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Electron-Atom Collision Studies Using
Optically State Selected Beams

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I. Introduction

This report discusses progress made during the current contract period on our research program to study collisions between spin-polarized electrons and optically prepared atoms. The objective of this work is to stimulate a deeper theoretical understanding of the electron-atom interaction by providing more complete experimental measurements on colliding systems. By preparing the internal states of the collision partners before scattering, we are able to extract substantially more information about the scattering process than is available from more conventional measurements of differential cross sections. We are principally interested in observing the role played by spin in low energy electron-atom collisions. The additional information provided by these spin-dependent measurements can greatly enhance our understanding of both exchange and the spin-orbit interaction in the scattering process.

We have made substantial progress in the past three years in our measurements both of elastic and superelastic scattering of spin-polarized electrons from optically pumped sodium. Our major accomplishments in the current contract year include:

- ◄► Determination, at an incident energy of 54.4 eV, of a spin asymmetry in elastic scattering which requires both exchange and the continuum spin-orbit interaction to be simultaneously important.
- ◄► Measurement of angular momentum transfer in superelastic scattering at 52.3 eV, corresponding to an incident energy for inelastic scattering of 54.4 eV.
- ◄► Investigation of a predicted autoionizing resonance in the total ionization cross section for sodium at incident energy of about 32 eV.
- ◄► Investigation of possible a possible sensitivity of channel electron multipliers to the spin orientation of incident electrons.¹

Major accomplishments described in the previous two annual progress reports include:

- ◀ Detailed measurements of the spin dependence in low-energy superelastic scattering of electrons from optically excited sodium atoms.²⁻⁴
- ◀ Development of a new theoretical framework with which to describe experiments that include preparation of the initial states.⁵
- ◀ Detailed studies of spin asymmetries arising from exchange and the spin-orbit interaction in elastic scattering from sodium at an incident energy of 54.4 eV.⁶

Each of these accomplishments will be discussed in the following sections. Primary emphasis in this report will be on work completed in the current year, but a brief summary of work described in the previous two annual reports is included for the sake of completeness.

We begin in Section II with a brief summary of our results for superelastic scattering from optically prepared sodium (*3P*). Section III discusses results of our studies of spin dependence in elastic scattering at 54.4 eV incident energy. New results presented include a determination of the "joint" asymmetry which tests for the simultaneous action of exchange and the spin-orbit effects, and preliminary results of superelastic scattering at 52.3 eV, corresponding to inelastic scattering at 54.4 eV incident energy. In Section IV we discuss results from a preliminary investigation of autoionizing resonances predicted to appear in the electron impact ionization cross section. Section V covers a study undertaken to probe the spin sensitivity of channel electron multipliers. Section VI contains bibliographic references and Sections VII and VIII contain lists of our recent publications and presentations, respectively.

II. Superelastic Scattering From Optically Pumped Sodium.

Superelastic electron scattering is the time reverse process to inelastic electron scattering. Electrons are scattered from atoms that have been prepared in an excited state, with detection only of scattered electrons having gained the excitation energy of the atoms. Specifically, we study the process

The main result obtained from this study is new and more detailed information about the inelastic scattering events resulting in transitions between the ground ($3S$) state and the excited ($3P$) state. Previous progress reports and recent publications²⁻⁵ have discussed the experimental details of our measurements and the theoretical framework we have developed on order describe our results. These details will not be repeated here, but the results will be summarized.

We describe⁵ the scattering as taking place in one of two independent scattering channels, corresponding to the two net spins into which the initial spins may couple. These channels are described by two independent sets of complex scattering amplitudes. Because of symmetries inherent in the scattering process, we choose to express these amplitudes in the so-called "natural" coordinate system, which has its quantization axis perpendicular to the scattering plane. This system is chosen because only angular momentum perpendicular to the scattering plane can be transferred to the atom in the collision.

In experiments such as ours in which initial states of the colliding pair are prepared prior to collision, but no analysis of final states is performed after collision,

the scattering process is completely characterized by what we refer to as scattering matrices, t and s , which describe scattering in the independent triplet and singlet channels, respectively.⁵ These are 3×3 matrices with rows and columns labeled by $\Delta M_L = +1, 0$, and -1 . When expressed in the "natural" frame, these matrices take on a particularly simple form, with the only non-zero elements being t_{11} , t_{-1-1} , and $t_{1-1} = t_{-11}^*$ for the triplet, and similarly for the singlet matrix. These matrix elements have a very simple interpretation. For example, t_{11} determines the partial cross section for excitation from the ground state, and via the triplet channel, of the $M_L = +1$ sublevel of the first excited state. Similarly, coherent excitation of the $M_L = +1$ and -1 sublevels, via the singlet channel, is described by $s_{1-1} = s_{-11}^*$.

Description of the initial state of the colliding system involves specifying the spin polarization of the incident electron and the optical pumping of the excited atom.⁷⁻⁸ The electron spin polarization is characterized by its components, P_x , P_y , and P_z , along the three coordinate axes. The initial state of the atom is described by a 6×6 density matrix with rows and columns labeled by (M_L, M_S) . We have given explicit expressions for the elements of this matrix for very general conditions of optical pumping.⁵ The elements of this matrix are determined by optical pumping parameters which correspond to multipole moments of the excited state. For convenience, we have also partitioned this matrix into four sub-matrices, σ_0 , σ_x , σ_y , and σ_z . These 3×3 matrices, with rows and columns labeled by $M_L = +1$ and -1 , describe the angular momentum and spin properties of the excited atom.

The scattering matrices and the initial state descriptions can be combined into a general expression with which to predict scattering intensities for very general experimental configurations and initial state preparations.⁵ Specifically,

$$I = \frac{C}{4} \left[\begin{aligned} & \text{Tr} [\sigma_0(3\mathbf{t} + \mathbf{s})] + \\ & P_x \text{Tr} [\sigma_x(\mathbf{t} - \mathbf{s})] + \\ & P_y \text{Tr} [\sigma_y(\mathbf{t} - \mathbf{s})] + \\ & P_z \text{Tr} [\sigma_z(\mathbf{t} - \mathbf{s})] \end{aligned} \right] \quad (2)$$

Here the constant C contains all purely geometric factors such as target and projectile densities, beam overlaps, detector efficiencies, etc.

This equation contains all of the basic information needed to make decisions about how best to prepare the electron and atom in order to extract specific information about the matrices $\mathbf{t}$ and $\mathbf{s}$. Experiments with unpolarized electrons can extract information only about the matrix sum, $(3\mathbf{t} + \mathbf{s})$.⁹ The addition of electron spin polarization allows us to determine the matrix difference $(\mathbf{t} - \mathbf{s})$ as well. Because the same matrix difference appears in each term, one sees that spin polarization along any one direction is sufficient to extract all the information that is available from spin-polarized measurements. We choose to use spin polarization along the z -axis, perpendicular to the scattering plane. From inspection of Eq. 2, one notices that this makes the experiment sensitive to the matrix σ_z . A particularly simple form for σ_z is accomplished by optically pumping with circularly polarized light incident perpendicular to the scattering plane. Circularly-polarized excitation generates an excited atom whose orbital angular momentum and spin are both oriented perpendicular to the scattering plane. This corresponds to the matrix σ_z having only one non-vanishing element.

There are four different observable scattering signals which correspond to the four relative orientations of electron and atom polarizations. We denote these by $I^{R\uparrow}$, $I^{R\downarrow}$, $I^{L\uparrow}$, and $I^{L\downarrow}$, where R and L refer to the handedness of the circularly polarized light used to excite the sodium atoms, and $\uparrow$ and $\downarrow$ refer to electrons polarized parallel

or antiparallel to the scattering plane normal. From these four signals, one can derive⁵ four experimental quantities which are proportional to the non-zero diagonal elements of the scattering matrices, t and s :

$$T_{11} = \frac{1}{2} [(\frac{1}{|P_z|} + 1)I^{R\uparrow} - (\frac{1}{|P_z|} - 1)I^{R\downarrow}] \propto t_{11} \quad (3a)$$

$$T_{-1-1} = \frac{1}{2} [(\frac{1}{|P_z|} + 1)I^{L\downarrow} - (\frac{1}{|P_z|} - 1)I^{L\uparrow}] \propto t_{-1-1} \quad (3b)$$

$$S_{11} = \frac{1}{2} [(\frac{3}{|P_z|} + 1)I^{R\downarrow} - (\frac{3}{|P_z|} - 1)I^{R\uparrow}] \propto s_{11} \quad (3c)$$

$$S_{-1-1} = \frac{1}{2} [(\frac{3}{|P_z|} + 1)I^{L\uparrow} - (\frac{3}{|P_z|} - 1)I^{L\downarrow}] \propto s_{-1-1} . \quad (3d)$$

Because of difficulties associated with the absolute measurements necessary to extract the scattering matrix elements directly, it is worthwhile to define relative quantities which, together with one absolute measurement of the spin and orientation averaged differential cross section, are sufficient to completely determine the scattering matrices. Similarly to the case of scattering with unpolarized electrons,⁹ we extract the angular momentum transferred to the atom, separately now for the singlet and triplet scattering channels. We also extract the ratio, r , between the singlet and triplet contributions to the scattering. These three quantities are defined by⁵

$$L_{\perp}^t = \frac{T_{11} - T_{-1-1}}{T_{11} + T_{-1-1}} = \frac{t_{11} - t_{-1-1}}{t_{11} + t_{-1-1}} \quad (4a)$$

$$L_{\perp}^s = \frac{S_{11} - S_{-1-1}}{S_{11} + S_{-1-1}} = \frac{s_{11} - s_{-1-1}}{s_{11} + s_{-1-1}} \quad (4b)$$

$$r = \frac{T_{11} + T_{-1-1}}{S_{11} + S_{-1-1}} = \frac{t_{11} + t_{-1-1}}{s_{11} + s_{-1-1}} \quad (4c)$$

and contain all the information one can obtain from the relative measurements of the four quantities $I^{R\uparrow}$, $I^{R\downarrow}$, $I^{L\uparrow}$, and $I^{L\downarrow}$.

We have measured these three quantities as a function of scattering angle at two fixed incident energies of 2.0 and 9.26 eV, and as a function of incident energy at a scattering angle of 30° .^{2-3,5} The results are shown in Figs. 1-6. In all figures, the solid points are the experimental results with error estimates of one standard deviation from counting statistics. Figs. 1 and 2 show the results at 2.0 eV incident energy. From Fig. 1, one sees that angular momentum is generally more effectively transferred through the triplet than through the singlet scattering channel. In either case, the

Fig. 1. Angular momentum transferred at incident energy of 2.0 eV, corresponding to inelastic energy of 4.1 eV. Theoretical results are the four-state close-coupling calculation of Ref. 10. Triplet channel (● experiment; — theory); Singlet channel (□ experiment; --- theory). Error bars are one standard deviation from counting statistics.

(Moore & Haines (1972))

angular momentum transfer peaks at about 35° , perhaps slightly earlier for singlet than for triplet. The data for the triplet channel are consistent with complete angular momentum transfer of $L_\perp = 1\hbar$ at a scattering angle of 35° . Thus, excitation of $\text{Na}(3S)$ into the $3P$ -state by pure triplet scattering would leave the excited atom in a D state, showing a pronounced minimum in the angular momentum transfer near 90° . Angular momentum transfer for the triplet channel remains large, ≥ 0.5 , throughout most of the angular range. The four-state close-coupling results of Moores and Norcross¹⁰ are included in Fig. 1 for comparison. The agreement is reasonably good at angles less than 90° . For angles greater than 90° , there is a marked discrepancy in the triplet channel between theory and experiment. It is perhaps interesting to note that while theory predicts the angular momentum transfer for the triplet channel quite well at forward angles, with most discrepancy in the singlet channel, the situation is reversed for larger angles.

The ratio of triplet to singlet scattering is shown in Fig. 2. In the forward scattering direction and for angles larger than 90° singlet scattering is roughly 30–40% greater than triplet scattering. But there is a pronounced peak in this ratio at about 65° where triplet becomes about 50% larger than singlet. The four-state close-coupling results are in excellent agreement with the experimentally determined cross section ratio in this energy and angular range.

Fig. 2. Ratio of triplet to singlet scattering at incident energy of 2.0 eV, corresponding to inelastic energy of 4.1 eV. Theoretical results are the Four-state close-coupling calculation of Ref. 10. (• experiment; — theory). Error bars are one standard deviation from counting statistics.

Our results for these parameters at an incident energy of 9.26 eV, presented in Figs. 3 and 4, show somewhat different behavior. Fig. 3 shows that the triplet angular momentum transfer peaks at smaller scattering angles and has a lower peak value than was seen at 2.0 eV incident energy. Though the data for L_1^S have more scatter, there is indication that the transfer efficiency may peak at an angle larger than 40° . In Fig. 4 we see that the triplet and singlet scattering cross sections are about equal at small angles, up to about 25° , with triplet dominating at larger angles. Also shown in the

Mc Donnell (1977)

Fig. 3. Angular momentum transferred at incident energy of 9.26 eV, corresponding to an inelastic energy of 11.36 eV. Theoretical results are the DWPO calculation of Ref. 11. Triplet channel (• experiment; — theory); Singlet channel (□ experiment; --- theory). Error bars are one standard deviation from counting statistics.

figures are the results of a distorted-wave polarized-orbital (DWPO) calculation.¹¹ While this calculation agrees reasonably well for $L_{\perp}^s$ and with $L_{\perp}^t$ at small angles, it does so at the expense of completely missing the overall trend toward triplet dominant scattering as the scattering angle increases.

Fig. 4. Ratio of triplet to singlet scattering at incident energy of 9.26 eV, corresponding to inelastic energy of 11.36 eV. Theoretical results are the DWPO calculation of Ref. 11. (• experiment; — theory). Error bars are one standard deviation from counting statistics.

At one scattering angle, 30° , we have made measurements as a function of incident energy from 1.3 eV to 12 eV. Fig. 5 shows that the general trend for more efficient transfer of angular momentum via the triplet channel is again evident. From Fig. 6, one sees that at incident energies below about 3 or 4 eV, the singlet cross section is seen to dominate, with triplet becoming dominant at higher energies. The results of both theoretical calculations are shown, where available, for comparison with the data. At low incident energies, below 2.9 eV, the close-coupling calculation¹⁰ shows very reasonable agreement, with significant discrepancy only for the singlet angular momentum transfer. At incident energies above 3 eV the DWPO results¹¹

may be used for comparison. While the agreement for $L_{\perp}^s$ is seen in Fig. 5 to be quite reasonable, the qualitative behavior for $L_{\perp}^t$ is rather different from that seen in the

Fig. 5 Angular momentum transferred at scattering angle of 30° . Energy scale is the superelastic incident energy, so 2.1 eV would be added for comparison with inelastic results. Theoretical results are the four-state close-coupling calculation of Ref. 10 up to 2.9 eV, and the DWPO calculation of Ref. 11 thereafter. Triplet channel ($\bullet$ experiment; — theory); Singlet channel ($\square$ experiment; --- theory). Error bars are one standard deviation from counting statistics.

experiment. Further, Fig. 6 shows that the calculation substantially underestimates the relative contribution of triplet scattering to the cross section.

Fig. 6 Ratio of triplet to singlet cross sections at scattering angle of 30° . Energy scale is the superelastic incident energy, so 2.1 eV would be added for comparison with inelastic results. Theoretical results are the four-state close-coupling calculation of Ref. 10 up to 2.9 eV, and the DWPO calculation of Ref. 11. thereafter. (● experiment; — theory). Error bars are one standard deviation from counting statistics.

We have also made preliminary measurements of superelastic scattering at an incident energy of 52.3 eV. This is equivalent to studying inelastic scattering at an incident energy of 54.4 eV, and we present the results in the following section along with results of elastic scattering at the same incident energy.

III. Elastic Scattering from Spin-Polarized Sodium.

The scattering of electrons from one-electron atoms is one of the most fundamental systems to investigate in the effort to better understand scattering processes in general. We have chosen to study sodium because, with its single valence electron outside a rather tightly bound and inert core, it provides a close approximation to an ideal one-electron system. Further, because the dipole polarizability in sodium is so strongly dominated by $3S-3P$ coupling, any theoretical treatment which correctly accounts for this coupling, such as close-coupled calculations, would be expected to predict very nearly correct cross sections for collisions involving the ground state. In this sense, sodium should be a near ideal system for testing the reliability of theoretical calculations.

Unfortunately, for the case of elastic scattering at intermediate energies of several times the ionization threshold, the status of theory is not so good.¹²⁻¹³ For incident energy of 54.4 eV, results of a four-state close-coupling calculation show marked disagreement with experimental determinations of the elastic differential scattering cross section for angles larger than about 40° .¹² The source of the disagreement is not at present understood, and the apparent inability of current theoretical methods to accurately predict cross sections for such an "ideal" system as sodium should be cause for some concern.¹³

In order to provide more detailed information for investigating possible sources of this discrepancy, we have measured the angular dependence of spin asymmetries in elastic scattering of spin-polarized electrons from spin-polarized sodium atoms. This study represents the first systematic measurement of these types of effects. Some of this work was reported in the previous annual report and in a recent publication.⁶ One

interesting outcome of our study was the observation that spin-orbit effects contribute about the same amount to the cross section as do exchange effects, at least at some scattering angles.

In our experiments, there are four different scattering intensities $I^{\uparrow\uparrow}$, $I^{\downarrow\downarrow}$, $I^{\uparrow\downarrow}$, and $I^{\downarrow\uparrow}$, corresponding to the four relative spin orientations of the incident electron and atom, which represent all the information one can obtain in an elastic scattering experiment without analysis after collision of the spin of the scattered electron or atom. We find it useful to derive from these intensities three relative quantities which, together with the determination of the spin averaged differential cross section, comprise a complete measurement. Many sources of systematic error are removed by the self-normalization inherent in the spin asymmetries we determine. We define the following three spin asymmetries:

$$A^{exch} = \frac{1}{P_e P_a} \frac{(I^{\uparrow\downarrow} + I^{\downarrow\uparrow}) - (I^{\uparrow\uparrow} + I^{\downarrow\downarrow})}{(I^{\uparrow\downarrow} + I^{\downarrow\uparrow}) + (I^{\uparrow\uparrow} + I^{\downarrow\downarrow})}, \quad (5a)$$

$$A^{so} = \frac{1}{P_e} \frac{(I^{\uparrow\uparrow} + I^{\downarrow\downarrow}) - (I^{\uparrow\downarrow} + I^{\downarrow\uparrow})}{(I^{\uparrow\uparrow} + I^{\downarrow\downarrow}) + (I^{\uparrow\downarrow} + I^{\downarrow\uparrow})}, \quad (5b)$$

$$A^{joint} = \frac{1}{P_e} \frac{(I^{\uparrow\uparrow} + I^{\downarrow\downarrow}) - (I^{\uparrow\downarrow} + I^{\downarrow\uparrow})}{(I^{\uparrow\uparrow} + I^{\downarrow\downarrow}) + (I^{\uparrow\downarrow} + I^{\downarrow\uparrow})}. \quad (5c)$$

where P_e and P_a are the degrees of polarization of the electron and atom beams, respectively.

The first asymmetry, A^{exch} , is the normalized difference between antiparallel and parallel intensities, averaged over "up" and "down" orientations. Although its value is influenced by the spin-orbit interaction, we refer to it as the "exchange" asymmetry because, it reduces to the pure exchange asymmetry in the absence of a spin-

orbit interaction and it vanishes in the absence of exchange. The spin-orbit asymmetry, A^{so} , is the normalized difference between incident electron spin "up" and spin "down" intensities, averaged over atomic spin orientations. Its value, though influenced by exchange, reduces to the conventional spin-orbit asymmetry in the absence of exchange, and vanishes if there is no spin-orbit interaction.

The final asymmetry, A^{joint} , is the normalized difference between scattering from "up" and "down" atoms, averaged over the incident electron spin. This asymmetry is so-named because it is nonzero only if both exchange and the spin-orbit interaction are simultaneously present.¹⁴

Fig. 7. Exchange asymmetry A^{exch} , as defined in Eq. 5a, vs. scattering angle. Theory (— two-state close-coupling calculation of Ref. 12; --- four-state close-coupling calculation of Ref. 15). Error bars are one standard deviation from counting statistics and do not include an overall scale uncertainty of $\pm 6\%$ of the asymmetry value.

In Fig. 7, we show the experimental exchange asymmetry A^{exch} . The most notable features are a broad negative peak of about -4% in the angular range from 30° to 60° , and a fairly sharp structure at about 108° , the minimum of the differential cross section. The broad negative feature indicates that triplet scattering dominates in that angular range.

Also shown for comparison in Fig. 7 are the two-state close-coupling results of Mitroy *et al*,¹² indicated by the solid line, and the four-state close-coupling results of Oza,¹⁵ indicated by the dashed line. The two calculations are in quite good mutual agreement, but quite significant discrepancies are seen between the theories and the experiment. In a qualitative sense there is similar behavior, in that 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. The source of the discrepancy is not yet understood, and further theoretical work will be required for its resolution.

We have also measured the spin-orbit asymmetry, A^{SO} , and the results are shown in Fig. 8. Here we see that this asymmetry has structure which is typical of asymmetries near a cross section minimum, indicating that the spin "up" and spin "down" cross sections have their minima at different scattering angles. The effect of the spin-orbit interaction on the scattering cross section, a few percent of the differential cross section, is roughly as large as the effect of exchange.

For theoretical comparison, we show in Fig. 8 an asymmetry from the fully relativistic static-potential calculation of Gregory and Fink.¹⁶ This shows quite good qualitative agreement with the data, although the measured spin asymmetry is somewhat larger in magnitude at the extreme values, and the angular position of the zero crossing is somewhat different.

Fig. 8. Spin-Orbit asymmetry A^{so} , as defined by Eq. 5b, vs. scattering angle. Theory (—) is the relativistic static-potential calculation. Error bars are one standard deviation from counting statistics and do not include an overall scale uncertainty of $\pm 6\%$ of the asymmetry value.

Though theoretical results are shown for comparison with both A^{exch} and A^{so} , we note that none of the theories are complete, because the close-coupling calculations predict no spin-orbit asymmetry, and the relativistic calculation predicts no exchange asymmetry. 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.¹⁷

When both exchange and spin-orbit effects are present, the third asymmetry, A^{joint} , need not vanish. Indeed, it has been suggested that this asymmetry could serve as an indicator for the presence of spin-orbit effects in situations where spin effects are dominated by exchange.¹⁴ Because our measurements show that both exchange and spin-orbit effects are in fact present at a scattering angle of 120° , we

have made preliminary determination of A^{joint} , with the results shown in Fig. 9. The experimental errors are as yet too large for conclusive interpretation, but the effect is

Fig. 9. Joint asymmetry A^{joint} , as defined by Eq. 5c, vs. scattering angle. Error bars are one standard deviation from counting statistics.

at best small at this incident energy. There are at present no theoretical predictions about the expected size of this effect for any scattering system. As our research progresses, we will continue to look for situations where this asymmetry is important. For example at lower incident energy, exchange plays a significantly more important role and the larger exchange effects could increase the size of the joint asymmetry.

One significant advantage of our experimental approach is that for each incident energy, we can measure not only the elastic contribution to scattering, but the dominant inelastic scattering channel as well. That is accomplished by measuring

superelastic scattering at an incident energy 2.1 eV below the incident energy for elastic scattering. Because of the unexpected discrepancy between theory and experiment for elastic scattering at 54.4 eV, we have begun an investigation of the corresponding inelastic scattering. We present in Fig. 10 our measurements of the angular momentum transfer, $L_{\perp}$, not resolved into the individual spin channels. The results of a two-state close-coupling calculation¹² are also shown for comparison. The agreement is quite good, particularly for the overall qualitative features. As the theoretical analysis is not yet complete, we can draw no specific conclusions at this time.

Fig. 10 Angular momentum transfer at 52.3 eV incident energy, corresponding to an inelastic incident energy of 54.4 eV. Theoretical results are two-state close-coupling results from Ref. 12. (• experiment; — theory). Error estimates are one standard deviation from counting statistic

The most significant aspect of these studies at 54.4 eV is that we have substantially increased the number of experimentally observed parameters, and hence have provided significantly more ground for comparison between experiment and theory. Future work of this type at other energies for Na and on other alkalis (as polarization methods permit) should provide a wealth of new information, and hopefully will generate the decisive material for resolving at least a few theoretical controversies.

IV. A Closer Look at Electron Impact Ionization of Sodium.

In the past year we also returned briefly to the investigation of electron impact ionization of sodium. The motivation this time was to conduct feasibility studies on the possibility of observing some predicted resonance features. Clark and Buckman¹⁸ have pointed out the strong similarity in the configurations of the negative ions Ne^- ($2p^5 3s 3p$) and Mg^- ($2p^6 3s^2 3p$). Each consists of a two or three electron $3s$ – $3p$ configuration bound to a $2p$ core. A similar configuration is seen in the recently predicted¹⁹ and observed²⁰ bound state of Ca^- . The sodium negative ion should also have a configuration of this type, *i.e.*, $2p^5 3s^2 3p$. This state would have an energy slightly above the $3p^5 3s^2$ state of neutral sodium, or around 32 eV. Since it is autoionizing, its existence could conceivably be detected as a resonance-like feature in the ionization cross section.

We measured the electron impact cross section with extremely high precision over the energy range 27 to 36 eV with the hope of observing such a feature. Because the observed features were small compared to the background of direct electron impact ionization, a low-order polynomial was subtracted from the measurements. The difference is shown in Fig. 11, with the error estimates indicating one standard deviation from counting statistics. Structure in the cross section is clearly visible in the 31–34 eV region, suggesting that resonances of the type suggested may indeed exist. For reference, the relevant excited states of neutral sodium are marked in the figure.

These preliminary results are encouraging because they are consistent with the existence of predicted resonance features, though more definitive measurements are clearly needed. It is expected that the additional information available from the spin

dependence of these features will allow us to investigate the spin character of autoionizing resonances of this type in further detail. We hope to continue experiments of this type as part of our ongoing program over the next few years.

Fig. 11 Total ion yield for electron impact ionization of sodium, after subtracting a smooth background from the data. Error estimates are one standard deviation from counting statistics. The solid curve is to guide the eye. Positions of excited atomic states of neutral sodium are marked.

V. Investigation of the Spin Sensitivity of Channel Electron multipliers.

Channel electron multipliers (CEMs) have become important and common detectors in a broad range of applications, especially those involving the detection of electrons. Many of these investigations, in particular electron-atom and electron-surface scattering experiments, are being extended to include polarized electron beams and detectors of electron spin-polarization. In all experiments to date, the CEMs have been assumed insensitive to the spin of the incident electron.

One motivation for the present study was the suggestion that a spin-sensitive detector could explain a very troubling observation in an investigation by Register, *et al*,²¹ of electron scattering from laser excited barium. They discovered an asymmetry in the scattered electron intensity, as a function of the polarization direction of the incident laser, which violated very basic symmetry principles. Because such an asymmetry could arise from a spin dependence in the detection efficiency of the scattered electrons,²² a direct test of the CEM spin sensitivity appeared desirable.

The potential for spin sensitivity in a CEM can be seen from a consideration of its operating principles. A CEM functions as a detector and amplifier through the process of secondary electron emission.²³ An electron incident on the inside surface of the front cone will be detected if it causes the emission of secondary electrons, which are accelerated by a high voltage placed across the resistive CEM until they again strike the CEM surface, causing further secondary emission. The process is repeated several times with the final gain being the product of the secondary emission yields. The secondary yield is largely dependent on the primary electron energy, incidence

angle, and CEM material. If the initial yield were dependent on the spin direction of the incident electron, the CEM gain would be spin sensitive.

Spin-dependent interactions between electrons and solid surfaces are well known for both magnetic targets, where the exchange interaction plays a role, and high-Z materials, where the spin-orbit interaction becomes significant.²⁴ Although CEMs are fabricated from non-magnetic (glass), eliminating exchange as the source of spin dependence, they do have a heavy lead doping²³ which could give rise to a spin sensitivity through the spin-orbit interaction. Spin-orbit effects in scattering from solids can be dramatic. For example, in low energy electron diffraction from tungsten,²⁵ the coefficient for the specular reflection of electrons with one spin orientation can be as much as nine times that of oppositely oriented electrons.

If the spin-orbit interaction produces an enhanced cross section for scattering to the right for spins oriented up, then oppositely oriented electrons will have an equally enhanced cross section for scattering to the left.²⁴ This sorting to the right or left could cause an electron, obliquely incident at a surface, to penetrate the surface more or less deeply depending on its spin orientation. Because the probability of low energy electrons escaping and becoming secondaries depends upon the depth from which they originate, the yield might depend upon the spin orientation of the incident electrons. We therefore looked for a difference in the CEM gain for spin up and spin down incident electrons when the beam struck the side of the cone at an angle of $\approx 70^\circ$ with respect to the surface normal.

The primary observable was the spin asymmetry, A_{cem} , defined by the usual relationship:

$$A_{cem} = \frac{1}{P_e} \frac{I_{\uparrow} - I_{\downarrow}}{I_{\uparrow} + I_{\downarrow}} \quad (6)$$

where $I_{\uparrow}$ ($I_{\downarrow}$) is the signal intensity for spin up (down) electrons, and P_e is the incident electron polarization, determined to be $23\% \pm 2\%$. The asymmetry was measured in both the pulse and analog modes of operation. In the pulse mode the CEM was operated with a reduced high voltage which resulted in an unsaturated pulse height distribution. If the pulse height distribution were saturated, variations in the initial secondary yield arising from spin effects would be masked because all pulses would have nominally the same saturated height and hence would have the same probability of detection. The discriminator setting was chosen by selecting a region of the pulse height distribution where pulse height variations would cause greatest change to the count rate. This somewhat unconventional setup was used in order to enhance the changes in count rate due to a spin dependent gain.

Measurements were made at several incident positions on the CEM cone. For all measurements, the observed asymmetries were less than 0.5% . Furthermore, successive measurements of the asymmetries on the left and right sides of the cone never differed by more than 0.05% . We conclude from this that the sensitivity of the CEM to the spin of an incident electron is certainly less than 0.5% , and perhaps even smaller.

Though we have considered only one energy, angle of incidence, and cone bias, and can not completely discount the possibility of larger spin dependencies in other modes of operation, it is unlikely that much larger effects could be found. We feel, therefore that CEM's can be assumed insensitive to incident spin, at least at the 0.5% level. While this eliminates a much desired resolution to the situation concerning laser-excited barium, it is a reassuring result for experimental efforts such as ours where spin insensitivity is assumed.

One further benefit to us of this study was an overall improvement in our electro-optic modulation of the circular polarized light which we routinely use to produce spin-polarized electrons. Because any intensity modulation of the laser resulting from the circular polarization modulation would produce spurious signals indistinguishable from the CEM spin sensitivity under investigation, extreme care was required for alignment of the optical system. We were able to significantly reduce measurement uncertainties related to such spurious intensity modulations. This will allow us in the future to reliably investigate even smaller spin effects.

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VII. Publications.

A. Publications in the current contract year

I. V. Hertel, M. H. Kelley, and J. J. McClelland, "Analysis of Collisional Alignment and Orientation Studied by Scattering of Spin-Polarized Electrons from Laser Excited Atoms", Z. Phys. D6 163-183 (1987).

J. J. McClelland, M. H. Kelley, and R. J. Celotta, "Large Angle Superelastic Electron Scattering", J. Phys. B20, L385-L388 (1987).

J. J. McClelland, M. H. Kelley, and R. J. Celotta, "Spin-Orbit and Exchange Effects in Low Energy Elastic Spin-Polarized Electron Scattering from Spin-Polarized Na", Phys. Rev. Lett. 58, 2198-2200 (1987).

I. V. Hertel, M. H. Kelley, and J. J. McClelland, "Analysis of Collisional Alignment and Orientation Studied by Scattering of Spin-Polarized Electrons from Laser Excited Atoms", Proceedings of ICPEAC XV (1987).

M. H. Kelley, J. J. McClelland, and R. J. Celotta, "Superelastic Scattering of Spin-Polarized Electrons from Optically Pumped Sodium", Proceedings of ICPEAC XV (1987).

M. H. Kelley, J. J. McClelland, and R. J. Celotta, "Elastic Scattering of Spin-Polarized Electrons from Spin-Polarized Na Atoms", Proceedings of ICPEAC XV (1987).

B. Manuscripts submitted for publication

R. E. Scholten, J. J. McClelland, M. H. Kelley, and R. J. Celotta, "Spin Sensitivity of a Channel Electron Multiplier", submitted to Rev. Sci. Instrum.

C. Publications in previous contract years

R. J. Celotta, "A Comparison of Electron Polarization Detectors", Proc. Int. Symp. on Polarization and Correlation in Electron-Atom Collisions, Münster, West Germany, 16 (1983).

M. H. Kelley, W. T. Rogers, R. J. Celotta, D. T. Pierce, "Spin Dependence in Electron Impact Ionization of Sodium", Proc. Int. Symp. on Polarization and Correlation in Electron-Atom Collisions, Münster, West Germany, 27 (1983).

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J. J. McClelland, M. H. Kelley, and R. J. Celotta, "Observation of Spin Dependencies in the Superelastic Scattering of Polarized Electrons by Na(3P)", Invited Papers of ICPEAC XIV, (1985).

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M. H. Kelley, J. J. McClelland, and R. J. Celotta, "Electron-Atom Collision Studies Using Optically State Selected Beams", Proc. Int. Symp on Correlation and Polarization in Electron-Atom Collisions, Pasadena, CA, Aug. 1985.

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VIII. Presentations

A. Presentations in the current contract year

"Elastic Scattering of Spin-Polarized Electrons from Spin-Polarized Sodium", J. J. McClelland, 18th Annual Meeting of the Division of Atomic, Molecular and Optical Physics, Cambridge, MA, 18-20 May, 1987.

"Superelastic Scattering of Spin-Polarized Electrons from Optically Pumped Sodium (3P)", J. J. McClelland, 18th Annual Meeting of the Division of Atomic, Molecular and Optical Physics, Cambridge, MA, 18-20 May, 1987.

"Analysis of Collisional Alignment and Orientation Studied by Scattering of Spin-Polarized Electrons from Laser Excited Atoms", M. H. Kelley, Fifteenth International Conference on the Physics of Electronic and Atomic Collisions, Brighton, England, July 1987.

"Superelastic Scattering of Spin-Polarized Electrons from Optically Pumped Sodium", M. H. Kelley, Fifteenth International Conference on the Physics of Electronic and Atomic Collisions, Brighton, England, July 1987.

"Elastic Scattering of Spin-Polarized Electrons from Spin-Polarized Na Atoms", R. J. Celotta, Fifteenth International Conference on the Physics of Electronic and Atomic Collisions, Brighton, England, July 1987.

"Scattering of Spin-Polarized Electrons from Optically Pumped Sodium", Invited Colloquium, Dept. of Physics, Wesleyan University, Middletown, CT, October 1987.

"Scattering of Spin-Polarized Electrons from Optically Pumped Sodium", Invited Colloquium, Dept. of Physics, University of Kentucky, Lexington, KY, October 1987.

B. Presentations in previous contract years.

"Recent Advances in the Use of the Electron Spin Polarization Measurements," R. J. Celotta, Invited Colloquium, JILA and University of Colorado, Department of Physics, CO, April 13, 1982.

"Electron Spin Polarization Measurements: Applications in surface and Atomic Physics," R. J. Celotta, Physics Department Colloquium, University of Oregon, Eugene, OR, April 15, 1982.

"The Application of Electron Spin Polarization Measurements in Surface Physics and Atomic Physics," R. J. Celotta, Interdepartmental Physics Colloquium, Westinghouse Electric Corporation, Pittsburgh, PA, April 29, 1982.

"Use of Polarized Electrons in Atomic Physics" (Invited), R. J. Celotta, XI Yugoslav Summer School and International Symposium on the Physics of Ionized Gases, Dubrovnik, Yugoslavia, August 25, 1982.

"Polarized Electron scattering in Surface and Atomic Physics," R. J. Celotta, Physics Department Colloquium, City College of the City University of New York, September 22, 1982.

"The Use of Polarized Measurements in Electron Scattering from Atoms and Molecules" (Invited), R. J. Celotta, 1st U.S.-Japan Symposium on Electron-Molecule Scattering, California Institute of Technology, Pasadena, CA, October 28, 1982.

"Electron-Atom Collision Studies Using Optically State Selected Beams," R. J. Celotta, Atomic Physics Program Contractors' Workshop, Oak Ridge National Laboratory, Oak Ridge, Tennessee, April 21, 1983.

"A Comparison of Electron Polarization Detectors" (Invited), R. J. Celotta, International Symposium on Polarization and Correlation in Electron-Atom Collisions, Münster, Germany, July 25, 1983.

"Spin Dependence in Electron Impact Ionization of Sodium," M. H. Kelley, International Symposium on Polarization and Correlation in Electron-Atom Collisions, Münster, West Germany, July 1983.

"Electron-Atom Studies Using Optically State Selected Beams," M. H. Kelley, R. J. Celotta, and D. T. Pierce, Workshop on Atomic Physics, NBS, Washington, DC, 26-27 April 1984.

"Near-Threshold Measurements of Spin Dependence in Electron Impact Ionization," M. H. Kelley, 15th Annual Meeting of the Division of Electron and Atomic Physics, Storrs, Connecticut, 30 May 1984.

"Theoretical and Experimental Diagnosis of Optical Pumping in Sodium," J. J. McClelland and M. H. Kelley, 15th Annual Meeting of the Division of Electron and Atomic Physics, Storrs, Connecticut, 30 May 1984.

"Threshold Ionization and Inverse Photoemission," R. J. Celotta (Invited) New York University, Physics Colloquium, April 1984.

"Electron Polarization Spectroscopy — Recent Advances," (Invited), R. J. Celotta, Canadian Association of Physicists 1984 Congress, Sherbrooke, Canada, June 18, 1984, Bull. Can. Assoc. of Physicists 40, 18 (1984).

"Polarized Electrons: Recent Advances," R. J. Celotta, Meeting of Latin American Surface Scientists, Oaxaca, Mexico, October 10, 1984.

"Electron-Atom Collision Studies Using Optically State Selected Beams," M. H. Kelley, Invited Colloquium, Atomic and Molecular Physics, Institute of Physics, Belgrade, Yugoslavia, 31 August 1984.

"Spin Dependence in Near Threshold Electron Impact Ionization," M. H. Kelley, XII Yugoslav Summer School and International Symposium on the Physics of Ionized Cases, Sibenik, Yugoslavia, 3-7 September 1984.

"Collision Studies Using Optically State Selected Beams," M. H. Kelley, Invited Colloquium on Atomic and Molecular Physics, Institute of Atomic and Molecular Physics, National Research Council of Italy, Pisa, Italy, 24 September 1984.

"Spin Polarized Electrons," R. J. Celotta, Physics Colloquium, Pennsylvania State University, University Park, PA, 6 December 1984.

"Spin Dependent Interactions in Superelastic Electron-Sodium Scattering," R. J. Celotta, DOE Atomic Physics Contractors' Workshop, University of North Carolina, Chapel Hill, NC, May 14, 1985.

"Optical Pumping in Sodium: An Experimental and Computational Investigation," J. J. McClelland, 16th Annual Meeting of the Division of Electron and Atomic Physics, Norman, OK, 30 May 1985.

"Diagnosis of Spin Polarization in an Optically Pumped Sodium Beam," M. H. Kelley, 14th International Conference on the Physics of Electronic and Atomic Collisions, Palo Alto, CA, July 1985.

"Electron-Atom Collision Studies Using Optically State Selected Beams: Superelastic Scattering," M. H. Kelley, 14th International Conference on the Physics of Electronic and Atomic Collisions, Palo Alto, Ca, July 1985.

"Observation of Spin Dependencies in the Superelastic Scattering of Polarized Electrons by Na(3P)," J. J. McClelland, 14th International Conference on the Physics of Electronic and Atomic Collisions, Palo Alto, CA, July 1985.

"Electron Atom Collision Studies Using Optically State Selected Beams," M. H. Kelley, Symposium on Polarization and Correlation in Electron-Atom Collisions, Pasadena, CA, August 1985 (Invited).

"Spin Polarized Superelastic Scattering from Sodium", Invited, J. J. McClelland, JILA, Boulder, CO, October 1985.

"Spin Dependence in Superelastic Electron Scattering from Excited Sodium", M. H. Kelley, DOE Atomic Physics Contractors' Workshop, April 15, 1986.

"Electron Impact Excitation of Na(3P) by Polarized Electron: Spin Dependence of the Alignment and Orientation Parameters as Studied by Superelastic Scattering", J. J. McClelland, 17th Annual Meeting of the Division of Atomic, Molecular, and Optical Physics, Eugene, Oregon, June, 1986.

"Spin Dependence in Scattering of Spin-Polarized Electrons from Optically Pumped Sodium Atoms", M. H. Kelley, Annual Meeting of Division of Atomic, Molecular and Optical Physics, Eugene, Oregon, June 20, 1986 (Invited).

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"Electron-Atom Collision Studies Using Optically State-Selected Beams", M. H. Kelley, Invited Colloquium, Dept. of Physics, Lehigh University, Bethlehem, PA, Sept. 19, 1986.