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Electron Collision Cross-Sections Measured with the Use of a Magneto-Optical Trap.

R. S. SCHAPPE, P. FENG, L. W. ANDERSON, C. C. LIN and T. WALKER

Department of Physics, University of Wisconsin-Madison
Madison, WI 53706, USA

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Abstract. – We present the first application of optically trapped atoms as targets for a scattering experiment. We report absolute total electron scattering cross-sections for ground-state Rb atoms in the range of 7–500 eV.

This paper reports the first measurements of collision cross-sections using a magneto-optical trap [1] as the target. In measuring an absolute scattering cross-section one can either monitor scattering of the incident particle beam or of the target. Monitoring the scattering of the incident beam requires making an absolute measurement of the target density, which often is difficult. Monitoring the scattering of the target has the advantage that one does not need to make an absolute measurement of the target density in order to obtain an absolute cross-section, although one must make an absolute measurement of the incident particle flux. The atomic beam recoil technique for measuring electron scattering cross-sections was pioneered by Bederson and his co-workers [2]. Visconti, Slevin and Rubin [3] applied this method to measure absolute total electron scattering cross-sections of alkali atoms including Rb. In crossed-beam experiments it is usually difficult to distinguish the nearly forward scattering from the incident beam. In this paper we show that it is advantageous to replace the atomic-beam target with a target of optically trapped atoms which is very sensitive to atomic recoil. Recent advances in diode laser technology have streamlined the construction and operation of magneto-optical traps [4]. The use of an optically trapped atomic target results in a relatively simple apparatus and straightforward interpretation of the data. The simplicity of the method and apparatus will make it useful for future reliable and reproducible benchmark measurements. As a demonstration of this new technique we have measured the total scattering cross-section for electron-Rb collisions for incident energies of 7–500 eV.

In addition to the need for reliable absolute cross-sections for understanding low-temperature plasmas and related phenomena, Bray [5] has recently emphasized the importance of these cross-sections toward testing theory. Studying Na, he calculated total and ionization cross-sections and obtained agreement with the total–cross-section measurements at the 20% level, but disagreed with total-ionization measurements by a factor of two.

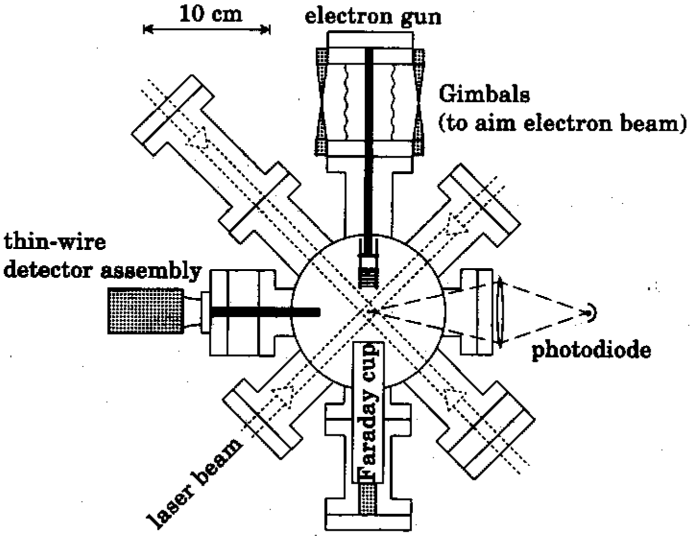

Fig. 1. – Schematic diagram of the vacuum chamber. Not shown are two of the laser beams, the magnetic-field coils, and the diode laser with its stabilization and modulation equipment. Dimensions are to scale.

More precise experimental results, such as those presented here, are clearly essential in order to test the state of the art in electron scattering theory.

The electron-scattering/magneto-optical trapping apparatus is depicted in fig. 1. A vapor-loaded magneto-optical trap (MOT) of Rb [6] is produced inside an ion-pumped stainless-steel vacuum chamber ($\sim 10^{-9}$ Torr), using light from a single external-cavity-stabilized diode laser [7] operating at the $5S_{1/2}(F=3)\rightarrow 5P_{3/2}(F'=4)$ transition of ^{85}Rb. The diode laser is modulated at 2.91 GHz [8, 9] in order to provide light at the $F=2\rightarrow F'=3$ transition needed to keep the atoms optically pumped into the $F=3$ level. The laser beams are 1.1 cm in diameter. Magnetic-field coils external to the vacuum chamber provide the magnetic-field gradient needed for the trap (28 G/cm). This apparatus produces a cloud of approximately 10^6 atoms in a 0.5 mm region of space, giving a density of $\sim 10^{10}\,\text{cm}^{-3}$ centered near $B=0$. The total number of atoms in the trap is proportional to the trap fluorescence which we detect with a photodiode and record on a digital oscilloscope. The temperature of the trapped atoms is typically 100 μK. An electron gun of a standard design [10] produces a nearly monoenergetic electron beam with a diameter of 2.5 mm–1 cm and with a total current in the range 50–300 μA, depending on energy. Since the electron beam is much larger than the cloud of trapped atoms, the current density is constant over the volume of the cloud. When the electron beam is turned on, atoms are ejected from the trap due to the electron-atom collisions at a rate

$$\Gamma_e = \sigma J/e\,, \tag{1}$$

where σ is the cross-section for ejecting the atoms from the trap, J is the electron current density, and e the electron charge. By measuring Γ_e and J, we determine σ directly from eq. (1).

The detailed operation of the experiment is as follows. The electron beam is pulsed on as part of a time sequence of events, summarized in fig. 2. The magnetic-field gradient is turned off, and becomes negligibly small in less than 0.5 ms. This ensures that the electron beam is not distorted by the magnetic field, and no magnetic forces are applied to the atoms. At the

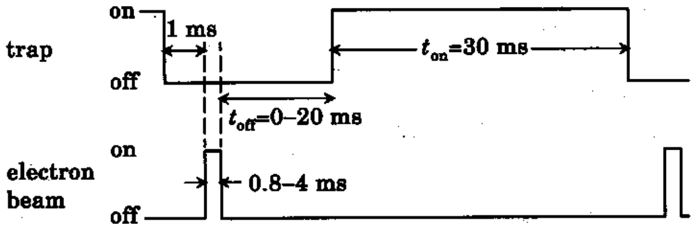

Fig. 2. – Rapid time sequence of the experiment. First, the magnetic field is turned off and the modulation frequency is shifted, effectively turning off the trap. After 1 ms, the electron beam is pulsed on. The recoiling atoms are allowed to travel on ballistic orbits for a time t_{off}, following which the trap is turned on again and the atoms are retrapped for 30 ms.

same time the 2.9 GHz modulation frequency of the diode laser is shifted by ~200 MHz, taking the laser out of resonance with the $F = 2 \rightarrow F' = 3$ transition. As a result of spontaneous Raman scattering the atoms are then optically pumped into the $F = 2$ state in about 0.3 ms, and cease to fluoresce. After 1 ms the electron beam is pulsed on for 0.8–4 ms. The atoms are then allowed to travel ballistically for a time t_{off}, which can be varied from 0–18 ms. This allows atoms with even very small recoil velocities to leave the trap. Assuming the radius of the trap capture volume to be equal to the radius of the laser beams, we estimate the capture velocity of our trap to be only 31 cm/s at $t_{off} = 18$ ms, corresponding to an electron scattering angle of only 1.6° at 10 eV. Finally, the trap is turned on again for $t_{on} =$ $= 30$ ms, which is sufficient time for recaptured atoms to return to the center of the trap. The value of the fluorescence at the end of trapping time is proportional to the number of atoms remaining in the trap.

Since the fraction of atoms ejected from the trap by one electron pulse is quite small, typically < 5%, we deduce Γ_e by observing the slow changes in the number of atoms in the trap. This is similar in principle to the photoionization technique developed by Dineen *et al.* [11]. The number of atoms N is determined by loading of the atoms from the background Rb vapor at a rate L and loss of the atoms from the trap due to collisions with the electrons at a rate $\Gamma_e f$ (f is the duty cycle of the electron beam) as well as collisions with vacuum residuals at a rate Γ_0:

$$\frac{dN}{dt} = L - (\Gamma_0 + \Gamma_e f)N. \tag{2}$$

Beginning with $N = 0$, we record the trap fluorescence transient

$$N(t) = N_0(1 - \exp[-(\Gamma_0 + \Gamma_e f)t]) \tag{3}$$

as the trap fills to a steady-state number of atoms, N_0. The transient is sampled at the end of each trapping cycle. We do this with and without the electron beam on, and from the two transients we determine Γ_e and thus σ from eq. (1). By collecting a series of such transients with variable values of the ballistic flight time t_{off}, we find that σ tends toward an asymptotic value as shown in fig. 3. Since increasing t_{off} allows slower atoms to escape the trapping volume, corresponding to smaller scattering angles, the asymptotic value represents the total scattering rate of Rb atoms by the electrons.

Given the asymptotic total scattering rate, we measure the electron beam current density J to determine the total scattering cross-section from eq. (1). The total electron beam current is measured with a Faraday cup (whose end plate is positively biased to prevent secondary electron escape) and an electrometer. The line-integrated transverse spatial profile of the

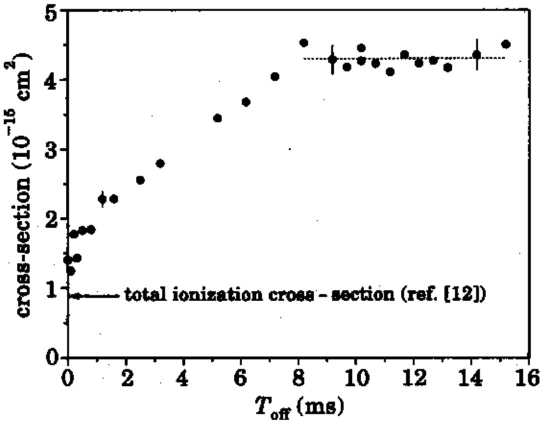

Fig. 3. – Dependence of the measured electron scattering cross-section $\sigma = e\Gamma_e/J$ on $t_{\rm off}$, the amount of time the trap is left off after the electron pulse, for an electron energy of 50 eV. The asymptotic value gives the total cross-section, while the value at $t_{\rm off} = 0$ gives an upper limit on the ionization cross-section.

electron beam is measured at the position of the atom trap with a scanning thin-wire (0.003 in. W) detector. Using the total electron beam current and an Abel transformation of the thin-wire signal, we determine the current density at the trap. The use of the Abel transform requires cylindrical symmetry of the electron beam. The thin-wire signal was found to be symmetric. The electron beam was quite stable, with variation of the current density of only a few percent over several days. The electron energy is determined using a retarding-potential difference method. The energy spread of the electron beam is less than 0.5 eV FWHM for energies below 30 eV and increasing slightly for higher energies. The electron gun assembly was mounted on a gimbal mount for precise aiming of the electron beam.

A number of systematic checks have been performed to ensure that the asymptotic cross-sections are accurate. The asymptotic cross-sections were studied while varying the laser intensity, laser detuning, laser beam diameter, $t_{\rm on}$, electron beam spatial profile, electron beam pulse duration, and the electron beam current density. As a result of these studies, and using various fitting functions to determine the asymptotic value of Γ_e, we estimate that the uncertainty in determining Γ_e is about 6%. The other principal source of uncertainty in our results is the determination of the spatial profile of the electron beam deduced from the scanning thin-wire measurements, the error in which we estimate at 7%. We, therefore, conclude that the overall uncertainty in our results is about 9%.

The total cross-section for electron scattering from Rb(5S) atoms is shown in fig. 4, along with the previous results of Viscotti *et al.* [3]. We find excellent agreement at 7 eV. Also shown in fig. 4 are absolute ionization cross-sections measured by McFarland and Kinney [12], and absolute 5S-5P optical cross-sections, normalized to theory at high energy, as reported by Chen and Gallagher [13]. Our total cross-sections in the high-energy range are smaller than the sum of these partial cross-sections.

We can also determine an upper limit on the ionization cross-section from our data by noting that for $t_{\rm off} = 0$ the measured cross-section is the sum of the total ionization cross-section and the large-momentum-transfer scattering from other processes. Figure 3 shows an example at 50 eV. At all energies we obtained upper limits consistent with the values of ref. [12].

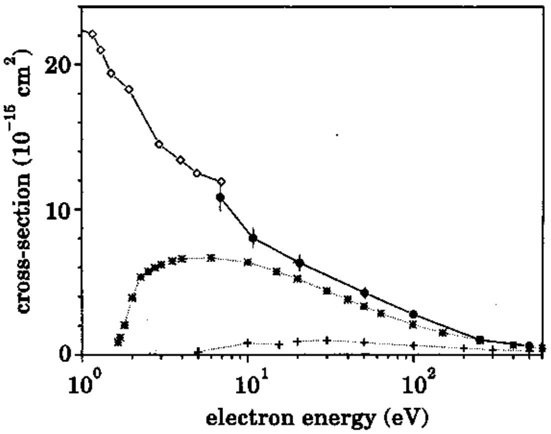

Fig. 4. – Absolute electron scattering cross-sections as a function of energy. ● Total cross-sections (this work). ◇ Crossed beam measurement (ref. [3]). * Optical cross-section for $5S$-$5P$, normalized at high energy to theory (ref. [13]). + Ionization cross-section (ref. [12]).

The principal advantage of our technique for determination of total cross-sections is the substantial simplification of the apparatus as compared to atomic beam experiments and the straightforward interpretation of the measurements. The system is quite compact; the vacuum chamber, diode laser, and all associated optics fit within $1\,\text{m}^2$. The data analysis consists of fitting two separate exponential transients and the measurement of the electron beam current density. The current density is the only absolute quantity required. Also we note that the atom trapping technology used is now quite widespread, especially with the ease of use of diode lasers. The advantages of having a well-localized, cold source of atoms for a target in a scattering experiment are great.

The use of a MOT for scattering experiments should prove to be a powerful tool for reliable measurements of cross-sections. The apparatus described here should be readily adaptable to measurements of scattering from heavy ions or atoms. Another advantage of MOTs is the ability to produce substantial quantities of excited-state atoms. It should be feasible to saturate the resonance transition and measure scattering from P states and to produce substantial populations in the D states as well. Since MOTs have been demonstrated for a wide variety of atoms, including the alkalis, the metastable rare gases, and the alkaline earths, there are a wide variety of species to which this technique is applicable.

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REFERENCES

[1] Foot C., *Contemp. Phys.*, 32 (1991) 369 gives a basic introduction to laser cooling and trapping. Other general references are Chu S. and Wieman C. (Editors), *J. Opt. Soc. Am. B*, 6 (1989) 2020; Arimondo E., Phillips W. and Strumia F. (Editors), *Laser Manipulation of Atoms and Ions, Proceedings for the International Summer School of Physics «Enrico Fermi», Course CXVIII* (North Holland, Amsterdam, New York) 1992.

[2] Rubin K., Perel J. and Bederson B., *Phys. Rev. A*, 117 (1960) 151; Bederson B. and Kieffer L., *Rev. Mod. Phys.*, 43 (1971) 601.
[3] Visconti P., Slevin J. and Rubin K., *Phys. Rev. A*, 3 (1970) 1310.
[4] MacAdam K. B., Steinbach A. and Wieman C., *Am. J. Phys.*, 60 (1992) 1098.
[5] Bray I., *Phys. Rev. Lett.*, 73 (1994) 1088.
[6] Hoffmann D., Feng P. and Walker T., *J. Opt. Soc. Am. B*, 11 (1994) 712.
[7] Wieman C. and Hollberg L., *Rev. Sci. Instrum.*, 62 (1991) 1.
[8] Myatt C., Newbury N. and Wieman C., *Opt. Lett.*, 18 (1993) 649.
[9] Feng P. and Walker T., submitted to *Am. J. Phys.*
[10] Fillipelli A., Lin C., Anderson L. and McConkey J., *Adv. At. Mol. Opt. Phys.*, 33 (1994) 1.
[11] Dinneen T., Wallace C., Tan K. and Gould P., *Opt. Lett.*, 17 (1992) 1706.
[12] McFarland R. and Kinney J., *Phys. Rev.*, 137 (1965) A1058.
[13] Chen S. and Gallagher A., *Phys. Rev. A*, 17 (1978) 551.