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Polarized Electron–Lithium Scattering

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An experiment is discussed that will measure spin-dependent asymmetries in the scattering of polarized electrons on polarized Li atoms. Results are presented for polarizing the atomic beam by the method of optical pumping and for techniques of polarization reversal in both beams which minimize systematic errors.

1. Introduction

This is a status report on an experimental program to study spin effects in scattering of polarized electrons by polarized one-electron atoms. The e–Li scattering is of particular interest because lithium is the simplest alkali-metal atom; in principle, lithium can exhibit all the effects of more complex atoms. The theoretical treatment is therefore a greater challenge than that of hydrogen but is not yet as involved as that of the heavier alkali metals. Relativistic spin–orbit coupling effects are small for lithium and do not complicate the analysis, but short-range correlations (e.g., virtual excitation of core electrons) might contribute to the e–Li scattering. Polarized particle scattering is expected to provide a very sensitive method for studying the important details of the scattering process and to provide a stringent test of the different scattering theories.

Different experiments on spin effects in electron scattering from one-electron

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atoms are being pursued at other laboratories: at Yale University e–H scattering[1] is being studied by using a Fano-effect polarized electron source;[2] at the University of Stirling, Scotland, e–K scattering[3] is being studied, and the polarized electron source is based on low-energy Mott scattering. In both experiments the atomic beam is polarized by state selection in a permanent six-pole magnet. We employ optical pumping for polarizing the lithium atomic beam, and the polarized electrons are produced by field emission from ferromagnetic EuS on tungsten.[4,5]

2. Theoretical Expectations

The experimental asymmetry Δ, measured with both incoming particles polarized, is defined as

$$\Delta = (C^{\uparrow\downarrow} - C^{\uparrow\uparrow})/(C^{\uparrow\downarrow} + C^{\uparrow\uparrow}) \tag{1}$$

where $C^{\uparrow\downarrow}$ and $C^{\uparrow\uparrow}$ are the count rates obtained with antiparallel and parallel particle polarizations, respectively. The theoretically interesting asymmetry of the differential cross sections $\sigma^{\uparrow\downarrow}$ and $\sigma^{\uparrow\uparrow}$,

$$A = (\sigma^{\uparrow\downarrow} - \sigma^{\uparrow\uparrow})/(\sigma^{\uparrow\downarrow} + \sigma^{\uparrow\uparrow}) \tag{2}$$

is connected to Δ by

$$\Delta = P_e P_{\text{Li}} A \tag{3}$$

where P_e is the electron-beam polarization and P_{Li} is the polarization of the lithium valence electrons.

Our goal is to measure with good energy resolution the asymmetry in elastic scattering and to extend these studies to very low electron energies (1 eV and below). At first, however, we will investigate electron impact ionization, as the groups at Yale and Stirling have done for the e–H and e–K scattering. The impact ionization is technically easier because the ion can be detected with minimal background problems. Since the Yale results[1] showed remarkable deviations from theoretical predictions, there is great interest in such measurements with other atoms. Also of great interest are experiments on electron impact excitation of resonance transitions (e.g., Li $2s \to 2p$) with polarized particles.[6]

The motivation for studying elastic e–Li scattering is discussed in a recent paper of Temkin and co-workers.[7] It would be very interesting indeed to compare their modified polarized orbital (MPO) calculations with experiment, particularly under conditions for which the MPO results differ significantly from those of close-coupling (CC) calculations.[8] For the differential cross section in the case of unpolarized particles, σ_0, the two theoretical methods yield almost identical results. In Figure 1 the values of σ_0 are plotted versus the cosine of the scattering angle θ for an electron energy of 0.1 Ry = 1.36 eV. The difference between the MPO and CC results is perhaps barely measurable in the vicinity of $\theta \sim 120°$ and negligible elsewhere.

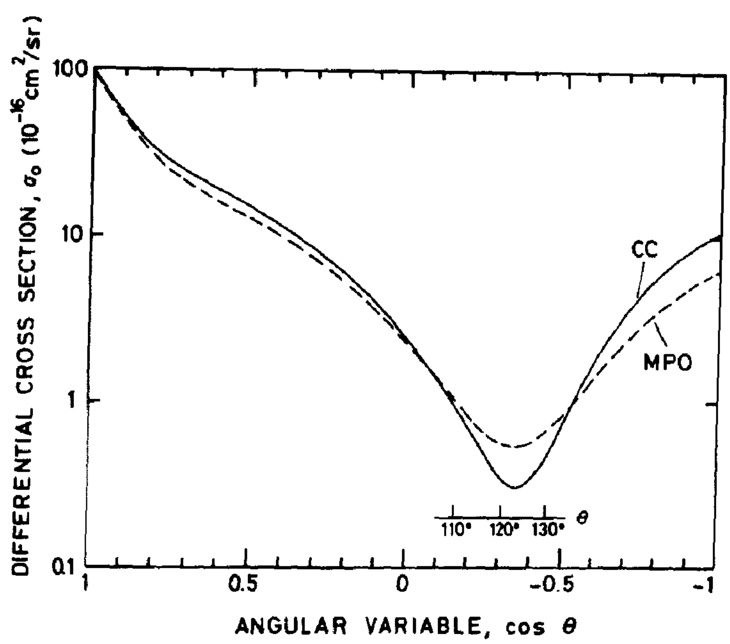

Figure 1. Differential elastic e–Li scattering cross sections for an electron energy of 1.36 eV, obtained from close-coupling results (CC)[8] and modified polarized-orbital calculations (MPO).[7]

However, for the asymmetry A the two methods lead to markedly different results, as shown in Figure 2. Thus elastic scattering with polarized particles should help significantly to clarify the problem.

The first measurements shall be made with a fixed scattering angle of $\theta = 120°$ and variable incident electron energy. The electron polarization will be monitored with the Mott detector. As a supplementary measurement we intend to scatter unpolarized electrons (also for $\theta = 120°$) from polarized Li atoms and measure the

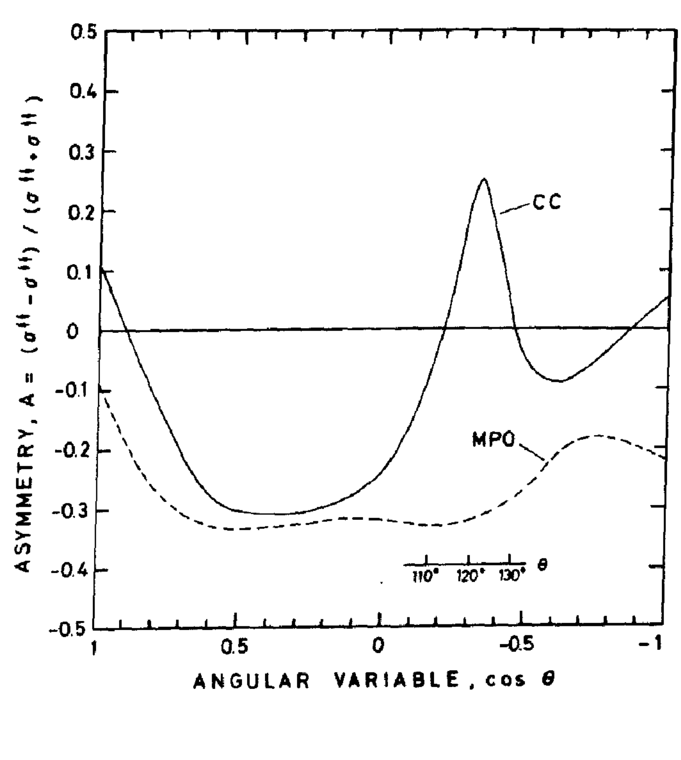

Figure 2. Asymmetry in elastic e–Li scattering for polarized incoming particles of 1.36 eV electron energy calculated from close-coupling (CC)[8] and modified polarized-orbital (MPO)[7] theory. Note that positivity of equation (5) requires that $A \geq -\frac{1}{3}$.

polarization of the scattered electrons

$$P_e' = BP_{\mathrm{Li}} \tag{4}$$

where B is another independent parameter which can be used, together with our measurements of A and other measurements of σ_0, to make a very thorough comparison with theoretical parameters. It is customary to describe the elastic scattering in terms of two complex amplitudes, either s and t, the singlet and triplet scattering amplitudes or, $f = (s + t)/2$ and $g = (s - t)/2$, the direct and exchange amplitudes. The amplitudes s and t are related to σ_0, A, and B by

$$|s|^2 = \sigma_0(1 + 3A) \tag{5}$$

$$|t|^2 = \sigma_0(1 - A) \tag{6}$$

$$|s| \cdot |t| \cos\alpha = \sigma_0(1 + 2B - A) \tag{7}$$

where α is the phase angle between s and t.

3. *Polarized Electron Source*

The polarized electron source provides a highly polarized, monoenergetic electron beam of extremely high brightness. Relevant technical data are listed in Table 1. The most recent work on the source has been concerned with electron polarization reversal. The direction of the electron polarization inside the EuS layer is the same

Table 1. Characteristics of Polarized Electron Source

Emitter—ferromagnetic EuS on tungsten tip	
Temperature	$\sim$10 K
Vacuum	$<10^{-10}$ Torr
Magnetic field	$\sim$50 G longitudinal
Electron beam	
Current, I	$\sim 10^{-8}$ A
Polarization, P	$\sim$0.85, transverse
Energy width, ΔE	$<$0.1 eV
Emittance, ε	0.8×10^{-6} rad cm
At energy, E_0	3 eV
Figures of merit	
$M_1 = IP^2$	7×10^{-9} A
$M_2 = M_1 \varepsilon^{-2} E_0^{-1}$	4×10^3 A rad^{-2} cm^{-2} eV^{-1}
$M_3 = M_2 \Delta E^{-1}$	4×10^4 A rad^{-2} cm^{-2} eV^{-2}

as the direction of magnetization of the emitting region. In operating the source with only a small longitudinal magnetic field applied at the tip, the magnetization is still tangential to the EuS layer, leading to a transverse polarization of the extracted field-emission beam. The azimuthal orientation of the polarization vector depends on the direction of magnetization in the emitting EuS layer. (Larmor precession in the applied longitudinal magnetic field is of no concern since it can be controlled by choosing the operating conditions.) We found that the EuS has an axis of easiest magnetization (and sometimes two axes) and that in cooling the tip below the Curie temperature the magnetization vector will orient itself parallel to that axis. By simply raising the temperature of the tip temporarily above the Curie point, and letting it drop again, the polarization will fall back to the former direction or reverse itself, apparently in a random fashion for the majority of our samples. This provides a convenient method for polarization reversal. Most important, this reversal is free of any possible systematic effects connected with changes in the electron optical settings of the source as these are unaltered during the reversal process. A few of our samples showed a preference of the magnetization vector for one of the two directions associated with the axis of easy magnetization. Here a reversal—again without any electron optical changes—can be achieved by applying a transverse magnetic field (2 kG) in the proper direction while the tip temperature is raised temporarily above the Curie point.

To avoid systematic effects in our asymmetry measurements which might be connected with drifts of the experimental parameters, the polarization directions of the incoming particles with respect to each other (antiparallel or parallel) will be reversed frequently. The atomic polarization, which can be switched with ease by simply reversing the circular polarization of the pumping light, will be altered in short intervals, the electron polarization in longer intervals.

4. Polarized Atomic Beam

The simplest method for polarizing an alkali atomic beam is passage through a six-pole magnet which accomplishes a high-field Zeeman-state separation such that atoms with $M_s = +\frac{1}{2}$ are transmitted and those with $M_s = -\frac{1}{2}$ rejected. This method, however, has a great disadvantage as the six-pole magnet cannot be reversed to transmit atoms with $M_s = -\frac{1}{2}$. In order to reverse the atomic polarization with respect to a given external magnetic field one would have to employ more elaborate schemes such as a fast adiabatic passage. Another drawback of the six-pole magnet is the fact that the atoms state-selected in a strong field reduce their electronic spin polarization when they enter a weak magnetic field in which the hfs coupling is reestablished. The achievable polarization depends on the nuclear spin I and is given by

$$P_{\mathrm{Li}} = (1 + 2I)^{-1} \tag{8}$$

For lithium-6 with $I = 1$ it follows that $P_{\mathrm{Li}} \leq \frac{1}{3}$. The reduced polarization consider-

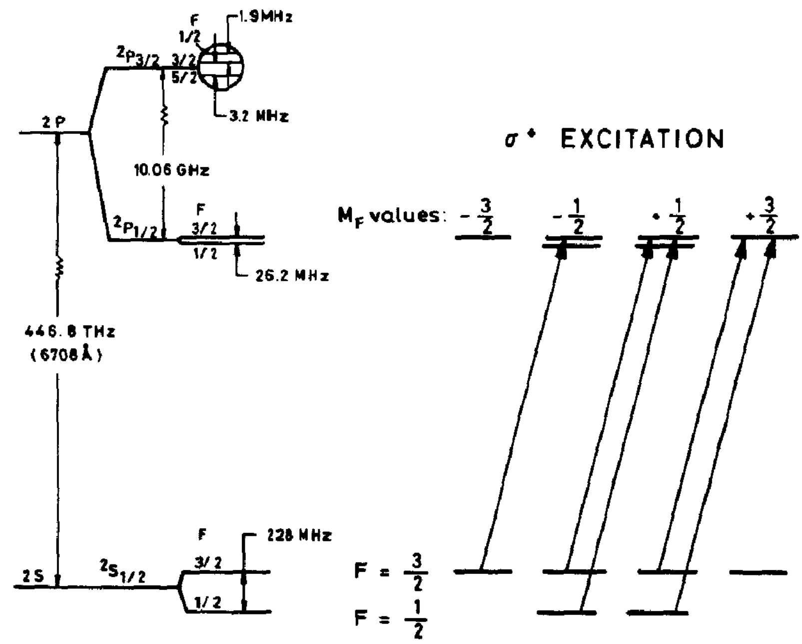

Figure 3. Energy-level diagram of lithium-6 and illustration of the relevant σ^+ excitations in the optical-pumping process which help to transfer the atoms into the ground-state sublevel ($F = \frac{3}{2}$, $M_F = +\frac{3}{2}$). Since the hfs components of the $P_{1/2}$ state are not resolved, excitations to the $F = \frac{1}{2}$ sublevels (not shown in figure) also participate in the pumping process.

ably decreases the experimental sensitivity. Both disadvantages can be avoided by employing the optical pumping method; it can, in principle, yield an easily reversible spin polarization close to unity.

The essence of the optical pumping method is to use the M dependence of the absorption and emission of circularly polarized resonance light to create an orientation in the ground state in which all spins are either parallel or antiparallel to the direction of the incoming radiation. In the case of lithium, the process is complicated by the hyperfine-structure interaction. Nevertheless, the pumping can still be accomplished provided a single-isotope beam is used and pumping transitions from both hyperfine levels can be equally induced.[10] Figure 3 depicts the energy levels of the ground state and first excited state of lithium-6, as well as the absorption processes which produce the orientation. By using a single-mode dye laser, bandwidth ~ 50 MHz, for exciting the lithium D_1 ($2S_{1/2} \rightarrow 2P_{1/2}$) transition we resolve the hyperfine structure of the ground state. We do not resolve the hyperfine splitting of the $2P_{1/2}$ state, but this is not of any disadvantage for the pumping process.

The lithium atomic beam system is similar to that described previously;[9] its relevant characteristics are listed in Table 2. The laser is tuned to the desired transition and maintained there using a microprocessor-controlled stabilization circuit similar to a scheme described by Düren and Tischer.[11] In order to be able to pump both hyperfine levels of the ground state, we split off a part of the laser beam by diffraction from an acousto-optical modulator operating at 228 MHz, thus creating two light beams with exactly the frequency difference corresponding to the hfs separation. In general, the light beam corresponding to the zeroth-order diffraction max-

Table 2. Characteristics of Polarized Atomic Beam System

Li oven	
Operating temperature	900°C
Li content	200 g
Running time	60 h
Heating power	1 kW
Orifice diameter	1.5 mm
Laser (Spectra-Physics Model 375 dye laser pumped by Model 164 argon ion laser)	
Light power	~20 mW cw
Frequency stabilization	5 MHz
Intensity ratio of light beams corresponding to zeroth and first-order diffraction from the acousto-optical modulator	4 : 1
Atomic beam at scattering region	
Cross section	7 mm²
Intensity	$>10^{14}$ atoms/sec
Mean atom velocity	2×10^5 cm/sec

imum is tuned to pumping of the $F=\frac{1}{2}$ level, and the laser is stabilized there; the light beam diffracted in first order by the acousto-optical modulator excites the $F=\frac{3}{2}$ component. This allows us to vary the relative power in each beam by simply varying the power delivered to the crystal. After being split, the two light beams are reflected by mirrors such that they are converging, then they are expanded cylindrically, passed through the quarter-wave plate, and brought to a common focus along the lithium beam (see Figure 4). We adjust the crystal so that both scattered

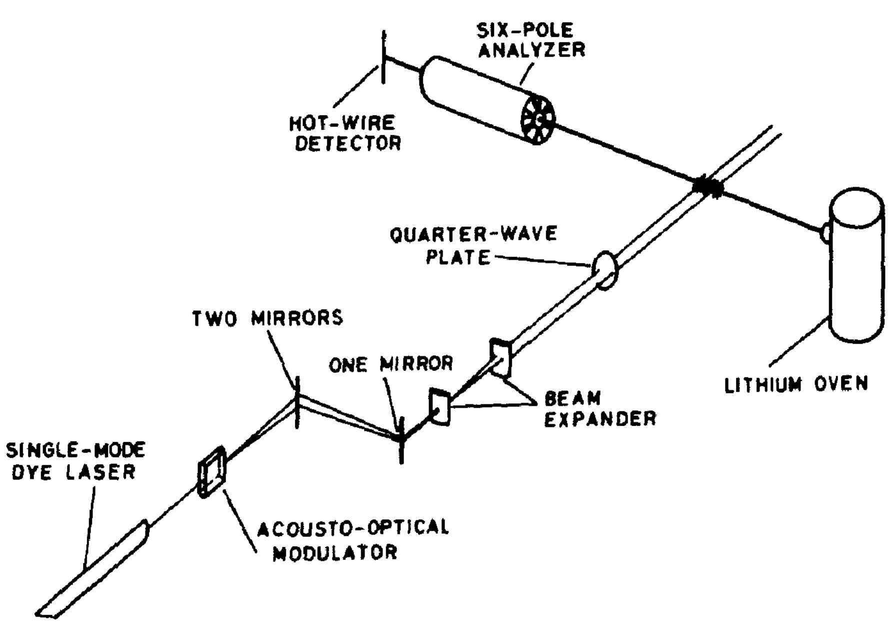

Figure 4. Schematic drawing of the laser light setup used for optical pumping.

and unscattered light beams lie in a plane perpendicular to the lithium beam, thus ensuring that any Doppler shift in the absorption will be in the same direction for both.

The lithium polarization is analyzed by transmitting the beam through a six-pole magnet following the pumping zone. At the exit of the six-pole magnet, the beam intensity is monitored with an oxidized-tungsten hot-wire detector. By using the intensity I_0 of an unpolarized beam as a reference signal, one can determine the polarization achieved by pumping alternatingly with σ^+ and σ^- light and measuring the intensities I^+ and I^-, respectively. Ideally, one would get for complete pumping $I^+ = 2I_0$ and $I^- = 0$. For incomplete pumping the polarization can be estimated according to

$$P_{\min} \leq P \leq P_{\max} \tag{9}$$

with

$$P_{\min} = (I^+ - 3I^- - 2I_0)/6I_0 \tag{10}$$

and

$$P_{\max} = (3I^+ - 2I^-)/6I_0 \tag{11}$$

The degree of polarization that we will ultimately obtain with this method is not yet precisely predictable as there are still a number of factors that have to be optimized. The polarization appears to depend sensitively on parameters such as relative intensity of the two laser beams and amount of laser beam expansion over

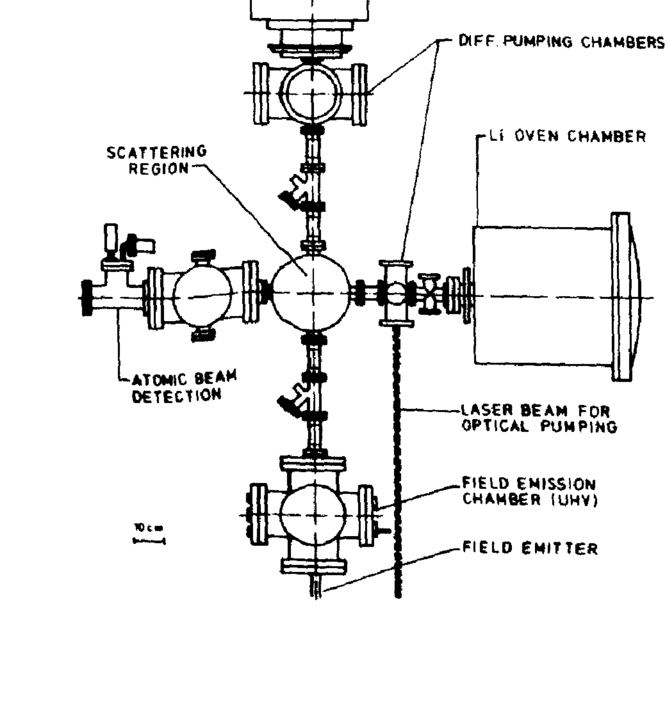

Figure 5. Layout of the apparatus of the *e*–Li scattering experiment.

the lithium beam, as well as on more common parameters such as laser intensity, retardance of the quarter-wave plate, etc. At this stage, the degree of polarization we obtain lies between $P_{min} = 0.57$ and $P_{max} = 0.69$ for a lithium beam intensity of $\approx 4 \times 10^{13}$ atoms per second.

The layout of the *e*–Li scattering experiment is shown in Figure 5. The scattering chamber is now being assembled. The crossed beams lie in the horizontal plane. The spin polarization of the ^{6}Li atoms is preserved by a weak magnetic guiding field oriented parallel to the atomic beam. At the scattering region the electron polarization is transverse to the electron beam direction; it lies in the horizontal plane parallel to atom polarization and atomic beam. The electron beam is slightly curved owing to the weak transverse magnetic field of about 20 mG. In the impact ionization experiment the Li^+ ions produced will be drawn out and accelerated toward the detector. In the differential scattering experiment the detector will be positioned at various scattering angles. The scattering plane lies in the vertical plane, orthogonal to the atomic beam.

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