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Earlier papers1 discussed the application of crossed beams of polarized electrons and atoms 
to the study of spin-exchange effects in impact ionization of atomic hydrogen. This Letter re- 
ports the measurement of spin-exchange effects in 90° elastic scattering of electrons by hydrogen 
atoms from 4 to 30 eV. The basic quantity which we determine is the asymmetry \( A_{90°}(1S-1S) \) de- 
defined by

\[
A_{90°}(1S-1S) = \frac{(d\sigma_{11} - d\sigma_{1\text{t}})}{(d\sigma_{11} + d\sigma_{1\text{t}})},
\]

where \( d\sigma_{11} \) and \( d\sigma_{1\text{t}} \) are the 90° elastic differential scattering cross sections for incident-elec- 
tron and hydrogen-electron spins antiparallel (\( 1\text{t} \)) and parallel (\( 1\text{t} \)). In terms of the direct and ex- 
change 90°-elastic-scattering amplitudes, \( f(90°) \) and \( g(90°) \), respectively, \( A_{90°}(1S-1S) \) can be ex- 
pressed as1,2

\[
A_{90°}(1S-1S) = \frac{(1 - r)}{(1 + 3r)} = \frac{Re(f^*g) / d\bar{\sigma}}{d\bar{\sigma}},
\]

where \( r = |f - g|^2 / |f + g|^2 \) is the triplet-to-singlet cross-section ratio and \( d\bar{\sigma} \) is the spin-averaged 
differential cross section given by the weighted sum of the singlet and triplet cross sections, or

\[
d\bar{\sigma} = \frac{1}{4}|f + g|^2 + \frac{3}{4}|f - g|^2.
\]

Theoretically, electron-hydrogen elastic scattering is the simplest and most fundamental of 
all electron-atom collision problems. Nonetheless, it cannot be solved in closed form. Below 
the \( n = 2 \) excitation threshold (10.2 eV), the detailed Kohn variational computations of \( s-, p-, \) and \( d- \)wave phase shifts3 are generally regarded as accurate to at least 1 mrad. In addition, 
polarized orbital4 and close-coupling5 truncated expansion of the wave function have been successful in reproducing not only the broad features of the cross section but in many cases the narrow 
features of the resonances as well. Thus, agreement between measured and calculated values of 
\( A_{90°}(1S-1S) \) below 10.2 eV must be viewed not only as a confirmation of theory but also as a 
vital check of the experimental method.

Above the \( n = 2 \) threshold, however, calculations become increasingly difficult, reflecting the 
necessary inclusion of additional states (often synthesized pseudostates) in the wave-function 
expansion6,7 and the use of \( R \)-matrix techniques.8 These calculations, as well as those such as 
Glauber, Feddeev-Watson, second-order potential, eikonal, and eikonal-Born calculations,9,10 
which are essentially high-energy approximations,
must be regarded as having questionable validity in the intermediate energy region (10–100 eV). Although many of the calculated values of the spin-averaged cross sections in this region are in good agreement with the measured values, such agreement does not guarantee that calculated values of the scattering amplitudes $f$ and $g$ are correct, as has been clearly demonstrated in the case of impact ionization. Comparisons of theoretical and experimental values of polarization-dependent asymmetries are generally required for detailed tests of the various approximation methods.

The experimental method which we used to determine $A_{\text{dep}}(1S \rightarrow 1S)$ is essentially the same as that used for determining $A_{\text{tot}}(1S \rightarrow 1l)$, the total cross-section asymmetry for impact ionization, described previously. In brief, longitudinally polarized electrons are produced in a Fano-effect polarized electron source, in which circularly polarized uv light photoionizes an unpolarized Cs atomic beam. The helicity of the extracted electron beam is the same as the helicity of the incident light. Thus the electron polarization can be reversed by a $90^\circ$ rotation of either a linear polarizer or a quarter-wave retardation plate, with the electron optics remaining unchanged.

As shown in Fig. 1 the electrons are transported at 1 keV into either the interaction branch or the Mott polarimeter branch. In the interaction branch the electrons are decelerated to the desired energy, the absolute scale being determined by the onset of ionization at 13.6 eV. Following the intersection with the hydrogen beam, the unscattered electrons are reaccelerated to 1 keV into a Faraday cup, and the total current is digitized by an electrometer and a voltage-to-frequency converter (VFC). Electrons elastically scattered at $90^\circ$ are detected by an electron multiplier preceded by a filter lens which prevents inelastically scattered electrons from reaching the multiplier. The polar angle acceptance of the detection optics is $24^\circ$.

The atomic hydrogen beam is produced by effusion from a tungsten tube which is resistively heated to 2800 K to thermally dissociate the molecular gas. After collimation, the atomic $M_J = \pm \frac{1}{2}$ states of the partially dissociated beam are selected at high field in a permanent sextupole magnet and transported to the interaction region, with the atomic spins being adiabatically rotated either parallel or antiparallel to the electron beam, depending upon the orientation of a ~100 mG magnetic field in the interaction region. Appropriate shaping of the magnetic fields precludes Majorana depolarization.

Before entering the interaction chamber, the hydrogen beam is modulated by a 100-Hz tuning-fork beam chopper to permit real-time background subtraction. After leaving the chamber, the beam passes through a quadrupole mass analyzer (QMA) which monitors the relative amounts of atomic and molecular hydrogen. For incident electron energies above 13.6 eV, the ionization signal is monitored by a multiplier located along the hydrogen beam line downstream from the interaction region. The various experimental operating parameters are summarized in Table I.

Data acquisition is controlled by a PDP-15 computer. The digitized Faraday-cup output from the VFC is counted in a preset scaler which halts data taking after a preset charge has entered the cup. The electron events accumulated during the data interval are totaled on a pair of blind scalers corresponding to the 4-msec beam-on and 2-msec beam-off portions of each 10-msec hydrogen-beam chopper cycle. The H and H$_2$ quadrupole signals are similarly totaled as is the hydrogen-ion signal for incident electron energies above 13.6 eV. Also recorded for each data interval are the accumulated charge in the Faraday cup and the elapsed time of the interval. At the completion of the interval, the computer reads and clears the blind scalers, advances the quarter-wave plate by $90^\circ$, and reinitiates data accumulation. After ~40 revolutions of the quarter-wave plate the run is halted. Normally, a complete measurement at a given energy comprises sixteen runs corresponding to two revolutions of the linear polarizer in $90^\circ$ steps for each of the two directions of the magnetic field in the interaction region.
TABLE I. Experimental operating parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron beam:</td>
<td></td>
</tr>
<tr>
<td>Intensity at source exit</td>
<td>10 nA (av)</td>
</tr>
<tr>
<td>Intensity at interaction region</td>
<td>2 nA (av)</td>
</tr>
<tr>
<td>Polarization, $P_e^{a}$</td>
<td>0.62–0.75 (±5%)</td>
</tr>
<tr>
<td>Energy spread (FWHM)</td>
<td>3.0 eV</td>
</tr>
<tr>
<td>Emittance at 1 keV</td>
<td>20 mrad cm</td>
</tr>
<tr>
<td>Hydrogen beam:</td>
<td></td>
</tr>
<tr>
<td>Density at interaction region</td>
<td>$\sim 10^3$ cm$^{-3}$</td>
</tr>
<tr>
<td>Polarization, $P_H^{b,c}$</td>
<td></td>
</tr>
<tr>
<td>at high field</td>
<td>0.99 (±1%)</td>
</tr>
<tr>
<td>at low field</td>
<td>0.50 (±4%)</td>
</tr>
<tr>
<td>Fraction of events, $1-F_2^{c}$</td>
<td>0.80–0.95 (±2%)</td>
</tr>
<tr>
<td>Collinearity factor, $\cos \alpha$</td>
<td>0.985 (±1.3%)</td>
</tr>
<tr>
<td>Background gas pressure</td>
<td>$10^{-9}$ Torr</td>
</tr>
<tr>
<td>Detection solid angle:</td>
<td></td>
</tr>
<tr>
<td>Electrons</td>
<td>0.14 sr</td>
</tr>
<tr>
<td>Ions</td>
<td>$4\pi$ sr</td>
</tr>
<tr>
<td>Counting rates (16.9 eV):</td>
<td></td>
</tr>
<tr>
<td>Electrons</td>
<td>2.2 s$^{-1}$</td>
</tr>
<tr>
<td>Ions</td>
<td>29 s$^{-1}$</td>
</tr>
<tr>
<td>Signal–to–noise ratios (16.9 eV):</td>
<td></td>
</tr>
<tr>
<td>Electrons</td>
<td>1.3</td>
</tr>
<tr>
<td>Ions</td>
<td>7.0</td>
</tr>
</tbody>
</table>

$^{a}$Monitored periodically.
$^{b}$Calculated, including hyperfine depolarization.
$^{c}$Monitored continuously.

The real experimental asymmetry in the elastic electron signal, $\Delta_R$, for each run is defined as

$$\Delta_R = (N_+ - N_-) / (N_+ + N_-),$$  \hspace{1cm} (4)

where $N_+$ ($N_-$) is the sum of the beam-on (off) electron events for quarter-wave-plate positions 0 and 2 corresponding to $0^\circ$ and $180^\circ$, respectively, and $N_+$ ($N_-$) is the sum of the beam-on (off) electron events for the quarter-wave-plate positions 1 and 3 corresponding to $90^\circ$ and $270^\circ$, respectively. In addition to the real asymmetry, two false asymmetries, $\Delta_{F1}$ and $\Delta_{F2}$, can be constructed from quarter-wave-plate combinations $0+1-2-3$ and $0+3-1-2$, respectively, as tests of systematic errors. For both the real and false asymmetries, the values of $\Delta$ measured for each run are combined according to their statistical weights to give the final value for a given energy. The value of $\Delta_R$ so obtained is related to $A_{00}^{S}(1S-1S)$ according to

$$\Delta_R = P_e P_H^{b} \cos \alpha \Delta_{F1} A_{00}^{S}(1S-1S),$$  \hspace{1cm} (5)

where $P_e$ and $P_H^{b}$ are, respectively, the electron and atom polarizations, $\cos \alpha$ describes the collinearity of the $\sim 100$ mG magnetic field with the electron beam, and $F_2$ is the fraction of events originating from molecules. As in the previous impact-ionization measurement, $F_2$ is determined from $H_2$ QMA signals and electron event rates obtained at a hydrogen oven temperature of $\sim 1400$ K where the beam is essentially molecular in composition.

The value of $P_e$ is monitored periodically by Mott scattering during the experiment. For $P_H^{b}$ a calculated value is used, based upon the known properties of the sextupole magnet, the geometry of the hydrogen beam, and the effective magnetic moment of the hydrogen atom as a function of magnetic field.

Above an incident electron energy of 13.6 eV, a similar analysis is performed for the ionization asymmetry. These new ionization asymmetry measurements will be published elsewhere.

The results of our measurements of $A$ are tabulated in Table II and are shown in the upper portion of Fig. 2 with a number of theoretical calculations. Also shown in Fig. 2 are measurements of the spin-averaged cross section, $d\sigma^{S}$. Since the energy resolution of the polarized beam precludes the observation of any resonance structure in $A$, all resonance details have been omitted for $d\sigma$ as well as for $A$. As can be seen, although the measurements of $d\sigma$ agree well with most of

---

TABLE II. Results of data analysis. Uncertainties are one standard deviation; those for $A$ include systematic as well as statistical effects.

<table>
<thead>
<tr>
<th>ENERGY (eV)</th>
<th>REAL ASYMMETRY $A_{00}^{S}(1S-1S)$</th>
<th>FALSE ASYMMETRIES $\Delta F_1$, $\Delta F_2$</th>
<th>$\chi^2$(0)/deg. freedom</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.1</td>
<td>+0.003(46)</td>
<td>+01(15) +11(15)</td>
<td>10/16 16/16</td>
</tr>
<tr>
<td>6.0</td>
<td>-0.151(38)</td>
<td>+02(11) -14(11)</td>
<td>13/18 15/18</td>
</tr>
<tr>
<td>8.3</td>
<td>-0.192(37)</td>
<td>+01(05) +10(05)</td>
<td>12/24 37/24</td>
</tr>
<tr>
<td>10.0</td>
<td>-0.237(52)</td>
<td>+00(05) +02(05)</td>
<td>70/38 46/38</td>
</tr>
<tr>
<td>11.3</td>
<td>-0.276(52)</td>
<td>+01(13) -02(13)</td>
<td>17/14 14/14</td>
</tr>
<tr>
<td>13.8</td>
<td>-0.336(64)</td>
<td>+24(16) -13(16)</td>
<td>15/14 17/14</td>
</tr>
<tr>
<td>16.9</td>
<td>-0.285(55)</td>
<td>+06(13) +06(13)</td>
<td>26/25 19/25</td>
</tr>
<tr>
<td>19.8</td>
<td>-0.193(53)</td>
<td>+14(14) -28(14)</td>
<td>25/19 15/19</td>
</tr>
<tr>
<td>21.9</td>
<td>-0.212(55)</td>
<td>-10(16) +15(16)</td>
<td>11/17 8/17</td>
</tr>
<tr>
<td>24.0</td>
<td>-0.114(66)</td>
<td>-24(18) +26(18)</td>
<td>10/12 11/12</td>
</tr>
<tr>
<td>26.7</td>
<td>-0.200(42)</td>
<td>-26(12) +07(12)</td>
<td>27/27 23/27</td>
</tr>
<tr>
<td>30.0</td>
<td>-0.177(62)</td>
<td>-18(19) +10(19)</td>
<td>9/17 17/17</td>
</tr>
<tr>
<td>ALL RUNS</td>
<td>00(03) +04(03)</td>
<td>245/241 238/241</td>
<td></td>
</tr>
</tbody>
</table>

---

$^{a}$Monitored periodically.
$^{b}$Calculated, including hyperfine depolarization.
$^{c}$Monitored continuously.
the calculations, the measurements of $A$ agree well only with the theoretical prediction of Ref. 16 over the entire energy range shown. It is interesting to note that our measurement of $A$ at 13.8 eV is consistent with a value of $-\frac{1}{4}$, which is the lower bound on $A$ and reflects pure triplet scattering.

We wish to acknowledge the contributions of G. Baum and J. S. Ladish and to thank J. Brosious, R. Broughton, D. Constantino, A. Disco, L. Trudell, and the Yale University Gibbs instrumentation shop staff for their technical assistance. This research was supported in part by the National Science Foundation under Grant No. PHY81-05035, by the City University of New York under Grant No. PSC-CUNY RF 13414, and by the Deutsche Forschungsgemeinschaft. One of us (M.S.L.) wishes to thank the Sloan Foundation for providing support in the form of an Alfred P. Sloan Fellowship.

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(c)Permanent address: Bell Laboratories, Holmdel, N.J. 07733.
14Good agreement has been obtained in comparisons of such calculations with measured values in other experiments [M. J. Alguard et al., Nucl. Instrum. Methods 163, 29 (1979); V. W. Hughes et al., Phys. Rev. A 5, 195 (1972)]; moreover, the 47-cm length of the sextuple makes the degree of state selection quite insensitive to any uncertainties in the value of the pole-tip field strength.