Total cross sections for electrons scattered by $3^2P_{3/2}$ sodium atoms

B. Jaduszliwer, G. F. Shen, J.-L. Cai, and B. Bederson
Physics Department, New York University, New York, New York 10003
(Received 2 August 1984)

An electron and photon atomic-recoil technique has been used to measure absolute total cross sections for electrons scattered by $3^2P_{3/2}$ sodium atoms in the 6–25-eV energy range, with use of a new, high-resolution crossed-beam apparatus. A single-mode tunable ring dye laser is used to selectively excite the $F=3$ hyperfine level. Excited-state populations are determined by using the atomic recoil in resonant photon absorption. At 6 eV there is very good agreement with a previous measurement [B. Jaduszliwer, R. Dang, P. Weiss, and B. Bederson, Phys. Rev. A **21**, 808 (1980)].

The study of electron-atom collisions in the presence of laser fields is a natural extension of field-free collisions, at least as long as the power levels are low enough so that the field does not play a direct role in the collision dynamics. For such experiments, the laser acts as a tool to prepare the atom in states which are not accessible or not as easily controllable in field-free collisions. Hertel and Stoll[1] used this approach when they studied superelastic collisions of electrons with laser-excited sodium atoms, and analyzed their results in terms of the relative scattering amplitudes for the time-reversed process, electron impact excitation of the sodium atom.

An experimental program is in progress[2,3] at New York University to measure cross sections for elastic, inelastic, and superelastic electron collisions with laser-excited sodium atoms. Jaduszliwer, Dang, Weiss, and Bederson[3] measured absolute total cross sections for electron scattering by $3^2P_{3/2}$, $m_J=\frac{3}{2}$ sodium atoms in the 0.84–6-eV energy range. We report here on the extension of those measurements from 6 to 25 eV, although our present, magnetic-field-free data refer to a different atomic orientation.

The measurements have been carried out in a new atomic-beams apparatus described in detail elsewhere,[4] using basically the technique described by Jaduszliwer *et al.*[3] Figure 1 shows a diagram of the experimental arrangement. The mutually orthogonal atomic, electron, and laser beams overlap in the interaction region of the apparatus. The effusive atomic sodium beam is state selected by a hexapole electromagnet which focuses the atoms having $m_J=\frac{1}{2}$ in a strong field on the surface ionization detector, 4 m downstream, and deflects out of the beam the atoms with $m_J=-\frac{1}{2}$. Since the focal length of the hexapole magnet is velocity dependent, it also acts as a velocity selector, with $\Delta v/v=0.25$ full width at half maximum (FWHM).

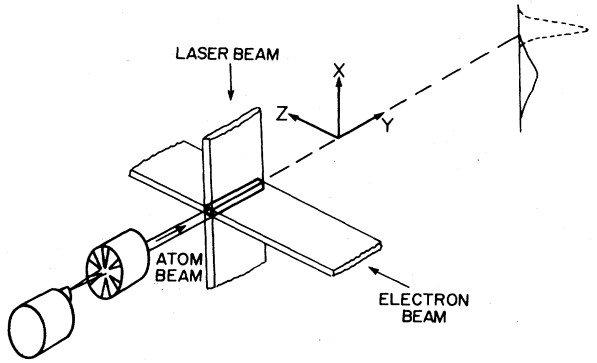

FIG. 1. Experimental arrangement. The effusive atomic sodium beam is incident along the y axis; the electron beam along the z axis, and the laser beam along the x axis. The atomic beam is focused and state and velocity selected by a hexapole electromagnet. The curves at right show the shape of the undeflected (dash line) and photon-deflected (full line) atomic beams.

The electron beam is ribbon shaped; its width is $l=2$ cm, and its height is 0.08 cm. Typical currents are about 300 μA, and the energy spread is 0.5 eV (FWHM).

A single-mode tunable ring dye laser using Rhodamine-6G typically outputs a 300-mW beam. Four mirrors steer it into the interaction volume, and a cylindrical lens telescope expands it to the same width as the electron beam, $l=2$ cm.

The atoms move adiabatically into the interaction volume, where the magnetic field is kept below 10^{-2} G. Thus, the atomic beam is state selected, before laser excitation, in the $F=2$, $M=-1,0,1,2$ states. Depending on operating conditions, a small fraction of the beam may enter the interaction region in $F=1$ states. This is easily diagnosed, because those atoms are not deflected by the laser beam in the fashion described below, and do not introduce any additional complication in the analysis of the experiment.

The laser photons are right-circularly polarized by a quarter-wave plate. The laser is tuned to the $^2S_{1/2}$, $F=2\leftrightarrow{}^2P_{3/2}$, $F=3$ transition, and under these conditions steady state is reached when all the atoms are either in the $^2S_{1/2}$, $F=2$, $M=2$ or $^2P_{3/2}$, $F=3$, $M=3$ states, referred to a quantization axis along the photon incidence direction.

After absorbing a photon from the laser beam, the atom will be recoiled by an angle $\gamma_0=h/mv\lambda$, where mv is the atomic momentum and λ the light wavelength. If the atom decays to the ground state by stimulated emission, it will recoil by an angle $-\gamma_0$, and no net recoil for the absorption-emission pair will be observed. Spontaneous decay photons are emitted in all directions; since the atom spends a time $\tau=l/v\simeq 2\times10^{-5}$ sec in the interaction volume, while the lifetime of the excited state is $\tau_0=1.6\times10^{-8}$ sec, many of such spontaneous photons are emitted, and the net momentum transfer to the atom *from the spontaneous photons* averages out to zero.[5] After N spontaneous photons are emitted, the net recoil angle of the atomic beam will be $N\gamma_0$, resulting in a downward displacement d of the atomic beam at the detector plane, a distance L away from the interaction volume. Typically, $d/L\simeq10^{-2}$, and d is several beam widths.[6] The fraction of the

transit time spent by the atom in the excited state is given by (for $N >> 1$)

$$f \simeq \frac{N\tau_0}{\tau} = \frac{mv^2\lambda\tau_0 d}{hLl} \tag{1}$$

and in the present experiment it ranged between 0.15 and 0.20.

In order to perform our total cross section measurements, the atomic detector is set at the peak of the photon-recoiled atomic beam. The electron gun is turned on and off, and the atomic beam signals I (electron gun on) and I_0 (electron gun off) are recorded. The effective total scattering cross section in the interaction volume is given by[7]

$$\sigma_{\text{eff}} = \frac{Hv}{I_e}\frac{I_0 - I}{I_0} \ , \tag{2}$$

where H is a geometry factor and I_e the electron number current. The atomic beam velocity v is measured as discussed by Jaduszliwer *et al.*;[3] I_e can be determined absolutely without much trouble, and it is clear from Eq. (2) that as long as the atomic detector is linear for small signal changes ($I_0 - I << I_0$)σ_{eff} will be determined absolutely.

In the absence of significant coherence between ground and excited states in the interaction volume, σ_{eff} can be expressed as a statistical combination of the ground state (σ_{3S}) and excited state (σ_{3P}) cross sections:[8]

$$\sigma_{\text{eff}} = f\sigma_{3P} + (1-f)\sigma_{3S} \tag{3}$$

and by using the ground-state total cross sections measured by Kasdan, Miller, and Bederson,[7] σ_{3P} can be determined.

Figure 2 shows our results, as well as the previous ones below 6 eV.[3]

Many scattering channels contribute to the total cross section in this energy range. Elastic ($3P \rightarrow 3P$) and superelastic ($3P \rightarrow 3S$) collisions will be dominant, but the contributions from excitation processes, particularly ($3P \rightarrow 3D$) and ($3P \rightarrow 4S$), and impact ionization will not be negligible. The only channel for which theoretical amplitudes are available is the superelastic channel, since this process is related to ($3S \rightarrow 3P$) ground-state impact excitation by detailed balancing, i.e., by a time-reversal operation. The different theoretical methods used to calculate 3^2P impact excitation amplitudes in the energy range we have explored, together with many of the calculations, have been reviewed by Bransden and McDowell.[9]

In general, atoms in P states will not present an isotropic charge distribution to the projectile electrons, thus making it necessary to accurately describe the mixture of J_z states produced by the laser-excitation process, where **J** is the relevant atomic angular momentum and $\hat{z}$ the direction of incidence of the electrons (i.e., the quantization axis in the collision frame). This subject has been discussed in detail by Macek and Hertel.[10] In the present experiment, the atoms are excited to the $^2P_{3/2}$, $F=3$, $M=3$ state in the photon frame, in which the quantization axis is $-\hat{x}$, since the photons are right-circularly polarized and incident in the $-\hat{x}$ direction. The electrons are incident in the $\hat{z}$ direction;

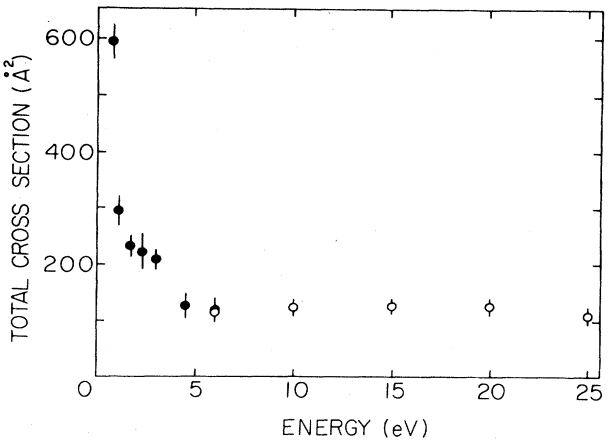

FIG. 2. Total cross sections for electron scattering on 3^2P sodium atoms. Black dots: Jaduszliwer *et al.* (Ref. 4). Open circles: this work. Error bars denote statistical errors and a maximum estimate of possible systematic errors.

the atomic state in the collision frame can be determined by using the appropriate rotation matrices and it is

$$\begin{aligned}|\Psi_{\text{coll}}\rangle = \tfrac{1}{8}\{|\tfrac{3}{2},\tfrac{3}{2}\rangle + \sqrt{3}|\tfrac{3}{2},\tfrac{1}{2}\rangle + \sqrt{3}|\tfrac{3}{2},-\tfrac{1}{2}\rangle + |\tfrac{3}{2},-\tfrac{3}{2}\rangle\} \\ \times \{|\tfrac{1}{2},\tfrac{1}{2}\rangle + |\tfrac{1}{2},-\tfrac{1}{2}\rangle\} \\ \times \{|1,1\rangle + \sqrt{2}|1,0\rangle + |1,-1\rangle\} \ ,\end{aligned} \tag{4}$$

where the first bracket refers to nuclear spin quantum numbers, $|I,M_I\rangle$, the second bracket, to the electron spin, $|S,M_S\rangle$, and the third to the orbital angular momentum, $|L,M_L\rangle$; this last bracket is the only one entering explicitly into the collisional dynamics.

In the previous experiment,[3] a field of 785 G obtained in the interaction volume, high enough to decouple nuclear and electron angular momenta. The magnetic field was parallel to the incident electron momentum, and the photons were linearly polarized with the electric field also parallel to the incident electron momentum. In that case, the photon and collision frames were identical, and the atomic state in the collision frame was

$$|\Psi_{\text{coll}}\rangle = |\tfrac{3}{2},\tfrac{3}{2}\rangle\,|\tfrac{1}{2},\tfrac{1}{2}\rangle\,|1,1\rangle \ , \tag{5}$$

again referring to **I**, **S**, **L**, respectively. At the one energy (6 eV) for which data were obtained in both the early and the present experiment, the cross sections are in very good agreement; $(120 \pm 41)\times 10^{-16}$ and $(118 \pm 24)\times 10^{-16}$ cm^2, respectively. This implies that the anisotropy contribution at 6 eV is at most of the order of the combined error, about 40%.

This research was supported by the National Science Foundation.

[1]I. V. Hertel and W. Stoll, J. Phys. B **7**, 583 (1974).
[2]N. D. Bhaskar, B. Jaduszliwer, and B. Bederson, Phys. Rev. Lett. **38**, 14 (1977).
[3]B. Jaduszliwer, R. Dang, P. Weiss, and B. Bederson, Phys. Rev. A **21**, 808 (1980).
[4]B. Jaduszliwer, P. Weiss, A. Tino, and B. Bederson, Phys. Rev. A **30**, 1255 (1984).
[5]This averaging out to zero takes place even for quite small numbers of spontaneous photons, as shown by L. Mandel, J. Opt. (Paris) **10**, 51 (1979).
[6]The photon-recoiled beam is broadened, due to the finite atomic velocity spread and statistical fluctuations in the number and direction of emission of the spontaneous photons.
[7]A. Kasdan, T. M. Miller, and B. Bederson, Phys. Rev. A **8**, 1562 (1973).
[8]Even if there is coherence between ground and excited states, any interference effects would normally be averaged out by the experiment.
[9]B. H. Bransden and M. R. C. McDowell, Phys. Rep. **46**, 249 (1978).
[10]J. Macek and I. V. Hertel, J. Phys. B **7**, 2173 (1974).