by a recirculating effusive oven. The beam is spin polarized perpendicular to the scattering plane by optically pumping with two frequencies of circularly polarized light. Pumping both the $3S_{1/2}(F=2) \rightarrow 3P_{3/2}(F=3)$ and $3S_{1/2}(F=1) \rightarrow 3P_{3/2}(F=2)$ transitions results in an atomic polarization P_a of 0.98 ± 0.01. This was measured at the interaction region by analysis of fluorescence from a probe laser beam. The sodium atoms are optically pumped before entering the collision volume, thereby allowing time for all of the atoms to decay to the ground

state before encountering the electron beam.

The electron detector consists of a retarding-field analyzer equipped with a channel electron multiplier. The detector is rotatable about the scattering center from $+95°$ to $-142.5°$ scattering angle with a resolution of better than $\pm 0.5°$. The angular acceptance is estimated to be $\pm 3°$. Zero scattering angle was determined by comparing cross sections and spin asymmetries for scattering to the left and right.

The data presented here are the result of 1 to 4 h of collection time per point. Data acquisition is computer controlled with modulation of the spins of the electrons and atoms as well as shuttering of the atom beam in order to measure the background signal rate. The electron-spin polarization is modulated at 200 Hz by application of a high-voltage square wave to a Pockels cell reversing the helicity of the circularly polarized light used for photoemission. The atom-spin polarization is reversed every 1–5 s by mechanically switching the helicity of the pumping light. In order to measure the background electron count rate, the sodium beam is blocked by a mechanical shutter for 1–5 s every cycle. A complete cycle is typically 10 s in duration. The time allocation between atom beam on and off is calculated at each scattering angle to minimize the size of the error in the resulting asymmetry, thereby making the best use of the data-acquisition time.

In Fig. 2, we show the spin-exchange asymmetry A_{ex} at 1.0 eV. The most prominent feature is that the asymmetry is dominated by triplet scattering over most of the angular range. In fact, the exchange asymmetry in the region of 60° to 80° is approximately -0.3, which corresponds to a triplet/singlet ratio of $r=14$. At large scattering angles, in the region of the minimum in the differential cross section [1] at 110°, we see that singlet scattering is slightly larger than triplet.

Figure 3 shows our results at 1.6 eV for A_{ex}. Here
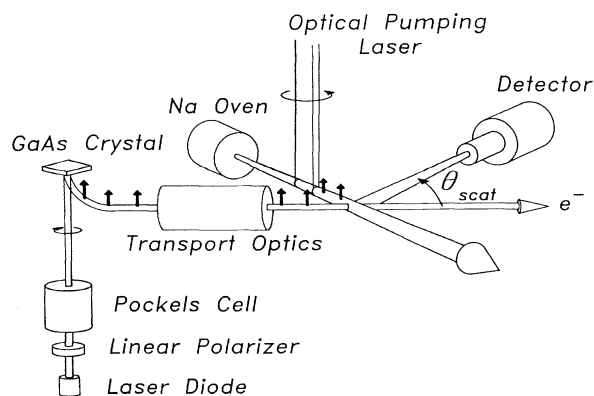

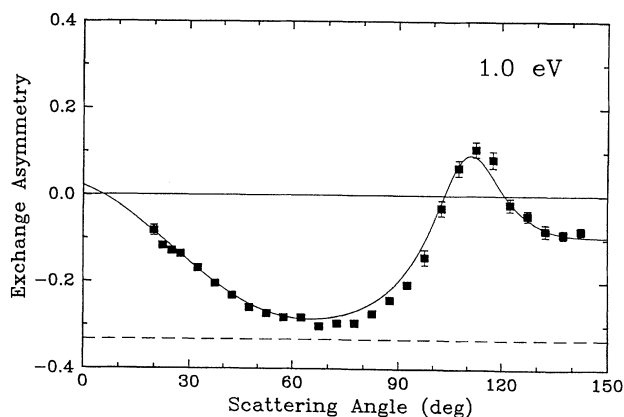FIG. 1. Schematic of experimental arrangement.

FIG. 2. Exchange asymmetry A_{ex} vs scattering angle for an incident electron energy of 1.0 eV. The solid line is the four-state close-coupling calculation of Ref. [7].
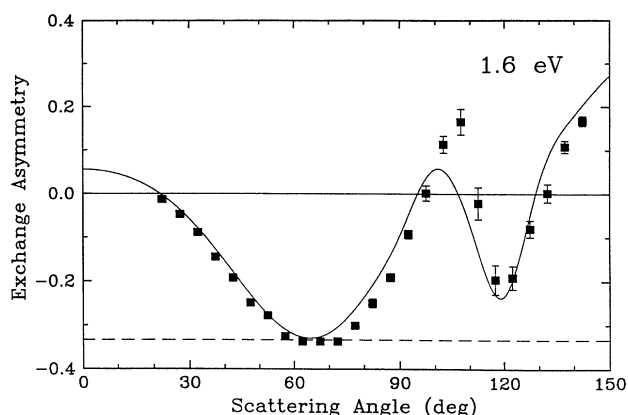
FIG. 3. Exchange asymmetry A_{ex} vs scattering angle for an incident electron energy of 1.6 eV. The solid line is the four-state close-coupling calculation of Ref. [7].

the range of comparison. The level of agreement obtained at this energy is rare for a comparison involving alkali metals, especially considering the agreement over the entire angular range. At 1.6 eV there is generally very good agreement, except in the region between 80° and 120°, where the theory slightly underestimates the role played by exchange for those angles.

These measurements provide data at an energy and in a system where all open channels can be included in a close-coupling calculation. The work also presents a case in which spin-resolved cross sections have been measured with a high degree of accuracy over a large angular range. This work strongly demonstrates the ability of close-coupling theory to accurately predict electron scattering at energies below the first excitation threshold.

again, triplet scattering dominates over singlet in general. In the vicinity of 110°, the rapid oscillation of A_{ex} can be attributed to a difference in the minima of the singlet and triplet differential cross sections. Interestingly, at angles beyond 120° the singlet cross section is larger at 1.6 eV, but the triplet is larger at 1.0 eV.

The error bars shown in both figures are derived from the propagation of the uncertainty due to counting statistics through the expression for the asymmetry. Error bars are plotted only when they exceed the size of the symbols used to represent the data. One-standard-deviation error bars are shown. Not included in this are the uncertainties in P_e and P_a; as can be seen from Eq. (1), these result in an uncertainty in the vertical scale of the figures, but do not affect the relative uncertainties of the individual asymmetry measurements.

In Figs. 2 and 3 we show the four-state close-coupling work of Moores and Norcross [7] at 1.0 and 1.6 eV. The agreement at 1.0 eV is seen to be excellent throughout

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