Absolute Cross Sections for Low-Energy Scattering of Electrons by Excited Sodium

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Electrons scattered by $3^2P_{3/2}$, $M_L = \pm 1$ sodium has been measured in the collision energy range up to 5 eV and in the angular range 0° to 30°. Absolute differential cross sections are reported for deexcitation to $3^2S_{1/2}$ and excitation to $4^2S_{1/2}$, obtained without normalization. The $3P \rightarrow 4S$ cross sections are over a factor of 2 times larger than those for the corresponding $3S \rightarrow 3P$ reaction, for the same final electron energy. Comparison with available theory is presented.

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The need for a better understanding of collision processes, particularly when one partner is electronically excited, not only exists for fundamental reasons, but also in order to provide data relevant to applied fields in which excited-state atomic collisions play a significant role, for example, high-electron-temperature plasmas that exist in tokamak fusion devices. Results using various formalisms tend to differ, partially due to the different models used for calculation [1]. In addition, calculations usually ignore resonance contributions at the excitation threshold where cross sections can be significantly affected [2]. Thus, experimental evidence is critical for comparison with theory, and to supply guidance in evaluating various computational techniques.

Experimental studies of low-energy-electron scattering by excited atoms, the simplest atomic collision process to be compared with theory, usually employ sodium atoms as a test case, due to their comparatively easy preparation in selected excited states. The technique common to all these studies has been the application of polarized laser light to excite an atomic beam, thereby controlling the alignment and the inherent angular momentum of the prepared target. A recent comprehensive review of this topic may be found in Andersen, Gallagher, and Hertel [3].

Combining the results of recent experiments involving the scattering of laser-prepared excited sodium by spin-polarized [4] and unpolarized [5] electrons with recoil analysis of the scattered atoms [6] yields an extremely sensitive test of collision dynamics, with results approaching a complete scattering experiment [7]. At the same time, Zhou, Norcross, and Whitten [8] have developed a code for high-precision cross-section calculations for low-energy-electron–sodium scattering, based on the R-matrix approach [9]; modified to include one- and two-electron polarization potentials to allow semiempirically for the effects of core polarization. These authors perform full close-coupling calculations, using up to eleven states to describe the target, for low partial waves. In order to produce consistent sets of K-matrix elements for intermediate partial waves all continuum-continuum exchange integrals are eliminated from the code; for very high partial waves the first Born approximation is employed to derive individual K-matrix elements. Most of the recent experimental results, up to about 5-eV total collision energy (for an electron collision with $3P$ sodium this corresponds to an excess of 2.1-eV energy of the excited atom above the ground state plus the initial electron energy), which is the range of validity for this theory, are generally successfully reproduced by the calculations (however, see Ref. [10]).

Here we present the first results of absolute differential cross sections $\sigma(\theta)$ for superelastically ($3P \rightarrow 3S$) and inelastically ($3P \rightarrow 4S$) scattered electrons by selected combinations of magnetic sublevels of $3^2P_{3/2}$ sodium, obtained without normalization. The total interaction energy in these experiments is up to 5.1 eV, so that our data can be compared directly with the Zhou, Norcross, and Whitten [8] calculation. The atoms are initially prepared by circularly polarized laser light (σ light) which results in unequal magnetic-sublevel populations for the initial hyperfine level. Accordingly, detailed balancing for superelastic scattering cannot be directly invoked to compare the inverse reactions $3S \rightarrow 3P$, which normally corresponds to electron scattering with all magnetic sublevels of the initial level equally populated (and summation over final magnetic sublevels with equal weights).

We have derived [11] exact equations that relate scattered electron and atom spatial distributions in order to take full advantage of the atomic recoil technique [12] used in the present experiment. This technique involves observation of the scattered atom beam after being cross-fired by an electron beam, in the presence of a mutually perpendicular laser beam tuned to the resonant $3^2S_{1/2}(F=2, M_F=2) \rightarrow 3^2P_{3/2}(F=3, M_F=3)$ transition. A standing-wave bidirectional laser field is used, thereby minimizing the effects of photon recoil, although the atom beam spatial distribution is widened somewhat by spontaneous emission and statistical effects. The incident electrons are unpolarized. The scattered electrons are not spin analyzed nor are the recoiled atoms state analyzed. Coordinate axes of the present experiment are such that the polar scattering angle θ lies in the scattering plane defined by the electron (z) and atom (y) axes of propagation ($\theta = 0°$ along $+z$ axis). Projection of the azimuthal scattering angle ϕ is in the plane of the atom and photon ($-x$) propagation axes ($\phi = 0°$ along $+y$ axis). Using atomic recoil, low-energy electrons scattered at both

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(θ,ϕ) and $(\theta,\pi-\phi)$ will cause atoms to recoil into the same position in the detector plane [11]. Therefore, for each θ both azimuthal angle scattering signals (ϕ and $\pi-\phi$) are recorded. Thus, the final differential cross section is the average of the collision cross sections for these two azimuthal angles. The present data correspond to collisions in the scattering plane, and thus ϕ is either 0 or π rad. Since the experimental resolution for azimuthal scattering angles is limited, the averaging around $\Delta\phi$ enlarged our uncertainty somewhat in the final data. Detection of the scattered intensity outside the nominal scattering plane is also possible, but recoil analysis in the present experimental setup is not feasible.

The choice of right-handed (σ^+) or left-handed (σ^-) circularly polarized laser light for sodium excitation results [4] in $M_L=+1$ or $M_L=-1$ magnetic sublevels, respectively, of the $3^2P_{3/2}$ prepared atoms, quantized along the laser propagation axis (natural frame [3]). The scattering intensities of these two states are symmetric with respect to a reflection of the azimuthal scattering angle ϕ about $\phi=\frac{1}{2}\pi$, for a given polar scattering angle θ. Consider an atom prepared in the $M_L=1$ state in the natural frame. In the present experiment the atom detector sees at the same time recoiled atoms corresponding to electrons scattered into both (θ, $\phi=0°$) and (θ, $\phi=\pi$). This means that our measured $\sigma(\theta)$ corresponds to the condition that 50% of atoms in the interaction region are in the $M_L=1$ and 50% are in the $M_L=-1$ state, both prepared in the natural frame. Therefore, the same scattering intensity should be observed with both σ^+ and σ^- laser excitation light. As a consequence, using the notation of Ref. [4], the experimentally determined cross sections should be compared with the calculated cross sections [8]

$$\sigma(\theta)=\tfrac{1}{2}(Q_{+1}+Q_{-1}), \tag{1}$$

with

$$Q_{+1}=3|f^T_{+1}|^2+|f^S_{+1}|^2 \tag{2}$$

and

$$Q_{-1}=3|f^T_{-1}|^2+|f^S_{-1}|^2, \tag{3}$$

where $f^T_{\pm1}$ and $f^S_{\pm1}$ are triplet and singlet scattering amplitudes in the natural frame, respectively, for transitions from $M_L=\pm1$ magnetic sublevels of the $3^2P_{3/2}$ state to a particular final state.

A complete analysis of experimental data, taking into account all relevant beam and apparatus parameters, yields for the observed scattering current [13]

$$I_s(z_D)=\frac{fi_0I_0(0)}{2h\Delta x\Delta z}\int_0^{\theta_{max}}\sigma(\theta)\sin\theta\,d\theta\int_{E_0-\delta E}^{E_0+\delta E}\mathcal{E}(E)dE\int_{z_1}^{z_2}Z(z)dz\int_{V_1}^{V_2}\frac{\mathcal{V}(V)}{V}dV\int_{x_1}^{x_2}X(x)dx\int_{\phi_1}^{\phi_2}d\phi\,. \tag{4}$$

Equation (4) takes into account the atom velocity distribution [$\mathcal{V}(V)$], the electron energy distribution [$\mathcal{E}(E)$], the spatial distribution of the atom beam [$X(x),Z(z)$], slit and detector geometries ($h,\Delta x,\Delta z$), and the fraction of excited-state atoms (f). In the present experiment $f=0.26$. The absolute $\sigma(\theta)$ curve represents the only set of unknown parameters. $I_s(z_D)$ and $I_0(0)$ are the atomic beam currents at the detector positions z_D and $z_D=0$, respectively, and i_0 is the total electron number current. The recoil analysis for small angle scattering requires accurate knowledge of the atom beam velocity distribution. For this purpose laser-induced Doppler shifted fluorescence measurements are employed [13]. The velocity distribution is determined at several different points within the atom beam cross-sectional area since it is affected by the radial dependence of the velocity selection property of the atom beam focusing hexapole magnet, which is part of the experimental setup.

The scattered intensities for small angle superelastic collisions are separately distinguishable since these result in momentum transfer to the atom beam counter to the initial electron momentum. Thus, the deflection signature is unique and analysis is straightforward, employing Eq. (4). Figure 1 shows the present $\sigma(\theta)$ results in units of 10^{-20} m^{2}sr^{-1} for 3-eV electrons superelastically scattered in the range of 1° to 30° along with the ten-state (3S, 3P, 4S, 3D, 4P, 4D, 4F, 5S, 5P, 5D) close-coupling calculation (10CC) by Zhou, Norcross, and Whitten [8], performed to compare with our results. The largest contribution to the estimated experimental error comes from the decreasing sensitivity caused by the solid angle factor $\sin\theta$ in the fitting procedure as θ decreases. Thus, the error gradually decreases with increasing θ. Theory and experiment are consistent given the estimated experimental error. Discrepancies are larger at larger angles. The experimental data are more forward peaked than the computed values, although the partial integral cross sections do not differ significantly.

In contrast to the superelastic case, inelastic collisions always result in momentum transfer to the atom beam in the direction of the initial electron momentum. The small angle inelastic deflection signature is superimposed on large angle elastic scattering signals. In the region of measurement the influence of superelastic scattering, which also contributes to the scattered intensity, is much smaller than that of elastic scattering. For this reason, only that part of the $3P\rightarrow4S$ scattering intensities for which the elastic contribution is not dominant is used for the evaluation. The reduction of the portion of scattered intensities taken into account for evaluation results in two $\sigma(\theta)$ curves that represent equally good fits of experimental points, yielding the same partial integral cross section of 6.2×10^{-20} m^2 over the range from 3° to 30°. The $\sigma(\theta)$ for $3P\rightarrow4S$ at 2 eV in units of 10^{-20} m^{2}sr^{-1}, shown in Fig. 2, present the average values of these two

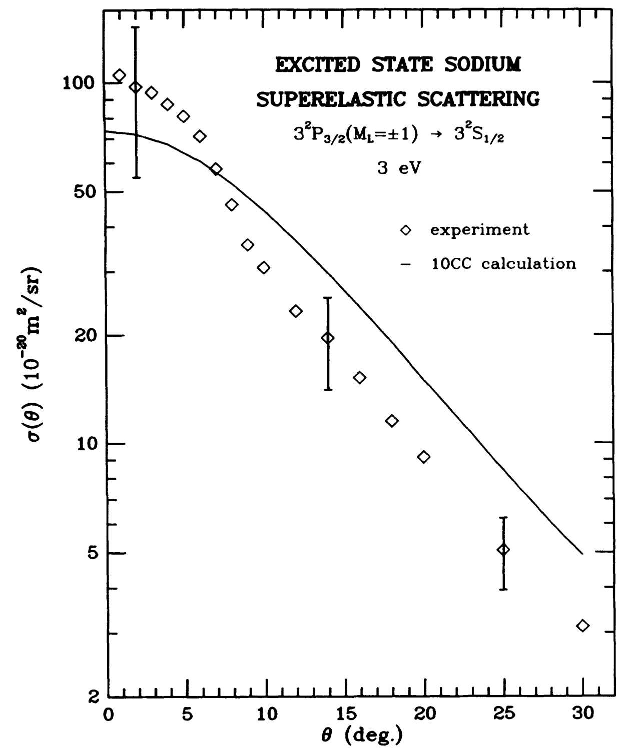

FIG. 1. Superelastic ($3P \rightarrow 3S$) differential cross section for 3-eV electron scattering by laser-excited sodium: ◇, present experiment; ——, ten-state close-coupling calculation of Zhou, Norcross, and Whitten.

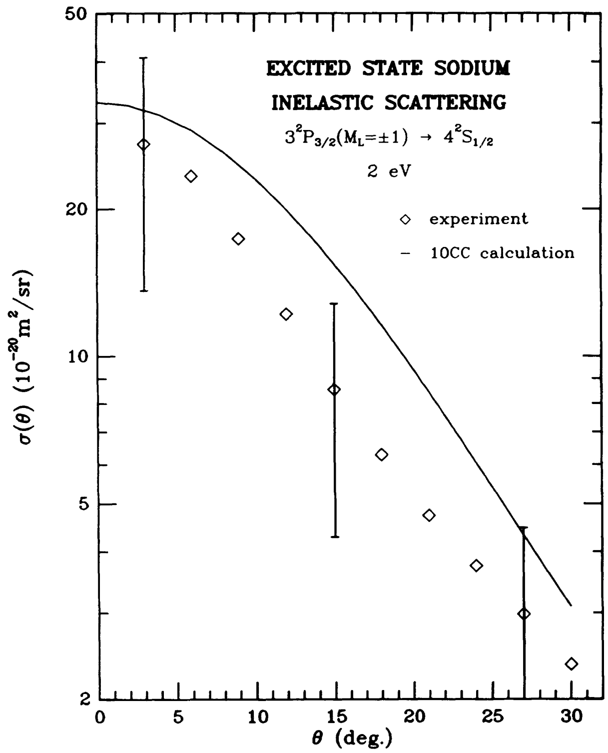

FIG. 2. Inelastic ($3P \rightarrow 4S$) differential cross section for 2-eV electron scattering by laser-excited sodium: ◇, present experiment; ——, ten-state close-coupling calculation of Zhou, Norcross, and Whitten.

curves. This averaging represents the dominant contribution to the estimated experimental error, and unlike the superelastic $\sigma(\theta)$, has the same value over the full range of the scattering angles. The calculated [8] $\sigma(\theta)$ with the 10CC approximation is presented in the same figure; the values also agree to within the experimental error of the present data.

To the best of our knowledge, the results shown in Figs. 1 and 2 are the first determinations of absolute differential cross sections for electron scattering from excited atoms, particularly the scattering from $3^2P_{3/2}$, $M_L = \pm 1$ sodium superelastically to $3^2S_{1/2}$ and inelastically to $4^2S_{1/2}$. Good agreement between our experimentally determined differential cross sections and the calculations of Zhou, Norcross, and Whitten [8] for the superelastic scattering is consistent with the agreement between the McClelland, Kelley, and Cellotta [4] measurements of alignment and orientation parameters in superelastic scattering and the same calculation. We note that the present results of $4^2S_{1/2}$ excitation from $3^2P_{3/2}$, $M_L = \pm 1$ show $\sigma(\theta)$ being in the range $(2 \text{ to } 40) \times 10^{-20}$ $\mathrm{m^2 sr^{-1}}$ at scattering angles up to 30° for the final electron energy 0.9 eV. In the case [14] of $3P$ excitation from $3S$ (resonant transition) for the same angular range and the same residual electron energy, $\sigma(\theta)$ is in the range $(1 \text{ to } 10) \times 10^{-20}\,\mathrm{m^2 sr^{-1}}$.

Employing the present experimental approach, our superelastic measurements are being extended up to 20-eV incident electron energy where the Zhou, Norcross, and Whitten theory is not applicable. Results with more experimental information will be presented in a forthcoming publication.

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[1] J. Mitroy, J. Phys. B **21**, L25 (1987); Phys. Rev. A **37**, 649 (1988).

[2] R. J. W. Henry, Phys. Rep. **68**, 1 (1981).

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

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

[5] X. L. Han, G. W. Schinn, and A. Gallagher, Phys. Rev. A

42, 1245 (1990).

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

[7] B. Bederson, Comments At. Mol. Phys. **1**, 41 (1969); **1**, 65 (1969).

[8] H. L. Zhou, D. W. Norcross, and B. L. Whitten, in Proceedings of the Sixth International Symposium on Correlations and Polarization in Electronic and Atomic Collisions and $(e,2e)$ Reactions, Adelaide, Australia, July 1991 (to be published); (private communication).

[9] K. A. Berrington, P. G. Burke, M. Le Dourneuf, W. D. Robb, K. T. Taylor, and Vo Ky Lan, Comput. Phys. Commun. **14**, 367 (1977).

[10] Discrepancies in $3P \rightarrow 3P$ cross sections between experiment [6] and theory [8] are unresolved at the present time.

[11] L. Vušković, M. Zuo, G. F. Shen, B. Stumpf, and B. Bederson, Phys. Rev. A **40**, 133 (1989).

[12] B. Jaduszliwer, P. Weiss, A. Tino, and B. Bederson, Phys. Rev. A **30**, 1255 (1984).

[13] T. Y. Jiang, C. H. Ying, L. Vušković, and B. Bederson, Phys. Rev. A **42**, 3852 (1990).

[14] C. H. Ying, L. Vušković, and B. Bederson, in Proceedings of the Forty-Fourth Gaseous Electronic Conference, Albuquerque, New Mexico, 22–25 October 1991, Book of Abstracts (unpublished), p. 133.