(e,2e) collisions with polarized electrons and excited, oriented and spin polarized targets

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Abstract. An experiment has been performed in which a polarized electron beam ionizes an orbitally oriented and/or spin polarized valence electron of sodium. The cross section for this reaction is measured for well-resolved vector momenta of the two electrons in the final channel. A tensorial re-coupling scheme has been developed in which the measured quantities are expressed in terms of independent, irreducible spherical tensor components. For a comparison with experiment we performed numerical ionization-cross section calculations within the Distorted Wave Born Approximation (DWBA) and the Dynamically Screened Three Coulomb Waves (DS3C) theory.

INTRODUCTION

Experimental results are presented which probe the spin, the orbital and the charge dependence of electron-atom ionizing collisions. This is achieved by performing ionization coincidence measurements on laser excited sodium atoms in which both the spin and the orbital projection quantum states of the electron-atom system are determined prior to the collision. To disentangle the spin-dependent from the orbital orientation effect a tensorial re-coupling scheme has been developed in which the cross sections are expressed in terms of independent, irreducible spherical tensor components. For comparison with experiment, numerical values for the tensorial components are calculated using the the Distorted Wave Born Approximation (DWBA) [1, 2] and the Dynamically Screened Three Coulomb Waves (DS3C) theory [3].

EXPERIMENTAL METHODOLOGY

As a detailed description of the apparatus has appeared in previous publications [4, 5], only a brief description will be given here. The primary polarized electron beam used to induce the ionization process (degree of Polarization $P_e = 24\%$) is generated by photoemission from a cesium and oxygen coated GaAs crystal under illumination by 810nm circularly polarized laser radiation. Inversion of the electron beam polarization from into, to out of the scattering plane (defined by the axes of the sodium and primary electron beams) is achieved by reversing the helicity of the diode laser radiation field through rotation of a quarter wave plate.

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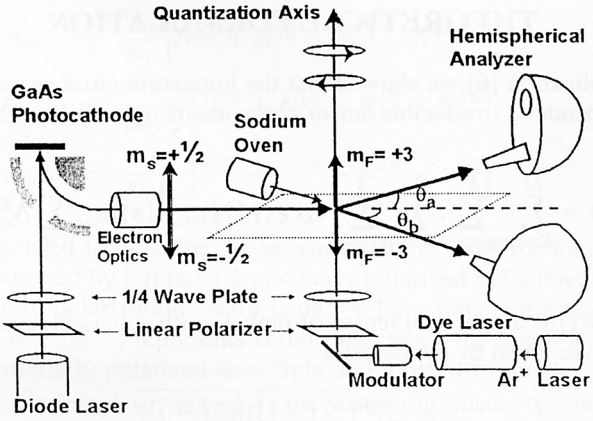

FIGURE 1. Schematic representation of the (e,2e) experimental apparatus. See text for details.

A frequency modulated 589nm circularly polarized laser beam is used to excite, spin polarize and in the case of the excited state atoms, orient the sodium target ensemble through pumping the 3s-3p transition with circularly polarized light. After a few excitation/decay cycles the target atoms gather exclusively in the two state system

$$3s^1\,{}^2S_{1/2}\ (F=2,\ m_F=+2\ (-2))$$
$$\leftrightarrow 3p^1\,{}^2P_{3/2}\ (F=3,\ m_F=+3\ (-3)) \qquad (1)$$

for pumping by left-hand σ^+ (right-hand σ^-) circularly polarized radiation.

Scattered electrons emitted in the scattering plane are measured in two electrostatic hemispherical analyzers, incorporating position sensitive detectors, located on opposite sides of the incident beam. Each analyzer is independently rotatable about the dye laser beam axis which defines the quantization axis in the present measurements.

The experiments consisted of measuring the (e,2e) count rates as a function of the emission angle θ_b of one of the two final state electrons, for a fixed emission angle θ_a of the other, for each of the four combinations of atomic and electron beam polarization directions. For excited state ionization, the reactions considered are:

$$e(\uparrow)+Na(m_F=+3), e(\uparrow)+Na(m_F=-3),$$
$$e(\downarrow)+Na(m_F=+3), e(\downarrow)+Na(m_F=-3). \qquad (2)$$

where $\uparrow$ ($\downarrow$) represent spin up (spin down) incident electrons.

THEORETICAL FORMULATION

In an earlier publication [6] we showed that the ionization cross section can be written in terms of independent, irreducible tensor components in the following manner:

$$\sigma(\Omega_a,\Omega_b,E_b)=\sum_{K=0}^{2J}\sum_{m_K=-K}^{K}\sum_{k=0}^{2s}\sum_{m_k=-k}^{k}c_K c_k\langle\{\mathbf{J}\}_{Km_K}\rangle\langle\{\mathbf{s}\}_{km_k}\rangle\sum_{SM_S}\Lambda^{Kk}_{m_K m_k}(SM_S) \tag{3}$$

where $\Lambda^{Kk}_{m_K m_k}(SM_S)$ is a spherical tensor of rank K with spherical components m_K. The constants c_K, c_k are given by the formula

$$c_j=2^j\sqrt{\frac{(2j+1)!!(2J-j)!}{j!(2J+j+1)!}}.$$

$\langle\{\mathbf{J}\}_{Km_K}\rangle$ denotes an averaged value of the tensor product of angular momentum operators $\mathbf{J}$. That $\Lambda^{Kk}_{m_K m_k}$ is a spherical tensor has immediate consequences as far as the rotational transformation properties are concerned. Tensors with rank $K=0$ and/or $k=0$ are scalar with respect to rotations generated by $\mathbf{J}$ and/or $\mathbf{s}$. The tensors with rank $K=odd$ ($k=odd$) are orientation parameters whereas for $K=even$ ($k=even$) the tensors can be regarded as alignment tensors.

The relation (3) is valid for an arbitrary mutual angle between the natural quantization axes of the incoming electron beam and the polarized atomic target. If the polarized electron beam and the polarized target have a common quantization axis (as is the case in the present experiment) the density matrices become diagonal and Eqs.(3) reduces to

$$\begin{aligned}\sigma(\Omega_a,\Omega_b,E_b)=\quad & \Lambda^{0,0}_{0,0}\left[P_{00}p_{00}+P_{00}p_{10}\frac{\Lambda^{0,1}_{0,0}}{\Lambda^{0,0}_{0,0}}\right.\\ &+\sum_{K=1}^{2J}\left(P_{(K=odd)0}p_{00}\frac{\Lambda^{(K=odd),0}_{0,0}}{\Lambda^{0,0}_{0,0}}+P_{(K=odd)0}p_{10}\frac{\Lambda^{K=odd,1}_{0,0}}{\Lambda^{0,0}_{0,0}}\right)\\ &\left.+\sum_{K=2}^{2J-1}\left(P_{(K=even)0}p_{00}\frac{\Lambda^{(K=even),0}_{0,0}}{\Lambda^{0,0}_{0,0}}+P_{(K=even)0}p_{10}\frac{\Lambda^{(K=even),1}_{0,0}}{\Lambda^{0,0}_{0,0}}\right)\right].\end{aligned} \tag{4}$$

For the experimental arrangement shown in Fig.(1) the ionization cross section for the orbital $m_L=0$ is zero [7]. Therefore (and due to the neglect of any spin-flip reactions) only four (out of eight) parameters in Eqs.(4) are independent. These are Λ^{00}_{00}, Λ^{10}_{00}, Λ^{01}_{00}, Λ^{11}_{00}. To relate the measured count rates with the tensorial parameters we have introduced above, we group them in the following way:

$$\sigma_{av}\;=\;\mathcal{K}'\left[N^{\uparrow\Uparrow}+N^{\uparrow\Downarrow}+N^{\downarrow\Uparrow}+N^{\downarrow\Downarrow}\right]=\mathcal{K}'N_\Sigma \tag{5}$$

$$A_{orb} = \frac{1}{N_\Sigma}\left[N^{\uparrow\Uparrow} + N^{\downarrow\Uparrow} - N^{\uparrow\Downarrow} - N^{\downarrow\Downarrow}\right] \quad (6)$$

$$A_{mag} = \frac{1}{N_\Sigma P_e}\left[N^{\uparrow\Uparrow} + N^{\uparrow\Downarrow} - N^{\downarrow\Uparrow} - N^{\downarrow\Downarrow}\right] \quad (7)$$

$$A_{m,o} = \frac{1}{N_\Sigma P_e}\left[N^{\uparrow\Downarrow} + N^{\downarrow\Uparrow} - N^{\uparrow\Uparrow} - N^{\downarrow\Downarrow}\right]. \quad (8)$$

Here $N^{\uparrow\Uparrow}$ ($N^{\downarrow\Uparrow}$) is used to describe the *measured* count rates for ionization when the target volume is pumped by left hand $\Uparrow$ circularly polarized radiation and ionized by an electron beam whose polarization vector is out of $\uparrow$ (or into $\downarrow$) the scattering plane. In the same manner $N^{\downarrow\Downarrow}$ ($N^{\uparrow\Downarrow}$) represents count rates when the target atoms are pumped by right hand $\Downarrow$ circularly polarized laser light and ionized by an electron beam whose polarization vector is into $\downarrow$ (or out of $\uparrow$) the scattering plane. $\mathcal{K}'$ is a normalization constant arising from the fact that the present measurements are relative and not absolute.

The above quantities are related to the tensorial parameters as follows: $\sigma_{av} = \sqrt{2}\Lambda^{00}_{00}$, $A_{orb} = -\frac{\sqrt{5}}{2}\Lambda^{10}_{00}/\Lambda^{00}_{00}$, $A_{mag} = -\frac{1}{2}\Lambda^{01}_{00}/\Lambda^{00}_{00}$ and $A_{m,o} = \frac{\sqrt{5}}{4}\Lambda^{11}_{00}/\Lambda^{00}_{00}$. The parameter σ_{av} is a scalar which describes the ionization cross section averaged over the projections of the electrons' spins and the sense of orbital rotation and is independent of the helicity of the laser light. The quantity A_{orb}, defined for a beam of *unpolarized* electrons, is proportional to the spin averaged *orbital dichroism*. It results from the dependence of the ionization cross section on the *orientation* of the atomic target ensemble. In contrast the tensorial parameter A_{mag}, hereafter referred to as the *magnetic dichroism*, changes sign when the polarization of the incoming electron beam is inverted but remains invariant under a change of the helicity of the photon (cf.Eq.7). It describes a spin up-down asymmetry for a polarized beam of electrons from an *aligned* ensemble of target atoms. The fourth independent tensorial component $A_{m,o}$ is an exchange induced antiparallel/parallel spin asymmetry and as such changes sign if the helicity of the photon is flipped or if the polarization of the incoming beam is inverted.

EXPERIMENTAL DATA AND COMPARISON WITH THEORY

The experimental results presented here are compared with distorted-wave Born approximation (DWBA) [1, 2] and the dynamically screened three-Coulomb wave model (DS3C) [3] calculations. Both these approximations reduce the scattering from the Na atom to a three-body problem by considering only the active (valence) electron of the Na atom [4]. The DWBA approach accounts for the short and long range interactions of both of the final-state continuum electrons with the field of the ion [1, 2], however their mutual electron-electron interaction is discarded from the treatment. In contrast, the DS3C method treats the three-body system in the final state as the sum of three decoupled two-body subsystems (the electron-electron, the electron-Na^+ and the electron-Na^+ two-body subsystems). The coupling of these three two-body subsystems is included in the theory via dynamical screening of the interaction strength of each of the three individual two-body subsystems [3].

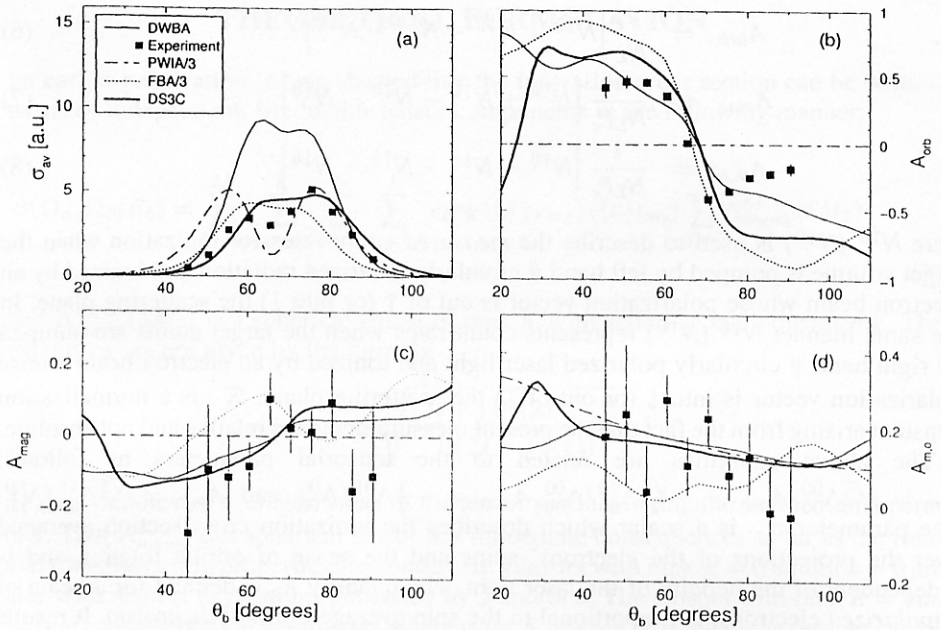

FIGURE 2. Comparison of the measured and calculated cross section parameters σ_{av} (a), A_{orb} (b), A_{mag} (c), and $A_{m,o}$ (d) (see Eqs. (5-8)), for ionization from the oriented and excited 3p state of Na with polarized electrons. The incident beam energy $E_0 = 151eV$ and the mean energy of the detected fast scattered electrons $\bar{E}_a = 127eV$ with corresponding scattering angle $\theta_a = 20^o$. The cross sections are plotted as a function of the slow electron scattering angle θ_b. The experimental average cross section (here seen in (a)) has been normalized to the DS3C theory. Solid and light lines are respectively the DS3C and DWBA calculations. Also shown by short and long dashes respectively are first Born approximation FBA (times1/3) and plane wave impulse approximation PWIA (times 1/3) calculations.

In Fig.(2) we compare the results of measurement with theory for the quantities (5-8). Four calculations are shown (see figure caption), however only the more sophisticated DS3C and DWBA calculations will be discussed here. The incident beam energy is 151eV and the mean energy $\bar{E}$ of the detected fast electrons is $127eV$ with corresponding scattering angle $\theta_a = 20°$. In Fig.2(a) the averaged cross section data is presented and the experimental results are normalized to the DS3C theory. Clearly neither the DS3C or DWBA calculation is able to accurately describe the double peak structure. For the parameter A_{orb} in Fig.2(b) the DWBA provides the better description, suggesting that final state electron-electron correlation may not play a significant role under these kinematics.

In Fig. 2(c) the parameter A_{mag} is shown. The physical origin of the structures revealed by A_{mag} are made clearer by expressing it in terms of the direct and exchange amplitudes $A_{mag} \propto \left\{\Re(f_{m_L=+1} g^*_{m_L=+1}) - \Re(f_{m_L=-1} g^*_{m_L=-1})\right\}/\sigma_{av}$ where f_{m_L} and g_{m_L} are the state-resolved direct and the exchange amplitudes. This relation makes clear that A_{mag} is in fact an exchange induced quantity and it diminishes if an interference between g_{m_L}

and f_{m_L} is unlikely, e.g. if $|g_{m_l}|/|f_{m_l}| \rightarrow 0$. When the direction of the ejected electron coincides with the direction of the momentum transfer (i.e. when $\theta_b \approx 64^o$) the direct scattering amplitude $|f_{m_l}|$ predominates [8] and hence A_{mag} becomes small, and it increases for larger deviations from $\theta_b \approx 64^o$ where exchange scattering can become significant. Fig. 2(d) shows the results for the spin asymmetry $A_{m,o}$. This parameter can as well be written in terms of the direct and exchange amplitudes f_{m_L} and g_{m_L}. $A_{m,o} \propto \left\{ \Re(f_{m_L=+1} g^*_{m_L=+1}) + \Re(f_{m_L=-1} g^*_{m_L=-1}) \right\} / \sigma_{av}$ (note in the present geometry the scattering from the state $m_L = 0$ does not contribute). In the binary collision regime, which is encompassed by the present kinematics, we can expect that in general $|f|$ will dominate (over $|g|$) so that $A_{m,o}$ is also generally small [8]. Both theories perform satisfactorily in comparison with experiment, although the large error bars preclude more definitive statements being made.

CONCLUSION AND FUTURE PERSPECTIVES

We have carried out (e,2e) cross sections measurements on sodium where the angular momentum projection state of the projectile and target are determined prior to the collision. To provide a general description we have developed a tensorial re-coupling scheme that factorizes the cross sections into components characterized by their spherical transformation properties. For a comparison with the experimental results we performed calculations including the Distorted Wave Born Approximation (DWBA) and the Dynamically Screened Three Coulomb Waves (DS3C) model. The results show that the initial state resolved ionization cross section depends both on the relative spin projections of the incident and bound state electrons and on the orientation of the initial atomic state. Reasonable agreement is found between theory and experiment. The theories can be improved by using improved descriptions of the initial state. Improvement in the experimental apparatus are underway by introducing new-generation toroidal electron analyzers and by employing an electron source of improved degree of polarization.

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