Measurements of Total Cross Sections for Positrons and Electrons Colliding with Atomic Hydrogen

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We have made the first measurements of total cross sections (Q_T) for 5 to 302 eV positrons (e^+) and 31 to 302 eV electrons (e^-) scattered by atomic hydrogen. A beam transmission technique is used where the e^+ or e^- beam passes through a low temperature scattering cell containing a mixture of hydrogen atoms and molecules generated in an adjacent radio-frequency discharge region. We obtain absolute Q_T's by using the factor required to normalize our present relative e^+-H_2 Q_T measurements to our prior absolute results. The present e^+- and e^--H Q_T's are found to be merged within about 5% between 31 and 302 eV.

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The scattering of positrons (e^+) and electrons (e^-) by atomic hydrogen are among the most fundamental atomic collision processes. This consideration along with the fact that hydrogen is the only atom for which the wave functions are known exactly make the e^+- and e^--H collision processes an attractive testing ground for scattering theories, and many different calculations of partial and total scattering cross sections have been reported for these collision systems. In addition to the opportunity these systems present for making direct comparisons between the scattering of particles and antiparticles from the simplest atom, detailed knowledge of e^--H scattering cross sections is important in research on fusion plasmas and in astrophysics, and interest in e^+-H scattering has been heightened by a need for partial and total e^+-H cross section information by astrophysicists attempting to understand details of the origin of 0.51 MeV annihilation gamma rays which have been observed coming from the direction of the center of the Milky Way galaxy and from solar flares [1].

In view of the substantial theoretical effort that has been devoted to e^+- and e^--H scattering, it may seem somewhat surprising that up to the present time there have not been any measurements of e^+-H total cross sections (Q_T), and no e^--H Q_T measurements have been made above 12 eV. However, absolute Q_T measurements for these collision systems are especially challenging due to the difficulty of obtaining a sufficiently high and accurately determined number density of target atomic hydrogen gas.

In this paper we report the first Q_T measurements for e^+'s and higher energy (<30 eV) e^-'s scattered by atomic hydrogen. We use a beam transmission technique to measure Q_T where the e^+ or e^- beam is passed through a scattering cell containing a mixture of atomic and molecular hydrogen generated in an adjacent radio-frequency (rf) discharge region as shown in Fig. 1.

Variable energy e^+ beams (obtained from a 0.004 mm thick tungsten moderator placed in front of a ^{22}Na e^+ source) whose energy distribution has a full width at half maximum (FWHM) of about 1 eV, or e^-'s (secondary e^-'s from the same moderator) with a FWHM of several eV, are guided by a lens system and a curved solenoid [2] to the scattering cell. The projectiles which emerge from the cell are detected by an off-axis Channeltron electron multiplier (CEM). A retarding potential grid assembly located between the scattering cell and the CEM is used to energy analyze the projectile beams and to provide additional discrimination (beyond geometrical considerations) against projectiles scattered through small angles [2]. The estimated angular discrimination of our apparatus for elastically scattered e^+'s (about 33° at 5 eV, 28° at 10 eV, 19° at 20 eV, and less than 11° above 50 eV) and e^-'s (about 13° at 30 eV and less than 7° above 50 eV) could make our e^+-H Q_T measurements about

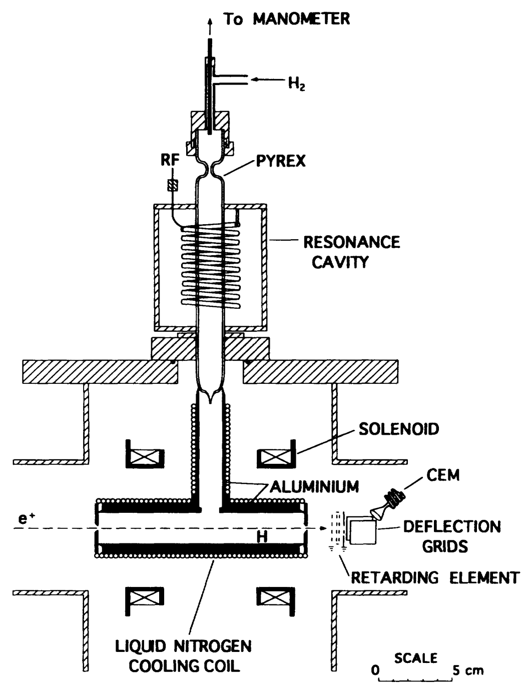

FIG. 1. Apparatus for measuring total cross sections for positron and electron-H collisions.

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3% too low above 20 eV, 13% too low at 10 eV, and 50% too low at 5 eV, and our e^--H Q_T measurements 10% too low at 30 eV and less than 5% too low above 50 eV [3]. We have essentially 100% discrimination against inelastically scattered projectiles [2].

The target gas flows into the cylindrical aluminum scattering cell from an adjacent Pyrex rf discharge tube. The discharge is excited by feeding about 25 W of rf at 29 MHz into a resonant coaxial cavity. The gas flowing into the scattering cell is H_2 when the rf discharge is off and a mixture of H_2 and H when the rf discharge is on. Recombination of H atoms in the scattering cell is minimized [4] by maintaining the cell temperature at about 150 K.

In an ideal beam-transmission experiment, Q_T can be obtained from the relationship

$$Q_T=(1/nL)\ln(I_0/I) \tag{1}$$

by measuring the projectile beam current (I_0) transmitted through an evacuated scattering cell of length L, and the projectile beam current (I) transmitted through the same scattering cell when it contains gas of number density n. In our experiment, we first measure relative total cross sections for e^+- and e^--H_2 scattering with the rf discharge turned off. These are *relative* cross sections because they are obtained using the pressure measured (using a capacitance manometer) above the rf discharge tube (as shown in Fig. 1), whereas the pressure is lower than this in the scattering cell. However, by determining the factor required to normalize our relative e^+-H_2 cross section at 100 eV to our corresponding earlier absolute e^+-H_2 Q_T measurement [5], and applying this same factor to all of our relative e^+- and e^--H_2 Q_T measurements, we are able to obtain absolute total cross sections, $Q_T(H_2)$ for e^+'s and for e^-'s.

Our present absolute e^+- and e^--H_2 Q_T's are shown in Fig. 2 along with prior measurements [5–8]. The very good agreement of our present Q_T's with the prior measurements supports the basic validity of our method for obtaining absolute Q_T's at all of the investigated energies for both projectiles using just the normalization factor required to normalize our present relative e^+-H_2 Q_T at 100 eV.

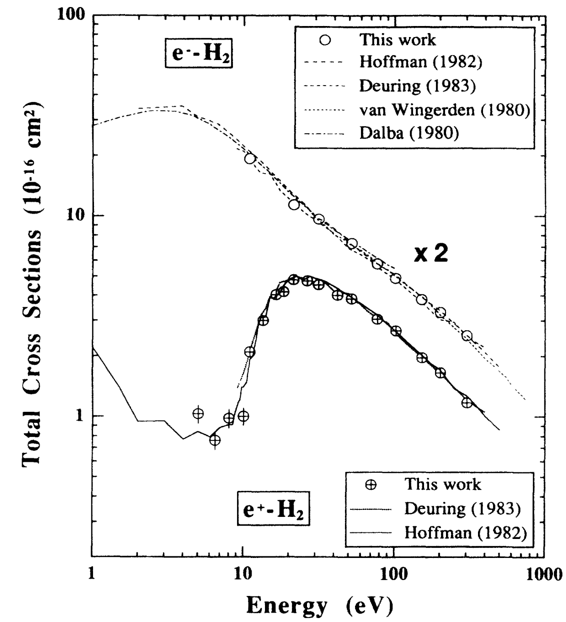

FIG. 2. Positron- and electron-H_2 total cross section measurements. The electron-H_2 cross sections are multiplied by 2 for graphical clarity. All of the prior measurements are represented by curves generated from straight line segments drawn between neighboring points. Statistical uncertainties for the present results in this and in the following figures are represented by error bars except where they are encompassed by the size of the symbols.

In order to obtain the total cross section $Q_T(H)$ for e^+'s or e^-'s scattered by atomic hydrogen, we determine the projectile beam attenuation with the rf discharge on $[(I_0/I)_{rf\,on}]$, and the beam attenuation with the rf discharge off $[(I_0/I)_{rf\,off}]$ with the flow of H_2 into the discharge tube kept constant. Using this information, $Q_T(H)$ can be determined from the relationship [3]

$$Q_T(H)=(1/2)^{1/2}Q_T(H_2)((1/f)\{[\ln(I_0/I)_{rf\,on}/\ln(I_0/I)_{rf\,off}]-1\}+1)\,, \tag{2}$$

where $f=1-n'(H_2)/n(H_2)$ is the degree of dissociation of the H_2, while $n'(H_2)$ and $n(H_2)$ are the number densities of molecular hydrogen in the scattering cell for the discharge on and off, respectively. In order to determine a lower limit on f, the gas effusing from the exit aperture of the scattering cell is chopped and monitored (using phase-sensitive detection) with a quadrupole mass spectrometer. This enables us to measure the ratio of the heights of the H_2 peaks in the mass spectrum with the rf discharge on and off, respectively, with the flow rate of H_2 into the discharge tube kept constant. This information enables us to deduce that f for the H_2 entering the mass spectrometer remains quite stable at a value of about 0.46 when the scattering cell temperature is maintained at approximately 150 K. We consider 0.46 to be a lower limit on f in the scattering cell since some of the H atoms entering the cell from the discharge recombine before leaving the cell. The upper limit of f in the scattering cell is simply taken as 1.00 since this would correspond to 100% dissociation of the H_2 in the cell. By using the extreme values of 0.46 and 1.00 for f in our scattering cell along with Eq. (2) we are able to determine upper and lower limits for e^+-H and e^--H Q_T values. It should be noted that a value of f in the scattering cell of 0.46 corresponds to 55% of all target particles in the scattering cell being atomic hydrogen, while a value of f of 1.00 corresponds to 100% of the particles in the scattering cell being atomic hydrogen.

Our measured upper ("This work 55%") and lower ("This work 100%") limits on e^+-H and e^--H Q_T values are shown in Fig. 3 along with prior measurements [9,10] and semiempirical results [11] (for e^-'s), and theoretical results [12–19] (for e^+'s and e^-'s). For graphical clarity, and due to limited space, we have selected only a few of the large number of available theoretical calculations considered to be good representations of the most reliable [12,18].

It is intriguing that the lower and upper limits for e^+-H and e^--H scattering at energies above 30 eV are very close to each other and also tend to agree with available calculations [12,15,17–19] and with the semiempirical results of de Heer, McDowell, and Wagenaar [11] (for the e^--H case). However, it may be worthwhile noting that the results of Scholz, Walters, and Burke [18], who have attempted to construct accurate e^--H Q_T's by adding together the best available integrated elastic, excitation, and ionization cross sections, are somewhat lower than our measured lower limits (and the semiempirical results of de Heer, McDowell, and Wagenaar [11]) from 30 to 50 eV.

Below 30 eV, our e^+-H lower and upper limits have larger separations than those at higher energies, but bracket the theoretical results of Higgins, Burke, and Walters [15] and of Winick and Reinhardt [14] for most of the energy range of overlap. Winick and Reinhardt have pointed out [14] that their results above 6.8 eV are not fully converged, and should be regarded as lower bounds on the actual Q_T's, and this may be responsible for their results being somewhat below our lower limits on Q_T at their highest energies.

A comparison between our measured $e^{+,-}$-H and $e^{+,-}$-H_2 Q_T's is shown in Fig. 4 along with some prior results [5,11–15,19]. It is seen that our e^+ and e^- Q_T's for H are merged to within about 5% over the entire energy range from 31 to 302 eV, and we have determined that this merging is not appreciably affected by angular discrimination considerations. Such a merging (or at least a very near merging) is supported by the calculations of Walters [12] and van Wyngaarden and Walters [19] (using a pseudostate close-coupling approximation that is supplemented by the second Born approximation) for 54.4–300 eV positrons and electrons. Our observed merging above 30 eV is remarkable when it is realized that the integrated elastic cross section for e^-'s is estimated [16] to be more than 4 times as large as that calculated [15] for e^+'s at 30 eV and still about 40% larger [12] even at 300 eV. This means that from at least 31 eV up to 302 eV, although the integrated elastic cross section is appreciably larger for electrons than for positrons, the sum of the integrated inelastic cross sections, including all excitations, ionization, and (for e^+'s) positronium formation must be just the right amount larger for e^+'s than it is for e^-'s to nearly exactly compensate for the differences in their integrated elastic cross sections. It is

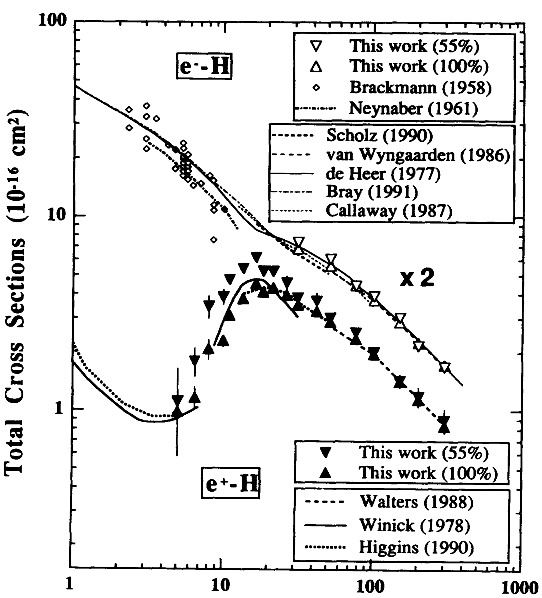

FIG. 3. Positron- and electron-H total cross sections.

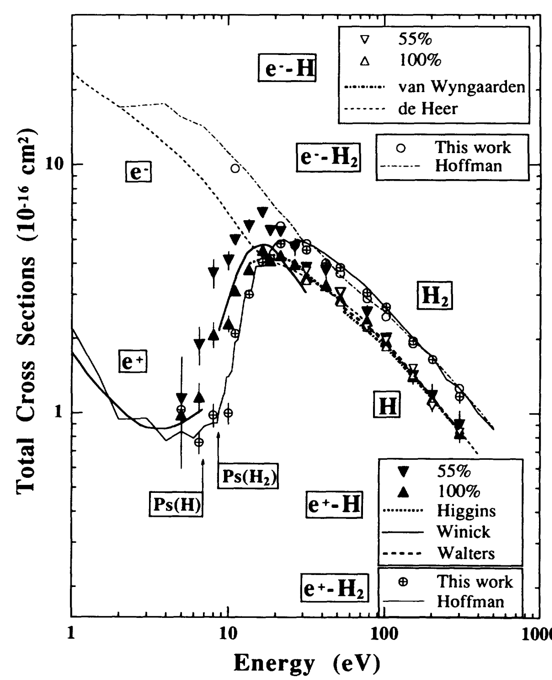

FIG. 4. Comparison of positron- and electron-H and H_2 total cross sections. Arrows indicate the locations of the positronium formation thresholds for H (6.8 eV) and H_2 (8.6 eV).

also intriguing that the e^+ and e^- Q_T's have merged to within 5% at an energy of 31 eV where the measured [20] positronium formation cross section comprises about 70% of Q_T for e^+-H scattering. Noise problems for e^- energies below 30 eV prevented us from investigating whether our observed merging of Q_T's extends to even lower energies. Our observed merging shows that although the partial cross sections that contribute to Q_T are behaving very differently for e^+'s and e^-'s, the various scattering channels for each projectile appear to be "coupled" with each other in the sense that the sums of the partial cross sections (i.e., the Q_T's) for e^+'s and e^-'s turn out to be nearly identical. In our prior work [2,5], we have observed this type of merging of the e^+ and e^- Q_T's for He and for H_2 near 200 eV, an energy at which (at least for He) the partial cross sections which contribute to Q_T are still behaving very differently [21].

In relation to the question of mergings of e^+ and e^- cross sections at unexpectedly low energies, it is of interest that a theoretical analysis by Dewangan [22] related to higher order Born amplitudes calculated in the closure approximation has been shown to imply [23,24] that if e^- exchange can be ignored in the e^--scattering case, and if the closure approximation is valid, then a merging (or near merging) of e^+- and e^--atom Q_T's can occur at energies considerably lower than the asymptotic energies at which the first Born approximation is valid.

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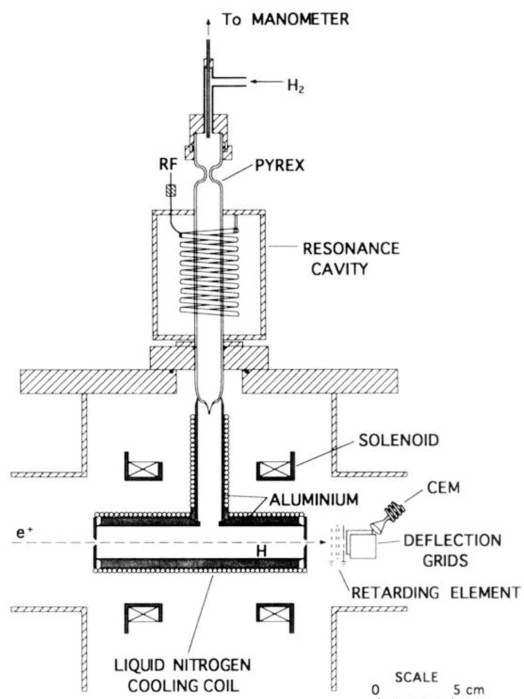

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