

Low-energy electron scattering from atomic hydrogen. II. Elastic and inelastic scattering

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We present measurements of differential cross sections for elastic electron scattering from atomic hydrogen at 20 eV and 40 eV incident electron energies and ratios of differential cross sections for electron-impact excitation of atomic hydrogen to the $n=2$, 3, and 4 levels at incident electron energies of 14.6 eV, 15.6 eV, 17.6 eV, 20 eV, 25 eV, and 40 eV with scattering angles ranging from 10° to 130° . We compare our results to available experimental measurements and recent convergent close-coupling calculations. Our results resolve significant discrepancies that existed between theory and past experiments.

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I. INTRODUCTION

In this paper we present additional measurements that were taken during and after the measurements of the doubly differential cross section (DDCS) for electron-impact ionization of atomic hydrogen at low energies which were presented in the previous paper [1], henceforth referred to as I. The present work consists of the following additional measurements regarding electron scattering from atomic hydrogen.

(1) *Differential cross-section ratios for excitation of the $n=2$, 3, and 4 levels of H from the ground state.* As discussed in I, the electron-impact excitation of the $n=2$ level of H was determined experimentally by Khakoo *et al.* [2] [using He $n=2$ differential cross sections (DCS's) as a standard], Grafe *et al.* [3] (using H₂ elastic DCS's as a standard), and Williams [4] (using He elastic DCS's as a standard) to be accurately described (within experimental errors) by the convergent close-coupling (CCC) method of Bray and Stelbovics [5] and Bray [6]. Grafe *et al.* [3] note that at 20 eV impact energy (E_0) and large scattering angles (θ), their measurements were higher than those of Williams [4]. This could possibly be due to the fact that their elastic scattering measurements, which were used to normalize their inelastic DCS's, also show raised backscatter. Agreement between the CCC and $n=2$ Lyman- α emission measurements of James *et al.* [7] is excellent. However, it is not clear if the CCC method adequately describes the excitation of the $n=3$ and $n=4$ levels of H as accurately as the $n=2$ level. The limited DCS measurements by Sweeney *et al.* [8] of the electron-impact excitation of the $n=3$ and $n=4$ levels, taken at $E_0=20$ eV and 30 eV, show good agreement with the CCC method, but these measurements were normalized to their e -H elastic DCS's which show backscattering problems [see (2) below] when compared to the CCC method. Early measurements of the cross sections for the excitation of the individual $n=3$ sublevels by Mahan *et al.* [9] show, within the considerable scatter of the results, reasonable agreement with the CCC method [10]. More recent experimental results employing emission measurements for the excitation of the H $n=3$ level were made by Kedzierski *et al.* [11] and James *et al.* [12]. In the measurements of Kedzierski *et al.* [11] the polarization of the Balmer- α emission of H was observed as a function of E_0 . Their data revealed significant disagree-

ments with the CCC method [11] especially at E_0 values below 40 eV. This could be due to a problem in the determination of cascade processes in the experimental results or to a breakdown in the parallelism of their electron beam at low incident energies leading to a lack of definition of the quantization axis. James *et al.* [12] measured the polarization of the Lyman- β emission of H as a function of E_0 , and their results show quite good agreement with the CCC method over the entire energy range measured including the range $E_0 < 40$ eV. These polarization measurements, however, are not differential with respect to the scattering angle of the electron. Additional definitive measurements regarding the excitation of H $n=3$ are therefore presently necessary. The purpose of this work is to extend our earlier H $n=2$ measurements to H $n=3$ and 4 by measuring relative DCS ratios between the H $n=2$, 3, and 4 levels.

(2) *Relative differential cross sections for low-energy elastic electron scattering from H.* Presently there exists a significant disagreement between the elastic e -H scattering DCSs of Williams [13] and Shyn and Cho [14], Shyn and Grafe [15]. Whereas the DCS's of Williams show very good agreement with the CCC method, those of Shyn and Cho [14] and Shyn and Grafe [15] deviate from the CCC method at large scattering angles—e.g., at $E_0=20$ eV. In fact, at $E_0=20$ eV and 40 eV, the disagreement between Shyn and Grafe [15] and the CCC method is significantly large. This discrepancy is interesting especially at $E_0=40$ eV because our previous measurements of the DCS's for excitation of the H $n=2$ level [2] were found to be in excellent agreement with the CCC method at this and all other incident energies from 30 eV to 100 eV.

The above two areas of discrepancy thus need to be resolved from an experimental standpoint. The present measurements address this discrepancy. Our present results are based on the excellent agreement between the CCC and earlier measurements from Khakoo *et al.* [2] of the DCS's for the H $n=2$ excitation with relative DCS errors below 10% in most cases. Similar agreement has been seen between the CCC and other experiment measurements of the H $n=2$ DCS at lower incident energies [4,6]. We thus use the H $n=2$ DCS's from the CCC method as our calibration standard.

II. EXPERIMENTAL METHOD

Our experimental setup has already been described in I. Our experimental technique differs from those of the previ-

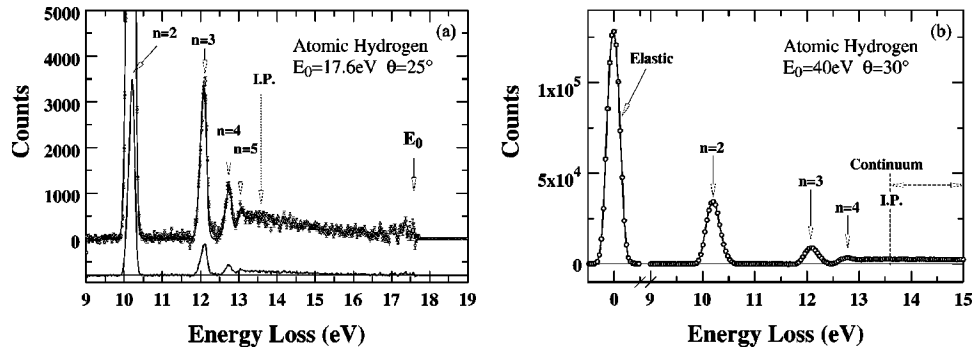


FIG. 1. Electron energy loss spectra of H obtained after the application of the background subtraction procedures described in I. (a) A spectrum of the $n=2$, 3, and partially resolved $n=4$ features. The upper spectrum is offset and multiplied by a factor of 5. The line is the unfolding fit to the spectrum. (b) A spectrum of the elastic scattering feature and the $n=2$, 3 and partially resolved $n=4$ features. See text for added discussion.

TABLE I. R_{32} , R_{42} , and relative elastic DCS's for electron scattering from H at various values of E_0 and θ . Estimated average uncertainties (one standard deviation) are given at bottom of the columns. See text for discussion.

E_0 θ (deg)	R_{32}						R_{42}						Elastic rel. DCS	
	14.6 eV	15.6 eV	17.6 eV	20 eV	25 eV	40 eV	14.6 eV	15.6 eV	17.6 eV	20 eV	25 eV	40 eV	20 eV	40 eV
10						0.164								0.046
12					0.164	0.190					0.057	0.067		
12.5			0.162						0.058					
14.5					0.164						0.051			
15	0.151	0.160	0.157	0.166		0.198	0.061	0.052	0.057	0.058		0.067		1.592
17					0.185						0.059			
17.5			0.169						0.055					
20	0.164	0.172	0.180	0.200	0.188	0.224	0.054	0.059	0.057	0.075	0.073	0.081	0.962	0.902
24						0.251						0.098		
25	0.176	0.193		0.180			0.068	0.069		0.074				
27					0.227						0.088			
30	0.204	0.205	0.216	0.226	0.215	0.264	0.077	0.075	0.080	0.081	0.080	0.106	0.600	0.412
37					0.237						0.086			
40	0.243	0.237	0.226	0.260		0.259	0.101	0.087	0.100	0.102		0.094	0.355	0.270
50				0.287		0.256				0.106		0.089	0.301	0.204
57					0.238						0.096			
60	0.242	0.237	0.242	0.276	0.238	0.277	0.089	0.092	0.095	0.128	0.076	0.107	0.216	0.156
70				0.269		0.269				0.098		0.113	0.183	0.098
80						0.260						0.082	0.127	0.068
87					0.292						0.090			
90	0.198	0.235	0.239	0.263	0.281	0.266	0.054	0.083	0.095	0.110	0.123	0.108	0.103	0.048
100						0.286						0.141	0.083	0.046
105				0.311						0.113			0.083	
110	0.190	0.253	0.282	0.325	0.251	0.281	0.063	0.122	0.122	0.131	0.172	0.113	0.070	0.034
115	0.212						0.066						0.065	
117					0.244						0.119			
120		0.281	0.310	0.303		0.289		0.138	0.148	0.126		0.118	0.067	0.029
125			0.318	0.348					0.133	0.134			0.058	
127	0.232						0.078							
130				0.343		0.281				0.147		0.121	0.060	0.027
134													0.062	
% error	10	8.9	7.8	8.7	8.5	7.5	18.5	17.5	14.2	13.4	18.7	14.1	12.5	14.5

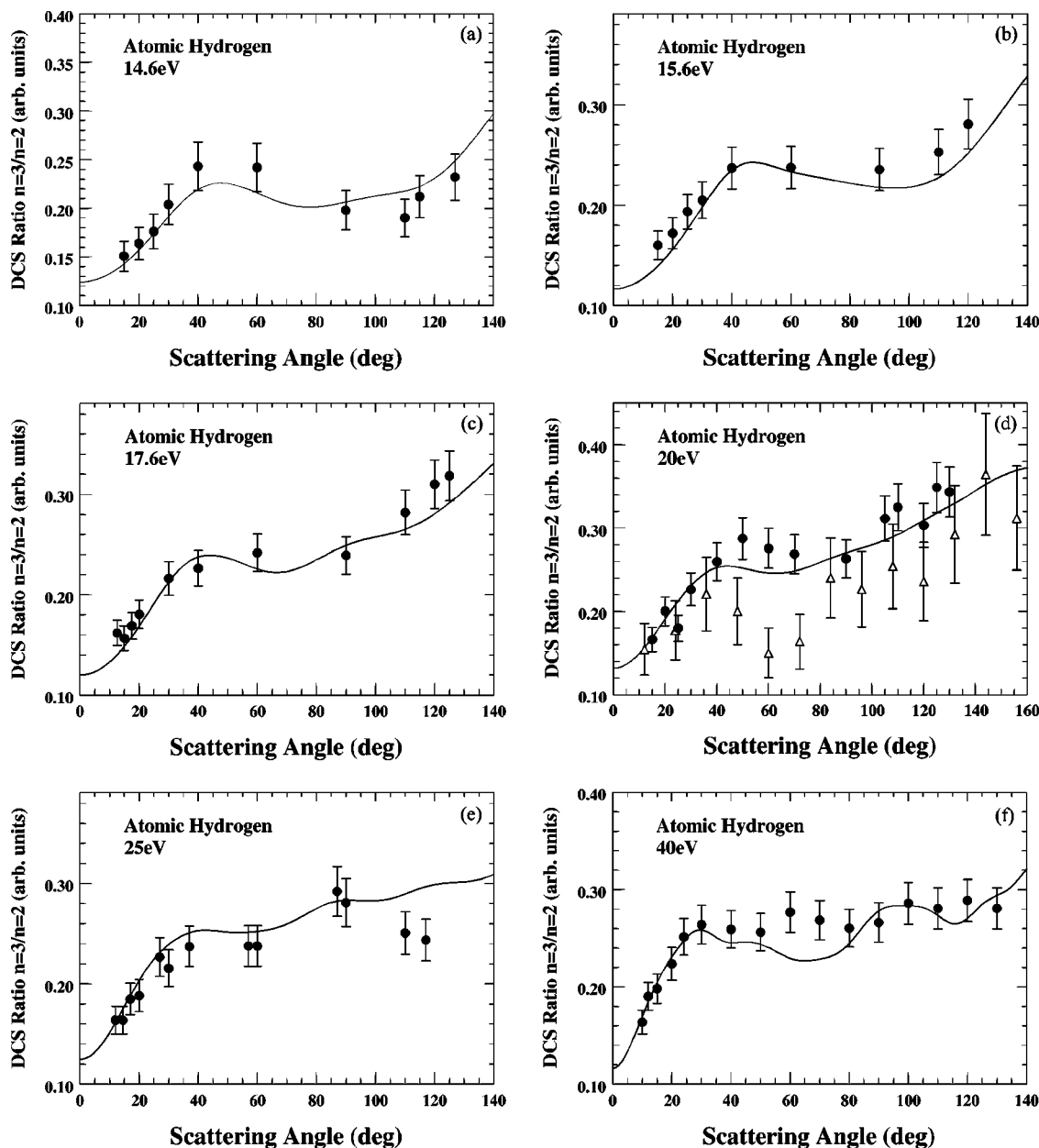


FIG. 2. R_{32} for H at (a) $E_0 = 14.6$ eV, (b) $E_0 = 15.6$ eV, (c) $E_0 = 17.6$ eV, (d) $E_0 = 20$ eV, (e) $E_0 = 25$ eV, and (f) $E_0 = 40$ eV. Legend: ● present work, △ Sweeney *et al.* [8], solid lines CCC [5,6]. Error bars constitute one standard deviation of uncertainty.

ous measurements because no recourse to the use of mass spectrometers is made. Improved measurements of the scattered electron backgrounds are made using a movable target source as described in I. Using this setup, we measured electron energy loss spectra which included the elastic and H $n = 2, 3$, and 4 separated features. These spectra were measured by taking energy loss spectra with the H discharge on and modulating the H target needle source to and from the collision region, and then repeating the measurements with the H discharge off. The subtraction procedures to determine the gas-related e -H scattering energy loss spectra have already been detailed in I. These spectra were corrected for the analyzer transmission efficiency using He as described in I, and the resulting areas under the peaks were related to the

corresponding DCS's. We note that because the He transmission correction did not cover the elastic scattering peak, this remained as a relative DCS but was normalized to the previous DCS's (experimental and theoretical) at small θ where the agreement between these data is excellent. The H $n = 2, 3$, and 4 intensities were determined by fitting these features with an instrumental profile derived from a multi-Gaussian determination of the H $n = 2$ feature [16]. A typical high-resolution unfolded spectrum is shown in Fig. 1(a). A typical spectrum that includes the elastic feature is shown in Fig. 1(b). In a few of the spectra we note the presence of tiny features that add small systematic errors—e.g., counts between the $n = 3$ and $n = 4$ features in Fig. 1(a). We estimated these features to add in the region of $< 10\%$ to the overall

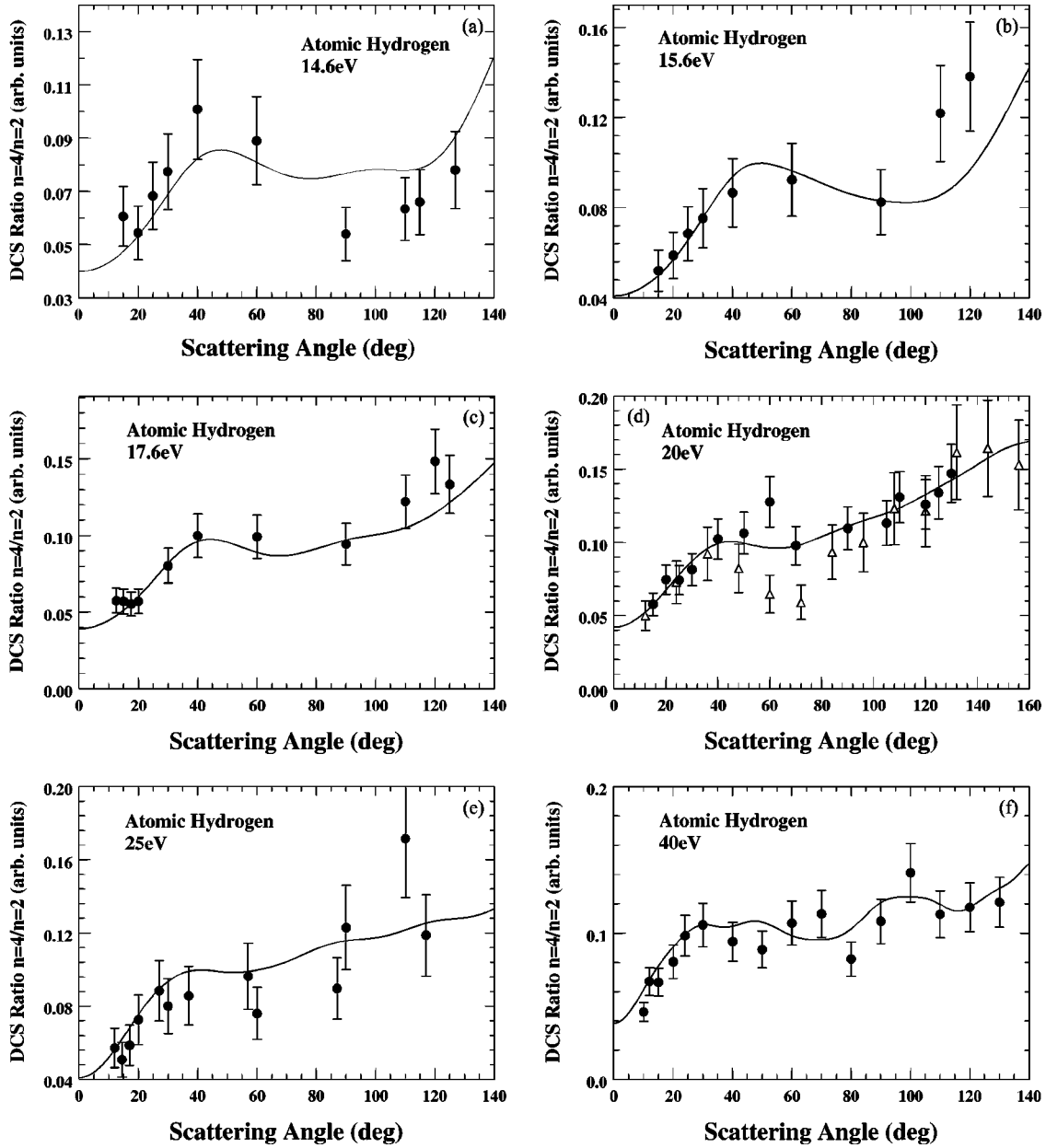


FIG. 3. R_{42} for H at (a) $E_0 = 14.6$ eV, (b) $E_0 = 15.6$ eV, (c) $E_0 = 17.6$ eV, (d) $E_0 = 20$ eV, (e) $E_0 = 25$ eV, and (f) $E_0 = 40$ eV. Legend: ● present work, △ Sweeney *et al.* [8], solid lines CCC [5,6]. Error bars constitute one standard deviation of uncertainty.

uncertainty. We also note that the unfolding of the H $n = 4$ feature is significantly more error prone since it is partially overlapped by the $n > 4$ levels. We have fitted our spectra with n up to 20 in an effort to account for this overlap, but the results of the unfolding for this level still suffer from an increased uncertainty.

Typical uncertainties in the analysis of the spectra include a 5%–10% transmission error (depending on E_0 and the difference in energy loss values of the transitions involved), a nominal 6% error due to uncertainties in the subtraction parameters, and 2%–3%, propagated statistical errors after the subtraction of the discharge on and off spectra. The present results are tabulated, graphed, and compared to existing theoretical and experimental DCS's. Our results are summarized

in Table I and plotted in Figs. 2–5 for comparison with other work.

III. RESULTS AND DISCUSSION

A. Inelastic scattering results

Figures 2(a)–2(f) show our DCS ratios for the H($n = 3$)/H($n = 2$) features (R_{32}). Figures 3(a)–3(f) show our DCS ratios for the H($n = 4$)/H($n = 2$) features (R_{42}). Typical errors for R_{32} are in the region of 7%–10% and for R_{42} in the region of 14%–19%. Clearly the R_{32} show excellent agreement with the CCC method at most E_0 and θ of this work. There is disagreement in a few regions, notably at large θ at

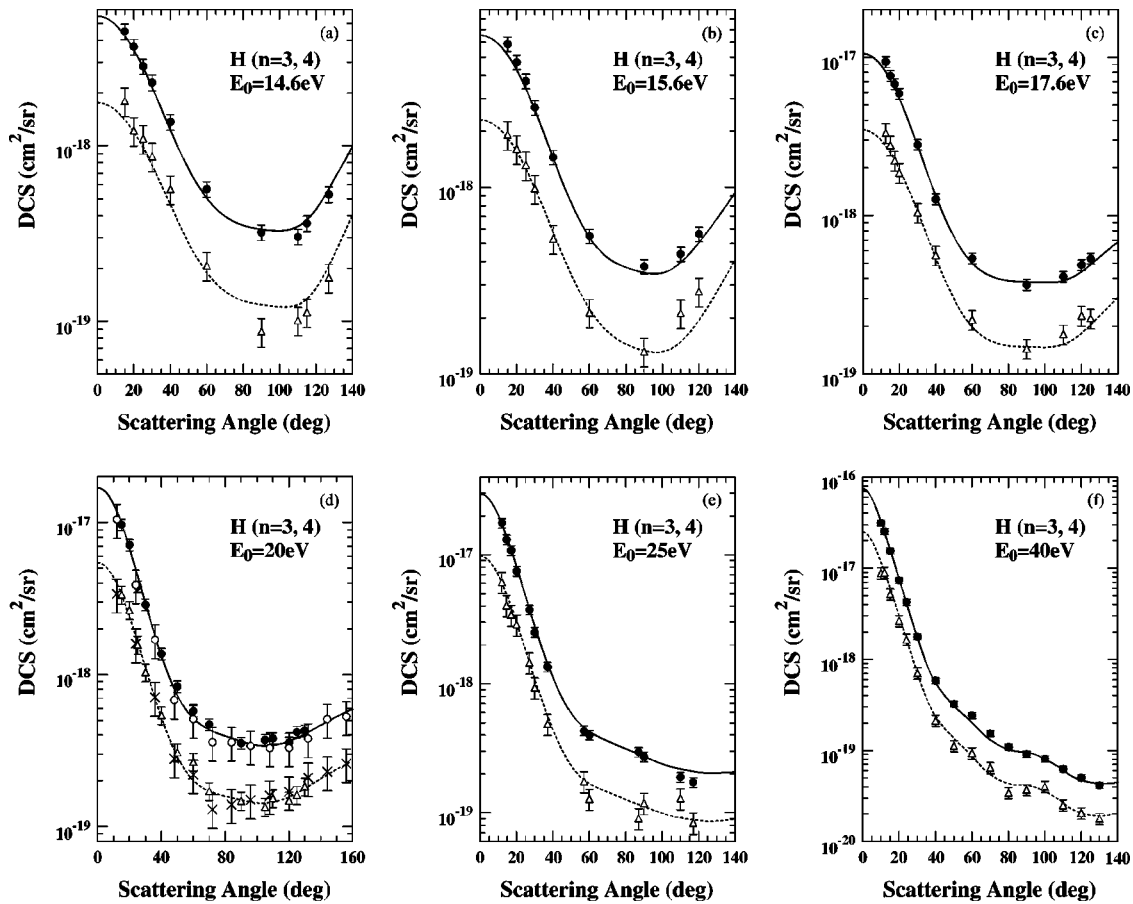


FIG. 4. DCS's for the electron-impact excitation of the $n=3$ and $n=4$ levels of H at (a) $E_0=14.6$ eV, (b) $E_0=15.6$ eV, (c) $E_0=17.6$ eV, (d) $E_0=20$ eV, (e) $E_0=25$ eV, and (f) $E_0=40$ eV. Legend: ● present work ($n=3$), Δ present work ($n=4$), \circ ($n=3$), and \times ($n=4$) absolute DCS's of Sweeney *et al.* [8] at $E_0=20$ eV, solid lines ($n=3$), and dashed lines ($n=4$) CCC [5,6]. Error bars constitute one standard deviation of uncertainty.

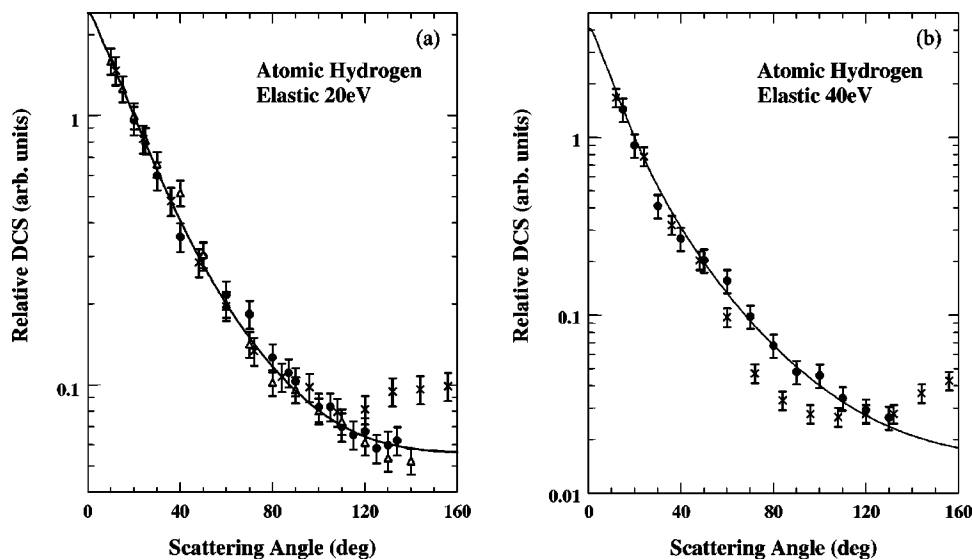


FIG. 5. Relative elastic DCS's for electron scattering from H at (a) $E_0=20$ eV and (b) $E_0=40$ eV. Legend: ● present work, Δ Williams [13], \times Shyn and Cho [14] (20 eV), and Shyn and Grafe [15] (40 eV), solid line CCC [5,6]. The experimental data are normalized to an average of 1 about $\theta=20^\circ$ whereas the CCC DCS=1 at this θ . Error bars constitute one standard deviation of uncertainty.

$E_0=25$ eV [Fig. 2(e)] and at $\theta=60^\circ$ and 70° at $E_0=40$ eV [Fig. 2(f)]. At $E_0=40$ eV we suspect that R_{32} should not show the modulating variation displayed in the CCC method but should instead be smoother. Comparison of the R_{32} at $E_0=20$ eV with the results of Sweeney *et al.* [8] [Fig. 2(d)] shows reasonably good agreement with the exception of the region around $\theta=60^\circ$ where their R_{32} values show a large dip that is in disagreement with our results and the CCC method. Likewise, our R_{42} is in good agreement with the CCC method at most E_0 and θ , although there are again a few areas of small disagreement such as large θ at $E_0=14.6$ eV and 15.6 eV [Figs. 3(a) and 3(b)]. Comparison of the R_{42} at $E_0=20$ eV with the results of Sweeney *et al.* [8] [Fig. 3(d)] again shows good agreement with the exception of the region around $\theta=60^\circ$.

We then converted our R_{32} and R_{42} values to H $n=3$ and $n=4$ DCS's using the accurate CCC H $n=2$ DCS's as a calibration standard. The agreement between our results and both CCC and the measurements of Sweeney *et al.* [8] is very good at all E_0 values as shown in Figs. 4(a)–4(f). However, we note that our R_{32} and R_{42} results offer a more stringent test of the CCC method since we are comparing two independent scattering channels. The present agreement indicates that the CCC method has largely converged and that small discrepancies such as that displayed in Fig. 2(f) can perhaps be resolved by including more channels in the CCC calculation.

B. Elastic scattering results

Figures 5(a) and 5(b) show our relative elastic DCS's compared to the CCC method [5,6] and the experimental DCS's of Williams [13] and Shyn and Cho [14] at 20 eV [Fig. 5(a)] and to Shyn and Grafe [15] at 40 eV [Fig. 5(b)]. Our relative DCS's are normalized to the absolute DCS's about $\theta=20^\circ$. We note that in Fig. 5(a) our relative DCS's are in very good agreement with those of the CCC method

and Williams for all θ of this work and do not reproduce the more backward-peaked scattering profile seen in the results of Shyn and Cho [14]. At 40 eV, Fig. 5(b), we see that our DCS's are again in good agreement with the CCC method but are in disagreement with the DCS's of Shyn and Grafe [15] by at least three standard deviations around $\theta=60^\circ-100^\circ$. We have not measured elastic DCS's at other incident energies because the present results clearly demonstrate that the CCC method obtains excellent values for the DCS's for elastic scattering from H. This is in disagreement with the observations of Shyn and Cho [14] and Shyn and Grafe [15] regarding the reliability of the CCC DCS's at large θ .

IV. CONCLUSIONS

We have presented new measurements of the DCS's for electron scattering from H for both elastic and inelastic processes. The singly differential cross sections presented in this paper coupled with the doubly differential cross sections presented in I, all measured using the movable target H source, provide a significant improvement in the experimental picture regarding electron scattering from H. These results show very good agreement with the CCC method for all differential electron scattering processes from atomic hydrogen over a wide range of incident electron energies and scattering angles.

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