Spin Asymmetries for Triple-Differential Electron-Impact Ionization of Lithium at 54.4 eV

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Up to now, all triple-differential cross-section measurements were performed with unpolarized electrons and atoms and, consequently, averaged over direct and exchange scattering. In our crossed-beam experiment, spin-polarized lithium atoms were ionized by spin-polarized electrons of 54.4 eV energy. In coplanar, asymmetric coincidence detection of scattered and ejected electrons, combined with electron-energy analysis, we measured a spin asymmetry which gives new information about the ionization process. Results are compared with recent calculations based on the distorted-wave Born approximation.

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The triple-differential cross section (TDCS), $d^3\sigma/d\Omega_A \times d\Omega_B dE_A$, of electron-impact ionization of atoms depends on the angles of the outgoing electrons A and B and on the partition of the energy between them, described by E_A and

$$E_B = E_0 - E_{\text{ion}} - E_A , \tag{1}$$

where E_0 is the incident electron energy and E_{ion} the ionization energy for the ejected atomic electron. By adopting nuclear-physics terminology, this process is usually called *(e,2e) scattering.*

Most $(e,2e)$ experiments belong to one of two categories. (1) *(e,2e) spectroscopy*, typically performed with noncoplanar, symmetric ±45° detector geometry and energies in the keV range for which the first-order theory is expected to be valid. Here the goal is to measure the momentum distributions of the bound electrons in atoms and molecules [1]. (2) *Ehrhardt-type experiments*, usually performed with asymmetric geometry at lower energies and with simple target atoms such as H, He, or Li. Here the goal is to test theories of electron-impact ionization [2]. Such tests have shown that first-order approximations suffice at high energies and manageable second-order approximations are satisfactory at intermediate energies. Therefore, the current experimental efforts are concentrated at low energies where exchange effects are known to be important. Results from this laboratory on the total ionization of lithium and other alkali atoms near threshold show pronounced effects of exchange scattering [3]. This is the reason we developed an $(e,2e)$ experiment with spin-polarized electrons and spin-polarized ^{6}Li atoms. We chose lithium because it is—aside from the experimentally more demanding atomic hydrogen—the simplest one-electron atom. The isotope ^{6}Li is used for technical reasons: It has a small hfs splitting of the ground state which insures an efficient high-field state selection in the hexapole magnet.

A typology of the simplest polarization experiments on exchange interaction in electron-atom scattering [4] shows that, in principle, three different polarization asymmetries A, A', and A'' (with the connection $A+A'+A''=1$) can be measured. For experimental reasons the determination of A is favored. It requires an experiment in which both interacting particles are initially polarized. The asymmetry is related to measurable parameters by

$$A = \frac{1}{P_a P_e} \frac{\sigma^{\downarrow\uparrow} - \sigma^{\uparrow\uparrow}}{\sigma^{\downarrow\uparrow} + \sigma^{\uparrow\uparrow}} . \tag{2}$$

Here P_a and P_e are the initial polarizations of atomic and electron beams; $\sigma^{\uparrow\uparrow}$ and $\sigma^{\downarrow\uparrow}$ are the cross sections for parallel and antiparallel beam polarizations. Here the "atomic" polarization refers to the polarization of the atomic *electron*, ejected in the collision; the atom's nuclear polarization is irrelevant.

The asymmetry A, determined according to Eq. (2), can be related to the direct and exchange scattering amplitude, $|f|$ and $|g|$, respectively, and the phase angle θ between them:

$$A = |f||g| \cos\Theta/\sigma_0 , \tag{3}$$

where σ_0 is the cross section for unpolarized particles (either unpolarized electrons, or atoms, or both). Instead of using *direct* and *exchange* amplitudes for describing two spin-$\frac{1}{2}$ particles, one can use the *singlet* and *triplet* amplitudes, $s=f+g$ and $t=f-g$, respectively. Since

$$\sigma^{\uparrow\uparrow} = |t|^2 \tag{4}$$

and

$$\sigma^{\downarrow\uparrow} = \tfrac{1}{2}|s|^2 + \tfrac{1}{2}|t|^2 , \tag{5}$$

it follows that a determination of A also yields the ratio of triplet-to-singlet cross section:

$$|t|^2/|s|^2 = (1-A)/(1+3A) . \tag{6}$$

Thus $A=1$ is equivalent to pure singlet scattering, and $A=-\frac{1}{3}$ to pure triplet scattering.

In the past we measured A for the total electron-impact ionization of various atoms [3,5,6], the autoionization of lithium ^4P states [7], and for differential elastic as well as inelastic electron scattering from lithium atoms [8,9]. The techniques for producing and monitoring polarized beams of electrons and alkali atoms have now been combined in the present experiment with the coin-

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cidence technique required for the study of triple-differential scattering. Preliminary results have been reported [10].

Triple-differential cross-section measurements involve five independent variables, namely, the polar and azimuth angles for both outgoing electrons and their energy partition. For planning the experiment, careful selection of the kinematical variables is necessary. We aimed for a high signal rate, a theoretically straightforward geometry, and an angular range for which high but varying values are to be expected. Therefore, our experiment has coplanar, asymmetric kinematics. The measurements reported here include one symmetric case at $\Theta_A = \Theta_B = 45°$ (Fig. 1). For the symmetric setting and equal energies ($E_A = E_B$), the enforced spatial symmetry of the wave function has the consequence that only antisymmetric spin states are allowed, and this means pure singlet scattering corresponding to $A = 1$. Thus this setting provides a useful experimental check.

For the electron scattering from low-Z atoms such as lithium, spin-orbit interaction can be neglected and, therefore, the orientation of the beam polarizations to the scattering plane is irrelevant. It is only necessary to ensure that the electron and atom polarizations are aligned parallel and antiparallel, respectively. For practical reasons the polarization vectors in this experiment are set perpendicular to the scattering plane. The low densities of the beams and the low signal rates associated with coincidence experiments led to the construction of hemispherical electron spectrometers with the widest possible angular acceptance (± 10°) and broadened energy resolution (approximately 3 eV FWHM).

Standard methods have been used for the production of the polarized lithium beam [3] and polarized electron beam [11]. The density of lithium produced at the interaction region by the resistively heated oven and polarizing hexapole magnets is about 10^9 cm^{-3}. The lithium-beam polarization is monitored using an analyzing hexapole magnet and spin flipper [12] during the experiment. A weak magnetic "guiding" field of 10^{-5} T parallel to the lithium beam at the interaction region was applied in order to prevent depolarizing Majorana transitions. This field produced a very minor rotation of electron trajectories in the scattering plane of 0.6°. The electron beam of typically 6 μA was accelerated to a transport voltage of 1250 eV and later decelerated to the required impact energy. It was focused with constant magnification and zero beam angle onto the interaction region. Use of a field lens and a wide-range zoom lens permits focusing from threshold energies (5 eV) to high energies (300 eV) without difficulty. The electron polarization is measured with a standard 100-keV Mott polarimeter at the beginning of each day's measurements. The electron optics lenses for the hemispherical spectrometers were designed to maintain a constant (and large) angular acceptance of ± 10° for all detection energies by allowing all lens voltages to scale with the detection energy. Five-element lenses provided (nearly) uniform transmission for electrons coming from the interaction volume defined by the lithium beam diameter of 2 mm. Standard methods were used for the coincident detection of electrons using Channeltrons and fast timing electronics [1]. Coincidence signal rates in these measurements varied from 0.3 s^{-1} at the maximum to about 0.003 s^{-1}. The measurement cycle for the spin asymmetry is listed in Table I and consisted of twelve sections, typically of 16 s duration each.

A spin-asymmetry data point was obtained from the average of hundreds of such cycles. The asymmetry, determined according to Eq. (2), depends only on the cross-section ratio $\sigma^{\uparrow\uparrow}/\sigma^{\downarrow\uparrow}$. Therefore, the *relative* cross sections provided by the number of coincidence-signal counts suffice. These counts for antiparallel and parallel beam polarizations are given by

$$\begin{aligned} N^{\downarrow\uparrow} &= N_1 + N_6 + N_9 + N_{10}, \\ N^{\uparrow\uparrow} &= N_3 + N_4 + N_7 + N_{12}, \end{aligned} \tag{7}$$

where the indices refer to the columns in Table I. "False asymmetries" can be defined, which are nonzero only if drifts in beam densities or polarizations occur during a measurement cycle. They were used as a guide for rejecting some measurement cycles (about 5% of the cases). The major contribution to the error of A is due to the statistics of the coincidence counts. A noise gate reduces the background of "noise coincidences" below the level of detectability.

The beam polarizations $P_e \approx 0.31$ and $P_a \approx 0.25$ were frequently measured. Their statistical fluctuations, which

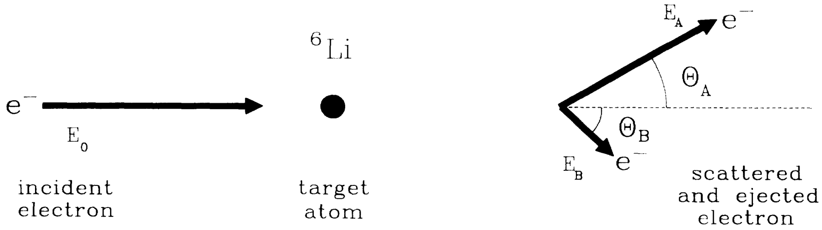

FIG. 1. Schematics of the studied collision. A beam of (polarized) electrons with incident energy E_0 intersects with a beam of (polarized) ^{6}Li atoms. In this first experiment the electron-detection angle Θ_A is set at 45° and Θ_B is varied. The two outgoing electrons have energies E_A and E_B.

TABLE I. Measurement cycle. ↑ = spin "up," ↓ = spin "down," and ··· = beam flag closed.

Number	1	2	3	4	5	6	7	8	9	10	11	12
P_e	↑	↑	↑	↑	↑	↑	↓	↓	↓	↓	↓	↓
P_a	↓	···	↑	↑	···	↓	↓	···	↑	↑	···	↓

enter into the error bars of the A data points in principle, are much smaller than those of the coincidence counts and therefore negligible here. For the systematic error associated with the determination of both polarizations we assign a relative uncertainty of 5% each, which —combined by taking the root of the sum of the squares —lead to a scale uncertainty of $\Delta A/A \approx \pm 7\%$ common to all data points.

Very few theoretical calculations are available for the exchange scattering amplitude g, or the spin asymmetry A. Some calculations concern atomic hydrogen [13,14] for which no experimental data are yet available. Recently a distorted-wave Born approximation has been applied to the calculation of intermediate energy triple-differential cross sections and asymmetry values for lithium [15]. The results are compared with our experimental data below. A difficulty in making comparisons with theory is the large ±10° angular resolution of each of the detectors. This requires the convolution of the "exact" theoretical results with the transmission function. From the theoretical values for the in-plane asymmetry, kindly provided by the authors for 2° intervals, we computed an approximated average over the angular resolution of the detectors for center angles in 2° steps. The average over the combined acceptance angle at each angular setting of spectrometer B is plotted as the dashed line in Fig. 2.

Figure 2 shows our measured spin asymmetries for 54.4 eV impact energy and symmetric detection energies, $E_A = E_B = 24.5$ eV. For better comparison we convoluted the theoretical results of Zhang, Whelan, and Walters [15] with the experimental angular resolution. The near-unity asymmetry at $\Theta_B = 45°$ due to the spatial symmetry of the electron wave function is confirmed. The theoretically predicted drop in the asymmetry to higher angles is also confirmed. The predicted increase of A at still higher angles is perhaps suggested but not yet confirmed by the data points. The larger error bars at larger angles are due to the much lower cross sections.

For the measurement reported here, the design parameters had been chosen to give the maximum asymmetry ($A = 1$) near the cross-section maximum (at angles of ±45°) in order to optimize the experimental conditions for this first polarized $(e,2e)$ experiment. However, the $A = 1$ obtained for spatial symmetry does not provide information about the collision process itself. Consequently, for subsequent measurements we will choose different parameters, e.g., $\Theta_A = 30°$. This will lead to $A = 1$ at $\Theta_B = -30°$. But at the cross-section maximum, which lies near $\Theta_B = -50°$ according to theory, the most accurately measurable asymmetry will depend on details of the collision process.

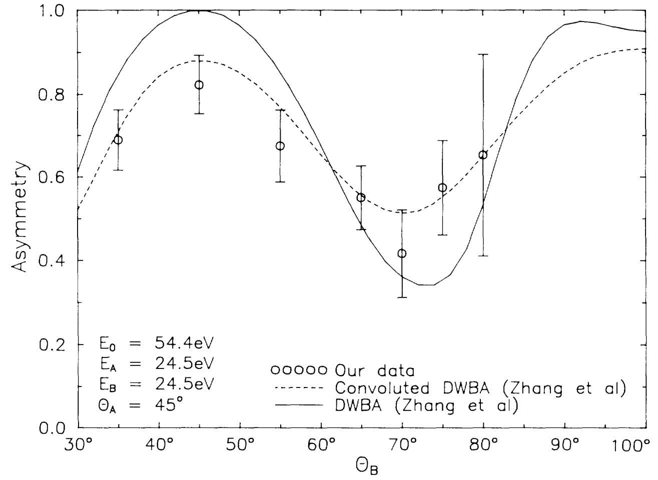

FIG. 2. Experimental results (data points with standard-deviation error bars) for $E_0 = 54.4$ eV, $E_A = E_B = 24.5$ eV, and $\Theta_A = 45°$ compared with the distorted-wave Born approximation (DWBA) calculations of Zhang *et al.* (solid line) and with the convolution of theoretical results and experimental angular resolution (dashed line).

Work is in progress on the design of new multicoincidence detectors with improved angular and energy resolution and on the development of an atomic hydrogen beam, and on the installation of rf transitions for obtaining higher atomic beam polarization. Going to lower energies is a major goal.

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