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Orbital effect in elastic electron scattering by a polarized excited target

Z. Shi, C. H. Ying, and L. Vušković
Physics Department, Old Dominion University, Norfolk, Virginia 23529

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Azimuthal asymmetry in elastic scattering has been measured for electron collisions with laser-excited, polarized $(3P)$ Na atoms. An observation of this asymmetry in the elastic channel is reported for incident electron energies in the range of 1 to 10 eV at polar scattering angle 135°. Data with selected magnetic sublevels provide a stringent test for available calculations where even the most successful one, the convergent close-coupling calculation, has difficulties at the large scattering angles.

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Scattering of polarized or unpolarized projectiles by a polarized target reveals detailed aspects of a scattering process. For this reason polarization-sensitive scattering studies have undergone significant development in nuclear [1] and atomic [2] physics. In this context we are studying the scattering of electrons by a polarized atomic target in its excited state. Such results contain more information than total and differential scattering cross-section measurements without polarization analysis. In addition to their importance as a prime testing ground for complex collision processes, the measurements provide data relevant to a variety of applied areas, such as high-electron-temperature plasmas. In recent years both experimental techniques and theoretical methods have developed rapidly and an improved understanding of electron-atom collisional dynamics has been achieved. From the experimental point of view, development of polarized projectile electron beams allows diagnosis of spin-dependent effects in the collision, such as singlet-triplet asymmetry and spin-orbit asymmetry [3], while the advent of the laser allows for electron collision studies with a specifically prepared initial state and analysis of the final state of the target atom [2].

The work presented in this paper is a study of an azimuthal asymmetry caused by a "dynamic orbital effect" in the electron collision by the polarized target atom with an orbital angular momentum perpendicular to the scattering plane. Qualitatively, this effect is due to the difference in the sense of rotation of the atomic valence electron in the $M_L=\pm 1$ states. The laser-excited, polarized $3P$ sodium atom is an ideal target to study this orbital effect, since almost 100% atomic polarization can be achieved by excitation with polarized laser light, and its relatively small spin-orbit interaction can be neglected [4] in this process.

Consider the collisional geometry illustrated in Fig. 1, where the polar scattering angle θ lies in the scattering plane defined by the collision frame [2] [electron (z) and atom $(-x)$ axes of propagation, $\theta=0°$ along $+z$ axes], and the projection of the azimuthal scattering angle ϕ lies in the plane of atom and photon $(-y)$ propagation axes. In such a configuration collisions in the scattering plane correspond to $\theta,\phi=0°$ and $\theta,\phi=180°$.

Consider now a $(3P)$ Na atom prepared in the orbital magnetic substate $M_L=+1$ perpendicular to the scattering plane (see Fig. 1). In this case, when the projectile electron passes the target atom from the left (or right) and scatters into a polar angle θ at an azimuthal angle $\phi=0°$ (or $\phi=180°$), the valence and projectile electrons will travel "parallel" (or "antiparallel") to each other during the scattering, for collisions with small impact parameters (large scattering angles). The effective interaction due to the Coulomb repulsive force between the two electrons will therefore be different in these two cases. Thus an azimuthal asymmetry in the differential cross-section measurements is expected. From reflection symmetry considerations, the scattering intensity at $\theta,\phi=0°$ for $M_L=+1$ is equal to the intensity at $\theta,\phi=180°$ for $M_L=-1$. One can experimentally double-check this asymmetry by comparing signals at $\theta,\phi=0°$ and $\theta,\phi=180°$ for a chosen M_L state and by comparing signals for $M_L=+1$ and $M_L=-1$ states at a chosen angle (θ,ϕ). Both sets are employed in the present experiment with consistent results obtained.

Such dynamical phenomena should be especially important under the following two conditions: the first is when the incident energy of the projectile electron is of the order of several eV, comparable to the kinetic energy of the valence electron. In that case, both electrons possess similar speeds,

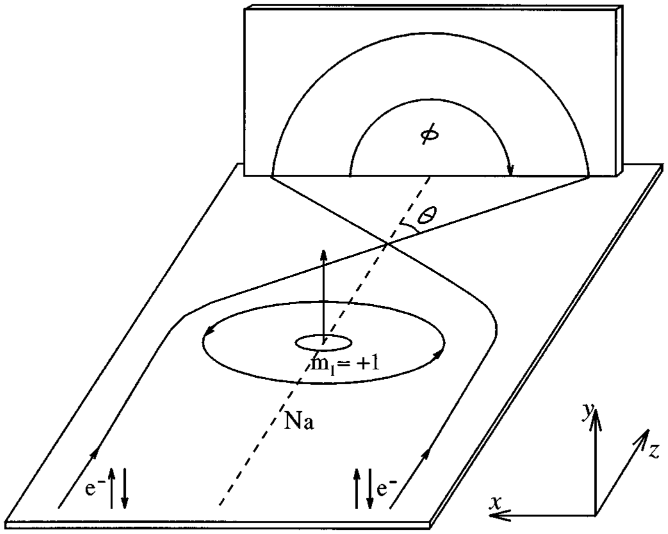

FIG. 1. Classical picture of orbital effect. Propagation of the photon, atom, and electron beams are along the $-y$, $-x$, and z axes, respectively.

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and the collision time is comparable to the revolution period of 10^{-15} s. The second condition requires that the two electrons collide at small impact parameters, corresponding to large scattering angles (where the influence of the long-range, i.e., polarization force, is negligibly small).

Excited $(3P)$ Na atoms were prepared by a single-mode ring dye laser tuned to the $3\,^2S_{1/2}$, $F=2 \rightarrow 3\,^2P_{3/2}$, $F=3$ transition and polarized in one of the magnetic substrates ($M_F=+3$ or $M_F=-3$) by employing σ^+ or σ^- circularly polarized laser light propagating perpendicularly to the scattering plane [5,6]. The orbital angular momentum is also in a pure magnetic substate $M_L=+1$ or $M_L=-1$, quantized along the laser propagation axis (natural frame [2]). The relative excited-state population f has been determined by measuring photon recoil deflection of the atom beam illuminated by the traveling-wave laser field [7]. In the present experiment $f=0.25\pm0.02$ was achieved, and we found it to be the same for both polarized states, $M_F=+3$ and $M_F=-3$. The elastically scattered electrons were detected [8] at ($\theta=135°$, $\phi=0°$) and ($\theta=135°$, $\phi=180°$) by a channeltron, after passing through plane mirror energy analyzers. The relative differential cross sections at these angles were obtained for the incident electron energy range from 1 to 10 eV for both ground and $3\,^2P_{3/2}$, $F=3$ ($M_F=+3$ or $M_F=-3$) states of sodium. Experimental details are planned to be discussed in a future publication.

In order to examine the asymmetry due to orbital effects in the differential cross section between the two magnetic substates of the $3\,^2P_{3/2}$, $F=3$ state, $M_F=+3$ and $M_F=-3$, at a fixed azimuthal angle, only relative measurements were required. Thus, all the experimental parameters, such as atom density, electron current, interaction volume, detection solid angle, and detection efficiency, can be expressed by only one coefficient η to link the signal counting rate to the differential cross section σ. When the asymmetry of the differential cross sections for $M_L=+1$ and $M_L=-1$ polarized states is measured, the coefficient η cancels out for a fixed electron incident energy and a selected azimuthal angle at a given θ. The ground-state scattering signal N taken with *laser off* and scattering signal from the mixture of ground- and excited-state atoms $N^{\pm}$ taken with *laser on*, where the sign ± refers to $M_L=\pm1$, can be expressed as

$$N=\eta\sigma_{3S}, \tag{1}$$

$$N^{\pm}=\eta[(1-f)\sigma_{3S}+f\sigma_{3P}^{\pm}], \tag{2}$$

where σ_{3S} is the $(3S)$ Na ground-state elastic differential cross section and $\sigma_{3P}^{\pm}$ is the $(3P)$ Na excited-state elastic differential cross section for $M_L=\pm1$ polarized states. We define an azimuthal asymmetry A as

$$A=\frac{\sigma_{3P}^{+}-\sigma_{3P}^{-}}{\sigma_{3P}^{+}+\sigma_{3P}^{-}}. \tag{3}$$

From Eqs. (1) and (2) one can derive A with respect to the measured quantities N, N^+, N^-, and f as

$$A=\frac{N^{+}-N^{-}}{N^{+}+N^{-}-2(1-f)N}. \tag{4}$$

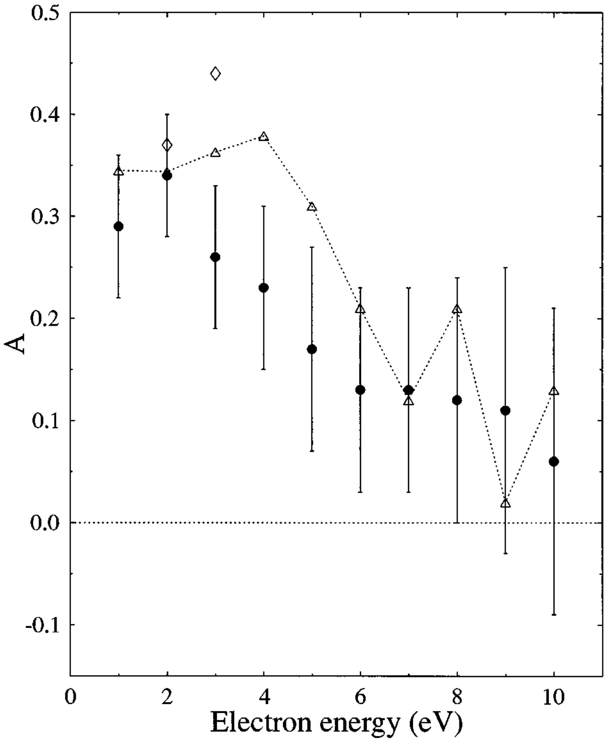

FIG. 2. Azimuthal asymmetry A at polar scattering angle 135° for elastic scattering of electrons by laser-excited, polarized $(3P)$ Na atoms in $M_L=+1$ and $M_L=-1$ states. Experiment: ●, present data with indicated error bars and an energy uncertainty of ±0.15 eV. Calculations: ◇, close-coupling [10]; △ connected with dotted line, convergent close-coupling [9].

One of the reduced Stokes parameters P_3 that is used to describe the atomic charge cloud after collision [9] can be obtained from the present experiment. This parameter as a spin-averaged quantity can be simply related to the measured asymmetry as

$$P_3=-A, \tag{5}$$

while the orientation parameter $L_{\perp}$, defined as the angular momentum transfer to an initially polarized atom target (or a final unpolarized atom for a proper time-reversed process), can be related to A [9] as

$$L_{\perp}=A(1-\rho_{00}^{n}), \tag{6}$$

where ρ_{00}^{n} is the natural frame density-matrix element for the $M_L=0 \rightarrow M_L=0$ transition. Unlike in the $3\,^2P \leftrightarrow 3\,^2S$ transition where ρ_{00}^{n} vanishes due to the symmetry restriction, ρ_{00}^{n} is nonzero in the $3\,^2P \rightarrow 3\,^2P$ collision process. Thus $L_{\perp}$ is no longer equal to $-P_3$. In order to determine $L_{\perp}$ experimentally one has to determine ρ_{00}^{n} independently. The experimental arrangement, including circularly polarized laser light used to determine A, can also be used to determine ρ_{00}^{n} if linearly polarized laser light is used for the initial-state preparation. ρ_{00}^{n} can be obtained with proper normalization of the scattering intensities corresponding to the atoms prepared with differently polarized laser lights.

The measured A is the asymmetry of the differential cross sections between two polarized states. In Fig. 2, A is presented as a function of electron energy. The indicated error bars originate from the counting statistical errors, as well as uncertainties in the determination of f and the degree of atomic polarization. The relatively large error bars are the consequence of the counting statistical errors (5% for each measured signal), coming from two major constraints in the experiment. First, the asymmetry corresponds only to the scattering intensity from the $3P$ state, while the measured signal is the mixture of the $3P$ and the ground-state scattering, which is almost three times larger. The second constraint is in the simultaneous measurement of f. This condition requires a very good collimation of the atomic beam. As a consequence, the atom-beam density in the interaction region was two orders of magnitude smaller than in the standard cross-beam scattering experiment.

Motivated by this experiment, numerical data have been calculated by Zhou *et al.* [10] using a ten-state close-coupling approximation based on an R-matrix method at incident electron energies of 2 and 3 eV; and by Bray *et al.* [9] using a convergent close-coupling (CCC) approximation in the energy range from 1 to 10 eV. The frozen core approximations were included in both calculations. The former are justifiable by observations only. The azimuthal asymmetry in the pure Coulomb scattering is a good test of the calculations since the existence of the asymmetry is due only to the valence electron, while the magnitude of the asymmetry is determined by the combined contribution of both the core and the valence electron. Data from the present measurements are compared with these calculations and also presented in Fig. 2. The calculated results are in qualitative agreement with the experiment; however, the measured asymmetry is generally less pronounced than those calculated in Refs. [9,10]. Therefore, it is of interest to assess how accurately the calculation reflects the relative roles of the valence electron and the core. The smaller asymmetry value obtained in the measurements seems to suggest that the core contribution is larger than assumed in calculations for the large angle scattering. The second aspect of the comparison is that the CCC calculation generates oscillation in the asymmetry at energies from 6 to 10 eV, while the experiment shows no such tendency. Even though the calculated results are within the error bars of the experiment, this oscillation, if real, is large enough to show up in the mean value of the data. Most likely, this oscillation is a shortcoming of the calculation due to difficulties with the convergence at the large scattering angles (see Fig. 6 in Ref. [9]).

To the best of our knowledge, the results of the orbital effect shown in Fig. 2 are the first observations of the azimuthal asymmetry in the elastic electron collision due to the M_L atomic state perpendicular to the scattering plane. The magnitudes of the measured asymmetry are found to be larger than a factor of 0.3 with a confidence level of 90% at incident electron energies below 5 eV. They are approaching zero at higher incident energies, which is consistent with a simple classical model. This asymmetry, caused by a pure Coulomb interaction, indicates the significance of the dynamical effect due to the orbital motion of the valence electron. If one exactly knew the scattering amplitudes, this asymmetry would be an expected outcome of the quantum-mechanical treatment of this collision process. The data with selected magnetic sublevel provide a different point of view of the collision process and serve as a stringent test of approximations used for calculations.

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[1] See, for example, *Workshop on Polarized ^{3}He Beams and Targets*, edited by R. W. Dunford and F. P. Calaprice, AIP Conf. Proc. No. 131 (AIP, New York, 1985); A. K. Thompson *et al.*, Phys. Rev. Lett. **68**, 2901 (1992).

[2] N. Anderson, J. W. Gallagher, and I. V. Hertel, Phys. Rep. **165**, 1 (1988).

[3] J. Kessler, in *Advances in Atomic, Molecular, and Optical Physics*, edited by D. Bates and B. Bederson (Academic, New York, 1990), Vol. 27, p. 81.

[4] J. J. McClelland, M. H. Kelley, and R. J. Celotta, Phys. Rev. Lett. **58**, 2198 (1987).

[5] J. J. McClelland, M. H. Kelley, and R. J. Celotta, Phys. Rev. A **40**, 2321 (1989).

[6] T. Y. Jiang, M. Zuo, L. Vušković, and B. Bederson, Phys. Rev. Lett. **68**, 915 (1992).

[7] M. Zuo, T. Y. Jiang, L. Vušković, and B. Bederson, Phys. Rev. A **41**, 2489 (1990).

[8] Z. Shi, Ph.D. thesis, New York University, 1995 (unpublished).

[9] I. Bray, D. V. Fursa, and I. E. McCarthy, Phys. Rev. A **49**, 2667 (1994); private communication.

[10] H. L. Zhou, D. W. Norcross, and B. L. Whitten, in Proceedings of the Conference on Correlations and Polarization of Electronic Atomic Collisions and $(e,2e)$ Reactions, Flinders University, Adelaide, 1991, edited by P. J. O. Teubner and E. Weigold [Inst. Phys. Conf. Ser. **122** (1992)]; private communication.