Measurement of absolute differential cross sections for the excitation of atomic hydrogen to its $n=3$ and 4 levels by electron impact

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Using a modulated crossed-beam method, we have measured absolute differential cross sections for the excitation of atomic hydrogen to its $n=3$ $(3\ ^2S+3\ ^2P+3\ ^2D)$ and $4(4\ ^2S+4\ ^2P+4\ ^2D+4\ ^2F)$ levels by electron impact. A wide range of scattering angles was covered, while the impact energies employed were 20 and 30 eV. Absolute integrated excitation cross sections were calculated from the differential ones. Our results are compared with those of others.

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I. INTRODUCTION

During the past few years there has been a revival of interest in the electron–hydrogen-atom collision system. This system is critically important in atomic physics because it represents the simplest example of a quantum three-body problem with at least one particle unbound, and also because the hydrogen atom's are the only atomic wave functions known analytically. Novel theoretical approaches—most notably the convergent close-coupling (CCC) method of Bray and co-workers [1–4] and the exterior complex-scaling technique of Resigno and co-workers [5,6]—have finally made plausible the claim to be able to calculate reliable, accurate cross sections for this collision system in the intermediate-energy range. The development of high-intensity atomic hydrogen beams has furthermore benefited experimentation considerably, making excitation cross-section measurements for this collision process much more feasible than they were just a few years ago [7]. Such cross-section measurements are what we shall discuss here.

The most recent experiments have concentrated on the $n=2$ excitation process. Khakoo *et al.* determined absolute $n=2(2\ ^2S+2\ ^2P)$ level excitation cross sections over a wide range of scattering angles for impact energies between 30 and 100 eV. They also calculated values for these cross sections with the CCC technique [8,9]. We made measurements of the same cross sections over the scattering-angle range from 12° to 156° and impact energies from 15 to 40 eV [10]. Agreement among these results is quite good. Agreement among the experimental values is especially promising, as the experiments were done using two entirely different normalization schemes. At lower energies our results agree well with the CCC method's cross sections, even high into the backscattering region, where we both found somewhat stronger scattering than the older measurements of Williams did [11].

Now that progress has been made for the $n=2$ excitation process, the next step is to investigate excitation of the higher levels. In this article we present measured absolute differential cross sections (DCSs) for the excitation of atomic hydrogen's $n=3$ and 4 levels by electron impact. No attempt was made to decompose the DCSs into contributions from sublevels of different angular momenta. We employed a modulated crossed-beam method and treated the impact energies of 20 and 30 eV. A wide range of scattering angles was employed. Absolute integrated cross sections (ICSs) were calculated from the DCSs. Comparison of our $n=3$ DCS results is made with the results of others. Unfortunately, to our knowledge no other $n=4$ results have yet been published—either experimental or theoretical—precluding any comparison here.

II. EXPERIMENT

Our experimental apparatus and procedures have been described extensively elsewhere in the physics literature [12–15]. We therefore provide only a rudimentary description of them here. Our system is housed in a dual-chamber, differentially pumped vacuum enclosure. The entire system is surrounded by three sets of mutually-perpendicular Helmholtz coils, which limit magnetic fields to less than 20 mG in the electron-atom interaction region.

Research-grade molecular hydrogen is introduced into an Evenson cavity located in the upper chamber. Here the hydrogen is dissociated by microwave discharge. The resulting beam was consistently $55\pm3\,\%$ atomic hydrogen as measured by a quadrupole mass spectrometer located in the interaction region. Just prior to entering this region the beam is chopped at audio frequencies by a toothed wheel.

Electrons are produced by a gun based on a tungsten filament. They pass through a 127° cylindrical energy selector, which has lenses at both its entrance and exit pupils. They are then accelerated to the required impact energy, which is calibrated by use of the 19.34-eV resonance of helium. The beam thus produced can be rotated from $-90°$ to 160°, has an energy spread of 180 meV full width at half maximum (FWHM), and has an angular spread of $\pm3°$ FWHM. Scat-

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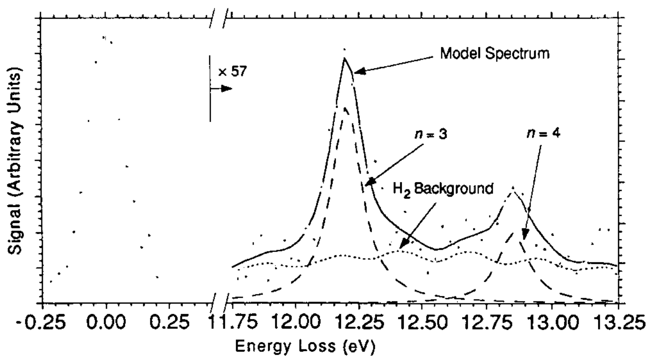

FIG. 1. A typical energy-loss spectrum for the excitation of atomic hydrogen by electron impact at an impact energy of 20 eV and a scattering angle of 36°. Dots denote measured data points, while the solid line denotes the fit to these points, and the dotted line indicates the chopper-closed background, due mostly to recombined molecular hydrogen. The difference between these two is the fit to the $n=3$ and 4 excitations, and is portrayed by the dashed line. Note the axis break in the figure.

tered electrons are collected by a detector attached to the lower chamber's wall. This detector has a 127° cylindrical energy analyzer with lenses at both its entrance and exit pupils. It subtends a solid angle of 5×10^{-4} sr, and ends with a Channeltron electron multiplier.

During measurements the impact energy and scattering angle are fixed, while the energy-loss window of the detector is swept over the region of interest. All this is under the control of a dedicated micromputer running locally developed software. This microcomputer also accumulates and stores the data, and performs the signal subtraction required by the beam modulation. The results are energy-loss spectra like the one shown in Fig. 1.

III. DATA ANALYSIS

Modulation of the hydrogen beam makes analysis of the data a little complicated, since the beam contains both atomic and molecular components. The method of contending with this is treated in detail elsewhere [16,17]. The result is that the absolute excitation DCS—denoted $d\sigma_{\mathrm{H},n=3,4}/d\Omega$ for $n=3$ or 4 as appropriate—is given by

$$\frac{d\sigma_{\mathrm{H},n=3,4}}{d\Omega}=\frac{S_{N,n=3,4}}{S_{\mathrm{H+H_2,elas}}}\left[\frac{d\sigma_{\mathrm{H,elas}}}{d\Omega}+\left(\frac{1-D}{\sqrt{2}D}\right)\frac{d\sigma_{\mathrm{H_2,elas}}}{d\Omega}\right]. \tag{1}$$

Here $S_{\mathrm{H},n=3,4}$ and $S_{\mathrm{H+H_2,elas}}$ denote the $n=3$ or 4 excitation and elastic signal strengths, respectively, while D indicates the dissociation fraction. $d\sigma_{\mathrm{H,elas}}/d\Omega$ and $d\sigma_{\mathrm{H_2},elas}/d\Omega$ are the atomic and molecular hydrogen elastic cross sections, respectively. For these we chose the values previously measured by our research group [18–20]. The spectra were corrected for the transmission efficiency of the detector with respect to energy. The signal strengths for Eq. (1) were determined from the spectra by least-squares minimization, with the signals represented as Gaussian line shapes [21].

TABLE I. Sources of uncertainty and net uncertainties in our measurements.

Source	Contribution (%)
Raw data (statistics)	20
Dissociation fraction	3
Transmission correction	4
Uncertainties in elastic DCSs	15
Total for DCSs	25
Extrapolation	10
Total for ICSs	27

With the DCSs available we computed the ICSs (denoted σ_i) by evaluating

$$\sigma_i=\int d\varphi\, d\theta \sin\theta \frac{d\sigma}{d\Omega}, \tag{2}$$

via the trapezoid rule. This required that we extrapolate our results to both 0° and 180°, which we did in a semiexponential fashion. Uncertainty introduced by this extrapolation—as well as that introduced in other ways—is given in Table I. This table also provides net uncertainties, which were determined by addition of the uncertainties' sources in quadrature, since these source uncertainties were independent of each other.

IV. DISCUSSION OF RESULTS

Our absolute $n=3$ excitation cross sections are provided in Table II, while our corresponding $n=4$ data are given by Table III. Figure 2 shows our $n=3$ DCSs at 20-eV impact. The calculated cross sections of Wang, Callaway, and Unni-

TABLE II. Absolute excitation cross sections for the $n=3$ level of atomic hydrogen by electron impact. Units for the differential cross sections are 10^{-18} cm^2/sr, while those for the integrated cross sections are 10^{-18} cm^2. Parentheses enclose extrapolated values.

	E (eV)	
θ (deg)	20	30
12	(10.5)	15.6
24	3.9	4.2
36	1.7	0.96
48	0.68	0.47
60	0.51	0.22
72	0.36	0.18
84	0.36	0.16
96	0.34	0.13
108	0.33	0.12
120	0.33	0.13
132	0.38	0.11
144	0.51	0.072
156	0.53	0.076
168	(0.55)	(0.078)
σ_i	11.4	10.8

TABLE III. Absolute excitation cross sections for the $n=4$ level of atomic hydrogen by electron impact. Units for the differential cross sections are 10^{-18} cm^2/sr, while those for the integrated cross sections are 10^{-18} cm^2. Parentheses enclose extrapolated values.

	E (eV)	
θ (deg)	20	30
12	(3.4)	4.3
24	1.6	1.4
36	0.71	0.40
48	0.28	0.19
60	0.22	0.085
72	0.13	0.073
84	0.14	0.082
96	0.15	0.069
108	0.16	0.073
120	0.17	
132	0.21	
144	0.23	
156	0.26	
168	(0.29)	
σ_i	5.28	

krishan at 19.58-eV impact are also included in this figure [22]. Both sets of cross sections agree well in terms of angular shape, exhibiting significant backscattering, but their results consistently run higher than ours in magnitude by about 25%. Figure 3 gives our $n=3$ cross sections at 30-eV impact. The impact energy nearest to 30 eV that Wang, Callaway, and Unnikrishnan treated was 35.36 eV, and their predicted DCSs for this energy are included in the figure. The energies here are close enough to each other yet far enough from threshold that meaningful comparison can be made. Agreement is quite good, although their DCSs appear to diminish a little more quickly than ours at high angles. This is to be expected since they employed a higher impact energy than we did. Cross sections computed by Bray at 30-eV impact are also given [1,23]. Agreement of our DCSs with these is also quite good, in most cases within the error bars of our experiment. Additionally, their DCSs exhibit high-angle behavior similar to ours. The only other absolute excitation DCS measurements were performed by Williams, Stelbovics, and Bray [24], but their values are not shown, as these values were for a substantially higher impact energy (54.40 eV), making comparison with our results meaningless.

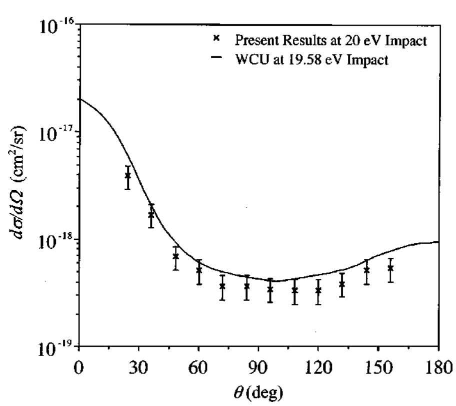

FIG. 2. Absolute differential cross sections for the excitation of atomic hydrogen's $n=3$ level by electron impact at 20-eV impact. Also shown are the calculations of Wang, Callaway, and Unnikrishnan at 19.58-eV impact (denoted WCU).

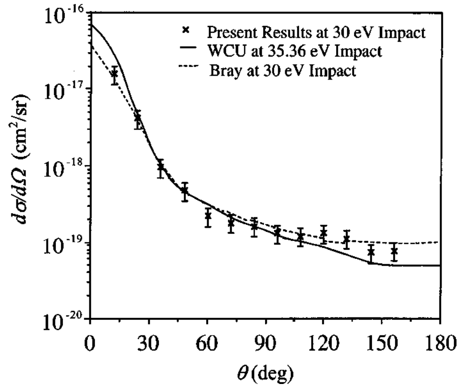

FIG. 3. Absolute differential cross sections for the excitation of atomic hydrogen's $n=3$ level by electron impact at 30-eV impact. Also shown are the calculations of Wang, Callaway, and Unnikrishnan at 35.36-eV impact (denoted WCU), and the calculations of Bray at 30-eV impact.

Figure 4 shows our DCSs for $n=4$ excitation for both 20- and 30-eV impact. At both impact energies the cross sections possess similar angular character, as much as they can be compared with each other. Backscattering is apparent in the 20-eV results. Unfortunately the stability of our apparatus is currently inadequate to accommodate the exceedingly long data integration times required for measurement of the very weak $n=4$ excitation signals for angles above 108°. No other DCS results have yet been published to our knowledge—either experimental or theoretical—so comparison here is impossible.

Tables II and III also provide our ICSs. Agreement among our ICSs and the most recent measured and calculated ones is quite good [25,26]. But as Refs. [25] and [26] discuss in detail the older theory and experiments indicate cross sections both substantially greater and substantially less than

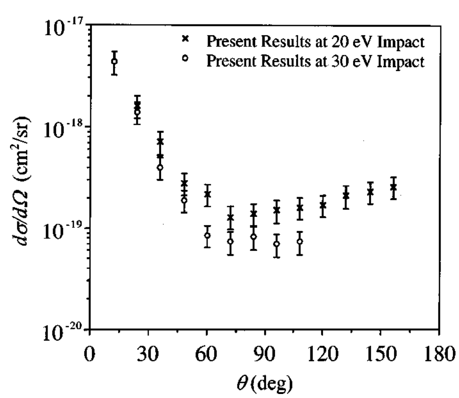

FIG. 4. Absolute differential cross sections for the excitation of atomic hydrogen's $n=4$ level by electron impact.

ours. This, combined with the agreement we have with the most recent DCS calculations, suggests (but clearly does not vindicate) the notion that measurement and calculation methods are finally becoming sophisticated enough to accurately treat the $n=3$ level excitation process. Unfortunately, no ICSs for $n=4$ excitation besides ours have yet been determined to our knowledge, making comparison impossible here.

V. CONCLUSION

We have conducted measurements of absolute differential cross sections for the excitation of atomic hydrogen to its $n=3$ and 4 levels by electron impact. The $n=3$ DCSs compare favorably with available theory. The $n=3$ ICS results agree quite well with the most recent theory and experiment, but not with the older theory and experiment. Unfortunately, we know of no other experimental or theoretical $n=4$ results for comparison. With the recent resurgence of interest in the inelastic electron–hydrogen-atom collision process, we greatly welcome additional research into the aspects of the process we treated here.

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