Determination of the absolute partial and total cross sections for electron-impact ionization of the rare gases

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Accurate values of the electron-impact ionization cross sections for the rare gases are needed in a variety of contexts. However, despite numerous investigations over many decades, uncertainty as to the correct values has persisted. The pioneering total-cross-section measurements of Rapp and Englander-Golden are generally regarded as the most reliable but no comprehensive study has independently verified their correctness. In this paper, measurements of electron-impact ionization cross sections of helium, neon, argon, krypton, and xenon are reported for energies ranging from the first ionization threshold to 1000 eV. These data confirm the essential correctness of Rapp and Englander-Golden's total measurements and at the same time provide a complete set of consistent absolute partial cross sections.

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I. INTRODUCTION

Electron-impact ionization of atoms and molecules is a fundamental collision process that occurs in a wide variety of natural and man-made plasmas and accurate ionization-cross-section data are required to quantitatively understand these environments. Furthermore, as calculation of these cross sections is difficult, a precise experimental determination is needed to provide a benchmark against which to test current theories [1]. The importance of such experiments has long been recognized and a large number of experimental studies of the rare gases have already been conducted. It is unfortunate, therefore, that from this large body of work no consensus as to the correct values has emerged.

The measurement of electron-impact ionization cross sections for gaseous targets has a very long history [2]. Pioneering experiments in the 1930s by Smith [3], Tate and Smith [4], Bleakney [5], and Bleakney and Smith [6] were subsequently extended by studies, using superior techniques and equipment. Work in this area has continued steadily and during the past decade much progress has been made towards establishing accurate electron-impact ionization cross sections for molecules. The cross sections for the rare gases on the other hand have received relatively little attention despite their considerable intrinsic interest and the fact that they are often used to normalize other measurements. Disagreements between the available absolute measurements and the magnitude of the uncertainties associated with some of them have prevented the confident assignment of precise values even to the total cross sections [7]. The absolute total charge production cross sections of Rapp and Englander-Golden [8] have, however, been widely accepted as the *de facto* standard, despite the fact that no single, comprehensive, independent study has been performed to confirm their accuracy. The partial cross sections are even less well established than the total cross sections and there remain many discrepancies, both in form and magnitude, between the rare-gas partial cross sections measured by various investigators [9,10].

A variety of experimental techniques have been employed to measure electron-impact cross sections but only a few truly independent absolute ionization-cross-section measurements have been reported. The most frequently cited work is that of Rapp and Englander-Golden [8] who used a static gas, parallel-plate technique and measured absolute total charge production cross sections. This method is straightforward and should lead to reliable data. Their basic experimental technique was later augmented by the inclusion of a mass spectrometer and was utilized by a number of other experimenters including Schram [11], Schram *et al.* [12–14], Gaudin and Hagemann [15], Nagy, Skutlartz, and Schmidt [16], and Straub *et al.* [10] for the measurement of partial as well as total cross sections. The inclusion of a mass spectrometer inevitably increases the complexity of the experiments and has been the major factor responsible for the large discrepancies between the results of different workers.

An alternative technique, incorporating a fast neutral-target beam, obtained by charge transfer, was used by Peterson and McDowell [17], Brooke, Harrison, and Smith [18], Montague, Harrison, and Smith [19], and Wetzel *et al.* [20]. This approach, however, while well suited to the study of chemically unstable neutrals, is less attractive for the study of stable species because of the need to determine the beam overlap function from the beam-intensity profiles. This is a difficult procedure that can lead to relatively large uncertainties in the final data. Furthermore, there is the possibility of contamination of the target atom beam by long-lived excited neutrals formed in the charge transfer process.

A number of other studies have been conducted in which relative cross sections were measured and subsequently normalized with the aid of previously published absolute data. Adamczyk *et al.* [21], Stephan, Helm, and Märk [22], Stephan and Märk [23], Krishnakumar and Srivastava [24], Ma, Sporleder, and Bonham [25], Syage [26,27], McCallion, Shah, and Gilbody [28], and Almeida, Fontes, and Godinho [29], and Almeida, Fontes, and Pontes [30] all normalized their data using the absolute electron impact measurements of others, frequently those of Rapp and Englander-Golden [8]. Shah *et al.* [31], on the other hand, normalized their data to a charge-transfer cross-section [32]; while Sorokin *et al.* [33] normalized their data using rare-gas absolute photoionization cross sections. In principle, if the normalization stan-

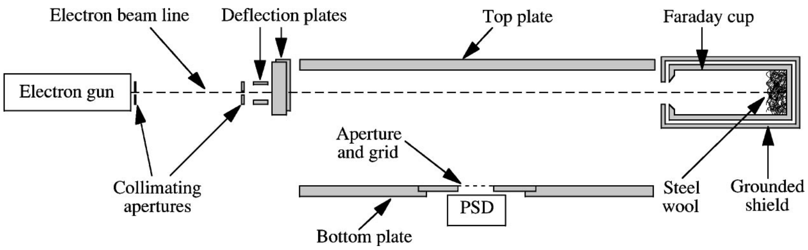

FIG. 1. Schematic diagram of the apparatus.

dards used in such studies are accurate, and if the systematic errors associated with the normalization procedure are relatively small, the resultant cross sections should be accurate. Notwithstanding their contribution to our general understanding of these processes, absolute cross sections derived in this manner are, however, of somewhat limited utility.

This unsatisfactory situation provided the stimulus for the present study which reports an independently absolute modern determination of the partial and total cross sections for electron-impact ionization of helium, neon, argon, krypton, and xenon from their respective ionization thresholds to 1000 eV [34]. The experimental technique used embodies the simplicity of the parallel-plate arrangement used by Rapp and Englander-Golden [8] coupled with an extremely short path length mass spectrometer together with a detector with which it is possible to demonstrate complete collection of all product ions. This approach overcomes many of the limitations of other techniques and is capable of providing very accurate absolute cross sections [35].

II. APPARATUS AND EXPERIMENTAL METHOD

The apparatus is shown in Fig. 1 and consists of an electron gun, a time-of-flight mass spectrometer with a position-sensitive detector (PSD), and an absolute capacitance diaphragm pressure gauge (not shown). It has been described in detail previously [10,36]. Briefly, during a cross-section measurement the entire vacuum chamber is filled with the target gas at a pressure of the order of 3×10^{-6} Torr. The electron gun produces 20-ns-long pulses at a repetition rate of 2.5 kHz. These pulses of electrons are directed through an interaction region, located between two plates maintained at ground potential, and are collected in a Faraday cup. Approximately 250 ns after each electron pulse, a fast 3 kV pulse is applied to the top plate to drive any positive ions formed by electron impact toward the bottom plate. Some ions pass through a grid-covered aperture in the bottom plate. They are then accelerated and subsequently they impact a PSD [37] that records their arrival times and positions. The ion arrival times are used to identify their mass-to-charge ratios while their arrival positions are used to determine the effectiveness of product ion collection. Under conditions in which very few of the incident electrons produce an ion, the partial cross section $\sigma(X)$ for production of ion species X is given by

$$\sigma(X)=\frac{N_i(X)}{N_e n l}, \tag{1}$$

where $N_i(X)$ is the number of X ions produced by a number N_e of electrons passing a distance l through a uniform gaseous target of number density n. $\sigma(X)$ is then determined by measuring the four quantities on the right-hand side of Eq. (1) [10,36]. Technical details concerning the PSD detection efficiency calibration and use of the capacitance diaphragm gauge may be found in Straub *et al.* [38] and Straub *et al.* [39], respectively.

The total (counting) cross section is the sum of the partial cross sections. The total charge production cross section, occasionally referred to as the gross cross section in the literature, is obtained as the weighted sum of the partial cross sections, i.e.,

$$\sigma^{total}=\sigma^{+}+2\sigma^{2+}+3\sigma^{3+}+4\sigma^{4+}+\cdots. \tag{2}$$

A discussion of the experimental uncertainties was given previously [10,36]. In the present study the uncertainties in the single-, double-, triple-, and quadruple-ionization cross section are given in the captions to Tables I–IV and are typically $\pm5\%$, $\pm5\%$, $\pm7\%$, and $\pm10\%$, respectively, except near the thresholds for these processes. The electron energy was established to better than ±0.5 eV by observing the single-ionization threshold for each gas.

III. RESULTS: TOTAL CROSS SECTIONS

When presenting new results it is common practice to include all previously published data for the purposes of comparison. However, there is a considerable body of total-cross-section data available for these targets and uncritical direct graphical comparison of all the measurements tends to suggest they are all of equal reliability and, in this instance, would certainly add more confusion than clarity. A more discriminating approach is taken here. Specifically, total-cross-section data that were normalized to the work of others, sometimes by circuitous routes, are not considered because the normalization process itself typically forces agreement between different data sets, generally without adding anything new. (The problems inherent in presenting such data are evident in Sec. IV). Also, it seems clear that the earliest studies (e.g., Smith [3], Tate and Smith [4], Tozer and Craggs [40], Asundi and Kurepa [41]) were compromised due to inaccurate pressure measurements [42] and they also are not discussed here.

The later and presumably more reliable studies, however, still quite often disagree with each other, occasionally markedly so, and it is difficult to distinguish the correct from the incorrect data. Clearly, when the results of two laboratories of apparently equal reliability agree for some reactions, but

TABLE I. Absolute helium and neon partial cross sections. The uncertainties in $\sigma(He^{+})$ and $\sigma(He^{2+})$ are $\pm5\%$ and $\pm7\%$, respectively, unless otherwise indicated. The uncertainties in $\sigma(Ne^{+})$, $\sigma(Ne^{2+})$, and $\sigma(Ne^{3+})$ are $\pm5\%$, $\pm5\%$, and $\pm7\%$, respectively, unless otherwise indicated.

Energy (eV)	$\sigma(He^{+})$ (10^{-17}cm^2)	$\sigma(He^{2+})$ (10^{-19}cm^2)	$\sigma(Ne^{+})$ (10^{-17}cm^2)	$\sigma(Ne^{2+})$ (10^{-18}cm^2)	$\sigma(Ne^{3+})$ (10^{-19}cm^2)
22.5			0.060		
25	0.037±0.004		0.250		
27.5	0.290±0.020		0.507		
30	0.568±0.040		0.805		
32.5	0.851		1.09		
35	1.09		1.41		
40	1.52		2.02		
45	1.90		2.50		
50	2.24		3.05		
55	2.47				
60	2.69		3.96		
70	2.96		4.75		
80	3.16		5.35	0.124±0.009	
90	3.28	0.042±0.013	5.73	0.309±0.019	
100	3.37	0.143±0.012	6.08	0.571	
110	3.41	0.249	6.40	0.928	
120	3.45	0.399	6.49	1.18	
130	3.47	0.527	6.61	1.51	
140	3.44	0.608	6.67	1.82	
150	3.38	0.735	6.75	2.09	
160	3.35	0.818	6.77	2.33	0.114±0.034
170			6.75	2.46	0.168±0.030
180	3.24	0.980	6.72	2.64	0.255±0.033
190			6.68	2.72	0.366±0.040
200	3.14	1.08	6.65	2.85	0.462±0.042
225	3.03	1.17	6.53	3.07	0.699±0.049
250	2.90	1.23	6.38	3.06	1.01
275			6.18	3.06	1.22
300	2.69	1.31	6.00	2.92	1.34
350	2.46	1.27	5.68	2.82	1.51
400	2.32	1.21	5.32	2.61	1.53
500	2.03	1.06	4.82	2.36	1.39
600	1.79	0.916	4.40	2.05	1.28
700	1.62	0.821	4.03	1.79	1.17
800	1.47	0.736	3.71	1.59	0.993
900	1.36	0.649	3.43	1.43	0.826
1000	1.24	0.579	3.21	1.30	0.719

disagree for others, neither set of data can be accepted with complete confidence. What is desired is a situation where the totality of the data from two or more laboratories consistently agree, since, while it is possible that two laboratories could consistently arrive at identical but incorrect results this is highly unlikely. This is the premise for the following analysis [43]. It is logical to start by considering the work of Rapp and Englander-Golden [8], whose absolute uncertainty is $\pm7\%$, and which is the most widely quoted. These data are generally thought to be accurate but no independent confirmation of this work in its entirety has heretofore been published. Thus in comparison with the data of Rapp and Englander-Golden [8], Schram *et al.* [12,14], whose measurements are limited to energies above 100 eV, agree for argon, krypton and xenon, but not for helium and neon where differences of up to 25% exist. The data of Gaudin and Hagemann [15] agree within the combined uncertainties for neon and argon but are lower than those of Rapp and Englander-Golden [8] by approximately 40% for helium. The data of Fletcher and Cowling [44], whose uncertainty is $\pm4\%$, but which only encompass neon and argon measurements, are generally consistent with the work of Rapp and Englander-Golden [8]. The data of Sorokin *et al.* [33], which are limited to energies above 140 eV and whose reported

TABLE II. Absolute argon partial cross sections. The uncertainties in $\sigma(\mathrm{Ar}^+)$, $\sigma(\mathrm{Ar}^{2+})$, $\sigma(\mathrm{Ar}^{3+})$, and $\sigma(\mathrm{Ar}^{4+})$ are $\pm 5\%$, $\pm 6\%$, $\pm 7\%$, and $\pm 12\%$, unless otherwise indicated.

Energy (eV)	$\sigma(\mathrm{Ar}^+)$ $(10^{-16}\mathrm{cm}^2)$	$\sigma(\mathrm{Ar}^{2+})$ $(10^{-17}\mathrm{cm}^2)$	$\sigma(\mathrm{Ar}^{3+})$ $(10^{-19}\mathrm{cm}^2)$	$\sigma(\mathrm{Ar}^{4+})$ $(10^{-19}\mathrm{cm}^2)$
17	0.159±0.011			
18.5	0.419			
20	0.604			
21	0.769			
22.5	1.00			
25	1.25			
27.5	1.58			
30	1.75			
32.5	2.07			
35	2.21			
40	2.41			
45	2.49	0.0045		
50	2.53	0.121		
55	2.53	0.392		
60	2.51	0.806		
65	2.51	1.14		
70	2.52	1.37		
75	2.51	1.47		
80	2.54	1.60		
90	2.55	1.74		
100	2.51	1.80	0.978	
110	2.48	1.81	2.10	
120	2.42	1.78	3.07	
140	2.33	1.68	4.71	
160	2.25	1.58	5.32	
180	2.17	1.51	5.44	
200	2.09	1.38	5.30	
225	2.01	1.26	5.09	
250	1.91	1.21	5.03	
275	1.80	1.09	4.91	
300	1.73	1.05	4.86	
350	1.58	0.923	5.80	0.163
400	1.47	0.846	6.13	0.426
500	1.27	0.662	6.79	1.04
600	1.13	0.562	7.24	1.29
700	1.01	0.513	7.08	1.31
800	0.914	0.448	6.83	1.47
900	0.850	0.412	6.40	1.31
1000	0.783	0.368	6.47	1.30

uncertainty is less than $\pm 3\%$, agree well with those of Rapp and Englander-Golden [8] for argon, krypton, and xenon, but deviate by approximately 20% for neon. The fast-beam work of Wetzel *et al.* [20] agrees with that of Rapp and Englander-Golden [8] to within the quoted $\pm 15\%$ uncertainty. Thus with the exception of the limited measurements of Fletcher and Cowling [44] and the imprecise data of Wetzel *et al.* [20] none of the work from other laboratories is in consistent agreement with the work of Rapp and Englander-Golden [8] or indeed with the work from any other laboratory.

TABLE III. Absolute krypton partial cross sections. The uncertainties in $\sigma(\mathrm{Kr}^+)$, $\sigma(\mathrm{Kr}^{2+})$, $\sigma(\mathrm{Kr}^{3+})$, and $\sigma(\mathrm{Kr}^{4+})$ are $\pm 5\%$, $\pm 5\%$, $\pm 8\%$, and $\pm 7\%$, unless otherwise indicated.

Energy (eV)	$\sigma(\mathrm{Kr}^+)$ $(10^{-16}\mathrm{cm}^2)$	$\sigma(\mathrm{Kr}^{2+})$ $(10^{-17}\mathrm{cm}^2)$	$\sigma(\mathrm{Kr}^{3+})$ $(10^{-18}\mathrm{cm}^2)$	$\sigma(\mathrm{Kr}^{4+})$ $(10^{-19}\mathrm{cm}^2)$
15	0.102±0.016			
16	0.367±0.026			
17	0.529±0.034			
18	0.732			
20	1.17			
22	1.48			
24	1.76			
26	2.14			
28	2.34			
30	2.55			
35	2.99			
40	3.24			
45	3.38	0.247±0.027		
50	3.45	0.825±0.091		
55	3.48	1.37		
60	3.45	1.87		
65	3.49	2.26		
70	3.45	2.53		
75	3.45	2.80		
80	3.43	2.98		
90	3.40	3.07	0.35±0.09	
100	3.33	3.08	0.69±0.14	
110	3.25	3.04	1.19±0.19	
120	3.20	3.02	1.63±0.18	
130	3.11	2.92	2.00±0.19	
140	3.05	2.73	2.09±0.19	
150	2.98	2.67	2.25	
160	2.91	2.55	2.49	
170	2.86	2.50	2.59	
180	2.78	2.36	2.75	
190	2.72	2.29	2.81	0.80±0.28
200	2.68	2.21	2.91	1.18±0.15
225	2.54	2.07	3.08	2.14±0.23
250	2.42	1.90	3.30	3.20±0.29
275	2.29	1.79	3.33	4.04±0.33
300	2.19	1.66	3.49	4.85
350	2.01	1.47	3.63	6.27
400	1.85	1.37	3.74	8.01
500	1.60	1.15	3.76	8.98
600	1.43	1.02	3.67	9.73
700	1.28	0.912	3.64	9.60
800	1.16	0.814	3.45	9.49
900	1.07	0.754	3.35	9.39
1000	0.984	0.670	3.18	9.01

Figure 2 shows the weighted sum of the partial cross sections obtained in the present investigation together with the total charge production cross sections of Rapp and Englander-Golden [8]. It is seen that in every case the two sets of data agree to within the combined experimental un-

TABLE IV. Absolute xenon partial cross sections. The uncertainties in $\sigma(Xe^{+})$, $\sigma(Xe^{2+})$, $\sigma(Xe^{3+})$, $\sigma(Xe^{4+})$, $\sigma(Xe^{5+})$, and $\sigma(Xe^{6+})$ are $\pm5\%$, $\pm5\%$, $\pm7\%$, $\pm9\%$, $\pm11\%$, and $\pm15\%$, unless otherwise indicated.

Energy (eV)	$\sigma(Xe^{+})$ (10^{-16}cm^2)	$\sigma(Xe^{2+})$ (10^{-17}cm^2)	$\sigma(Xe^{3+})$ (10^{-17}cm^2)	$\sigma(Xe^{4+})$ (10^{-18}cm^2)	$\sigma(Xe^{5+})$ (10^{-18}cm^2)	$\sigma(Xe^{6+})$ (10^{-19}cm^2)
12	0.17±0.05					
14	0.73±0.05					
16	1.37±0.08					
18	2.01					
20	2.43					
22	2.90					
24	3.33					
26	3.62					
28	3.80					
30	4.01					
35	4.48					
40	4.59	0.688				
45	4.60	1.74				
50	4.58	2.57				
60	4.62	3.63				
70	4.67	3.86				
80	4.64	3.98	0.10±0.01			
90	4.53	4.61	0.324			
100	4.44	5.03	0.764			
110	4.33	5.34	1.22			
120	4.19	5.30	1.58			
130	4.05	5.17	1.83	0.097±0.049		
140	3.97	4.91	1.88	0.33±0.17		
150	3.89	4.65	1.87	1.02±0.17		
160	3.78	4.39	1.77	1.54±0.20		
170	3.67	4.15	1.72	1.99±0.25		
180	3.58	3.97	1.66	2.74	0.013±0.006	
190	3.51	3.90	1.66	3.58	0.063±0.026	
200	3.44	3.73	1.58	4.26	0.18±0.07	
225	3.25	3.45	1.50	4.81	0.38±0.15	
250	3.06	3.25	1.42	4.83	0.62±0.19	
300	2.77	3.05	1.40	4.21	1.01±0.26	0.36±0.18
350	2.48	2.94	1.37	4.25	1.13	0.82±0.25
400	2.31	2.67	1.29	4.09	1.06	1.28±0.26
500	2.00	2.40	1.18	3.95	1.09	1.53
600	1.75	2.20	1.07	3.69	0.98	1.71
700	1.58	2.04	1.02	3.48	0.89	1.88
800	1.42	1.90	0.921	3.39	0.78	1.82
900	1.32	1.75	0.844	3.19	0.73	1.91
1000	1.21	1.70	0.825	2.94	0.69	1.88

certainties. Indeed, the greatest difference between the maxima of the respective cross sections is only 7%. Given that the precision of both data sets is ±5–7 %, that the measurements are entirely independent, and that data are available for five different targets, this is quite a stringent comparison. It should also be noted that this level of agreement was previously observed between the data from this laboratory and that of Rapp and Englander-Golden [8] for molecules studied by both groups [35]. In fact for every atom and molecule studied by the two laboratories agreement is observed to within the combined uncertainties. These considerations indicate that a high level of confidence should be accorded to these two data sets.

IV. RESULTS: PARTIAL CROSS SECTIONS

Examination of the previously published data for the partial cross sections reveals once again that there is no clear-cut

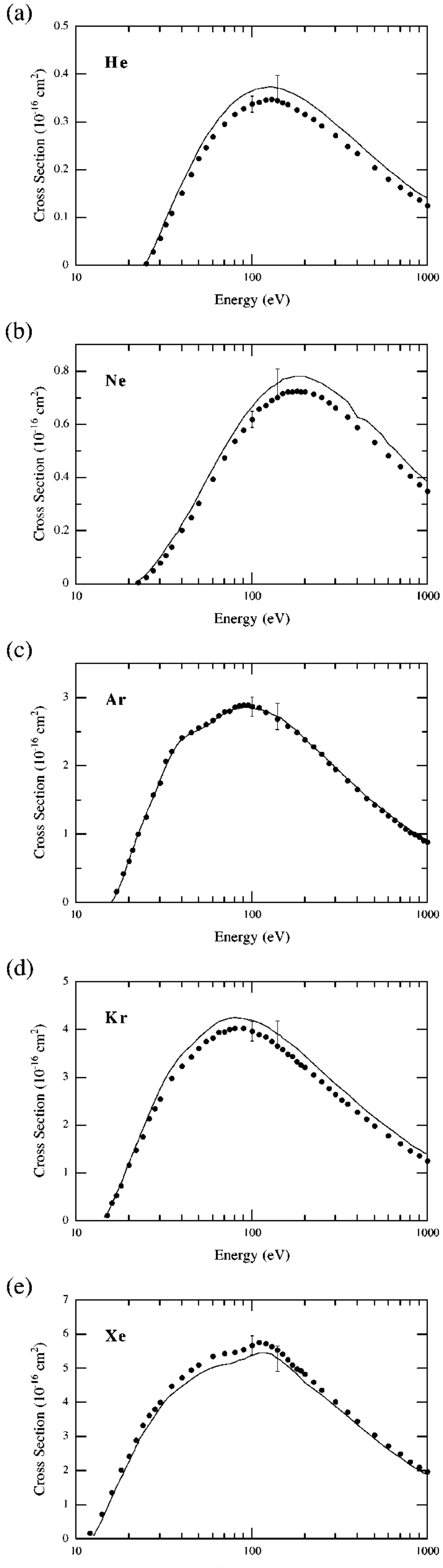

FIG. 2. Total charge production (gross) cross sections for helium, neon, argon, krypton, and xenon: present results (●); Rapp and Englander-Golden [8] (−).

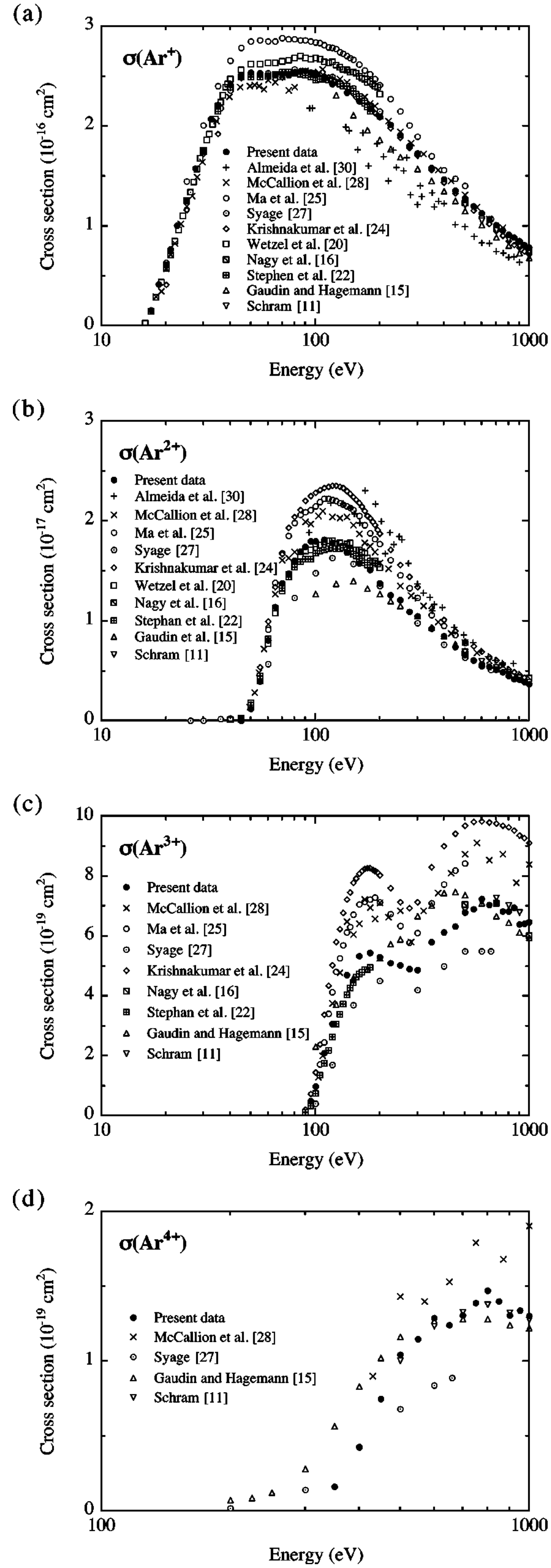

FIG. 3. Partial cross sections for production of Ar^{+}, Ar^{2+}, Ar^{3+}, and Ar^{4+}.

consensus as to the correct values. Both absolute measurements and relative measurements that have been normalized to other absolute data are considered because these latter measurements can in principle yield useful accurate data. There have been quite a few measurements of both types reported and the majority of them have already been reviewed by Wetzel *et al.* [20] and Krishnakumar and Srivastava [24]. The typical scatter between the various measurements is well illustrated in Fig. 3 which shows the present argon partial cross sections together with prior measurements. For Ar^+ the cross section appears to be established to within $\pm 10\%$, although note that the agreement between so many different workers is, in part, due to the fact that no less than four of these studies [22,24,26,28] were normalized to the work of Rapp and Englander-Golden [8]. The partial cross sections for production of Ar^{n+} multiply-charged ions are much less well established than that for production of Ar^+ and the agreement between those studies normalized to the work of Rapp and Englander-Golden [8] is considerably worse for multiply charged ions than for Ar^+. This latter observation is largely a consequence of the fact that normalization procedures based on comparison to known total cross sections are relatively insensitive to the multiply charged ion cross sections given that the total cross section is dominated by the cross section for the singly charged ions. Another point worth noting is that the reported uncertainties for the partial cross sections tend to be greater than for the total cross sections, which of course further hampers their comparison [45].

In an effort to distinguish the correct from the incorrect data we take as a starting point the conclusion we drew in the last section, namely, that the sum of the partial cross sections reported in this study give the correct values for the total cross sections. From this it may be argued that the individual partial cross sections must themselves be correct. However, because the cross sections for the multiply charged ions are much smaller than those for the singly charged ions, significant errors in their values could be present without seriously affecting the magnitude of the weighted sums. To address this possibility it is appropriate to review a few key features of the present experimental method. First we note that ions of all species are collected contemporaneously so that the electron beam intensity and the target gas number density are identical during the determination of all partial cross sections. Clearly, the collision path length is the same for all product ions. From Eq. (1) it is then apparent that the relative magnitudes of the cross sections for the different product ions are given solely by the relative magnitudes of the corresponding ion signals. It has been previously demonstrated that the various product ions are both collected and detected with the same efficiency [10,36,38]. Finally, the count rates are maintained at a few hundred hertz and tests have shown no variation of the cross sections with count rate. These considerations collectively ensure that, apart from uncertainties due to counting statistics, all partial cross sections are measured with the same accuracy. Thus if one partial cross section is measured correctly, then all the partial cross sections are measured correctly. Given the fact that their weighted sum leads to the correct value for the total cross section it follows that the partial cross sections themselves are correct.

We examine this conclusion in light of the previously published data and in this regard we again look, as we did in the case of the total cross sections, for consistency between the entire set of data from two or more laboratories. Once again it is found that very little agreement of this type is observed. In fact, for all five rare gases, only the present study, the work of Stephan *et al.* [22,23], and the work of Wetzel *et al.* [20] consistently agree with one another (Fig. 3). These comparisons, while perhaps not quite as compelling as they were in case of the total cross sections because the data of Stephan *et al.* [22], Stephan and Märk [23], and of Wetzel *et al.* [20] have significantly larger uncertainties than those of Rapp and Englander-Golden [8] and do not cover as large an energy range, are nevertheless clearly very supportive of the accuracy of the present results.

V. CONCLUSION

Electron-impact ionization of the rare gases has been studied very extensively over many decades. Many different experimental approaches have been utilized but no clear consensus has heretofore emerged as to the correct values for these cross sections. The problem is that when the data from any two laboratories are compared it is typically found that while they may agree for one process they may well disagree for another. In these circumstances there is no satisfactory way to distinguish the correct from the incorrect data. In an effort to establish a set of cross sections that may be accepted with confidence, we have performed a comprehensive experimental study and reviewed our measurements in the context of the other available data giving credence only to data sets that are replicated in their entirety by two or more laboratories. This approach is based on the premise that it is extremely unlikely that two or more laboratories could obtain identical, and yet incorrect, results for a wide range of processes. It is observed that, for all five rare gases, the present total cross sections are in very good agreement with the work of Rapp and Englander-Golden [8], long considered the *de facto* standard. The partial-cross-section measurements of Stephan *et al.* [22], Stephan and Märk [23], and Wetzel *et al.* [20], although of lower precision than those reported here, are also in agreement with the present values for every ionization process studied. The data reported here, therefore, represent a precise modern determination of the partial and total rare-gas cross sections and are uniquely consistent with both the *de facto* total-cross-section standard, and other comprehensive, though less precise, studies.

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