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The Pulsed Electron Beam Time-of-flight Method for measuring Absolute Total Cross Sections: Atomic Helium

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Abstract

Improvements in a previously reported experimental method have made it possible to obtain absolute total electron-scattering cross sections with a predicted accuracy of better than $\pm 2\%$ (1σ) for certain electron kinetic energies. As a first example of the application of the new procedures the cross section for helium is reported from 0·8 to 50·0 eV. Error estimates for all known sources of uncertainty are discussed in detail. The results confirm the earlier work of Kennerly and Bonham and the agreement is, on the average, better than 1% with no changes in the cross-section shape.

1. Introduction

Absolute total cross sections for electrons scattered by free atoms were already determined by Ramsauer (1921) before the discovery of the quantum theory. By 1932 six measurements of the total cross section for helium had been reported. These works have been reviewed by Bederson and Kieffer (1971). The importance of these measurements lies primarily in their use as calibration points for the development of sophisticated scattering theories for dealing with electron–atom scattering and for normalizing other experimental cross sections which can only be easily measured on a relative scale. Interestingly enough it was not until the work of Golden and Bandel (1965) that modern measurements with error estimates of $\pm 3\%$ were first reported for the incident electron energy range from 0·3 to 28 eV. However, results reported since that time in this same energy range have only lead to controversy. First came two theoretical studies by Sinfailam and Nesbet (1972) and Yarlagadda *et al.* (1973) which disagreed with the Golden–Bandel result by slightly more than 10%. Then Andrick and Bitsch (1975) reported total cross sections based on a phase shift analysis of relative experimental differential elastic cross sections for helium which were in good agreement with theory and in disagreement with the Golden–Bandel measurements. Next came an experimental absolute cross-section measurement reported by Kauppila *et al.* (1977) which was in good agreement with the three previous results. These last results were obtained using a newly developed time-of-flight apparatus. This marked the first reported use of a technique other than the Ramsauer method for measuring the total cross section directly in our range of interest. At about the same time Berrington and O'Malley (1977) reported a theoretical calculation in agreement with the previous two. Finally Kennerly and Bonham (1978), also utilizing a time-of-flight method, reported values in excellent agreement with theory and the Andrick–Bitsch and Kauppila experiments. In addition, data from

swarm experiments by Milloy and Crompton (1977) also seemed to lend support to the latter work.

At this point it might seem that the experiments by Andrick–Bitsch (AB), Kauppila *et al.* (K) and Kennerly–Bonham (KB) define the 'correct' value of the helium total cross section leaving the Golden–Bandel (GB) results to be explained by the existence of some source of undetected systematic error. However, a closer examination of the situation led to the following discoveries. First Steph *et al.* (1979) demonstrated the existence of a hitherto unknown uncertainty in the choice of an absolute scale in the AB data which led to an increase in their error estimate from 3% to 20%.

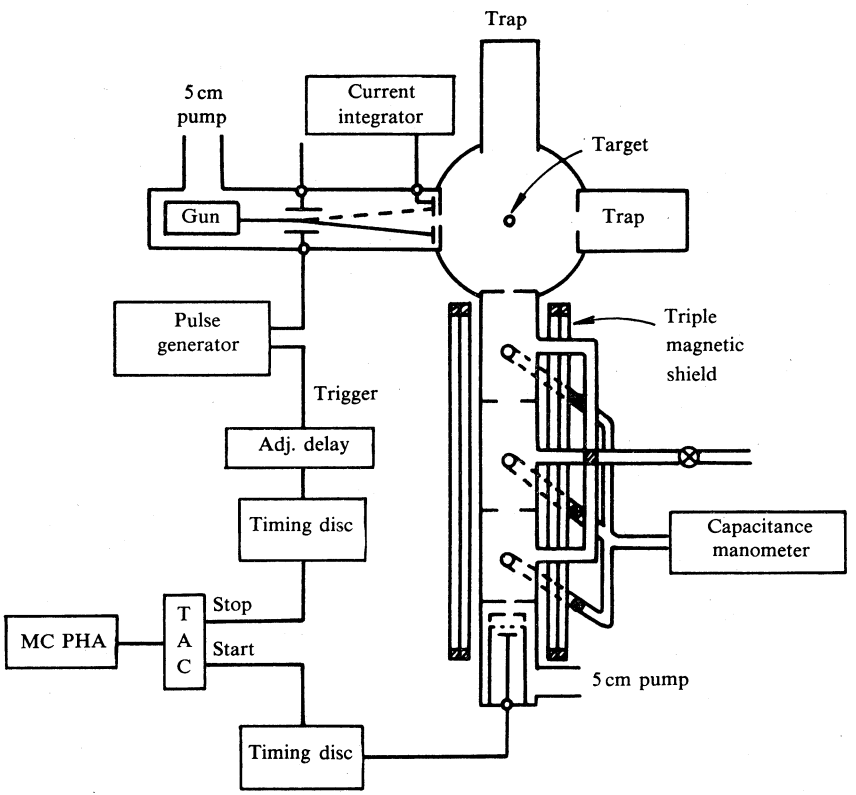

Fig. 1. Time-of-flight apparatus used to measure the total cross sections. Major changes from the work of KB include the three connecting lines to the transmission cell from the capacitance manometer with associated shut-off valves and the introduction of a diffusing element (cross-hatched square at the cross in the gas inlet system) to produce a more even distribution of gas in the transmission cell. Flight distance is ≈ 45 cm and the cell length ≈ 38 cm.

Careful reading of the K paper shows that the intent of their work was to use the comparison of their helium data with theory as a means of placing their positron scattering cross sections, obtained with the same experimental apparatus, on an absolute scale. They quote no overall error estimate in either their 1977 paper or in a later paper by Stein *et al.* (1978). The fact that they seem happy to have obtained agreement to within 5% of the theoretical values leads one to suspect that their original expectations might have been somewhere around the 10% level. The only known flaw in the Kennerly–Bonham data was the reliance on the manufacturer's

calibration and assumed linearity of the pressure measuring device used. This was not, however, a problem unique to this experiment. On the theoretical side, since *a priori* calculations are still not in the realm of the possible, approximations had to be made and no reliable assessment of the uncertainties in the final results were reported. Finally it is only fair to note that several sources of possibly overlooked errors could have existed in the older GB measurements.

The purpose of this work will be to report our efforts to improve on the KB work and to compare our latest results with the KB and all other available results which have appeared since or have not been compared with the KB results before. It must be stressed that we cannot determine, after the fact, what went wrong in other experiments but we can, as we hope to demonstrate here, make a careful reanalysis of the original KB experiment.

2. Experiment

The apparatus and method of analysis have been outlined in detail by Kennerly (1977) and KB. We shall emphasize here only the major changes. In Fig. 1 a schematic diagram of the apparatus is shown. The major design changes are:

(*a*) The capacitance manometer was connected to the absorption cell at three points as shown. Each connection has its own shut-off valve so that the pressure of any one, two or three segments of the absorption cell can be measured. This makes it possible to check for pressure gradients in the gas cell.

(*b*) A diffusing element consisting of a sintered stainless steel (2 μm filter) plug was inserted at the cross junction of the gas inlet system. This change guarantees a more even flow of gas into all parts of the absorption cell.

(*c*) A new absorption cell with mating holes for all gas inlet ports and gas measuring ports was made which could be inserted inside the former absorption cell. The interior diameter of the cell was 2·86 cm. Two baffles designed to prevent the detection of wall-scattered electrons were inserted inside the absorption cell. This change was not made to improve the measurement accuracy but rather to accommodate the study of chemically active gases by making it easier to clean or replace the cell. The new insertable cell, baffles and apertures were made entirely from aluminium, coated with graphite and carefully grounded to the vacuum jacket.

(*d*) Gas inlet ports with adjustable needle valves were attached to the vacuum chamber surrounding the secondary electron target source and the detector. The needle valves were adjusted so that the sample gas being studied could be admitted to the target and detector areas in such a way that the two areas were exposed to a pressure of sample gas during measurements with the absorption cell empty which was the same as when the cell was full. Actually this was already done for the target area in the KB experiment. The sample pressure in both modes of operation was monitored by nearby ion gauges in both target and detector areas. The monitoring was not, however, done during the course of an actual run.

(*e*) Electrically controlled high-vacuum valves were installed so that the entire experiment, consisting of alternate runs with and without sample gas in the absorption cell, could be carried out under computer control. The pressure was monitored continuously during the experiment by use of a strip chart recorder. The length of time for measurement with sample gas and without could be independently adjusted.

These changes do not represent an improvement over the original KB experiment but do relieve a great deal of tedium from data collection and make it easier to test for time-dependent effects in the measurement by collecting data at very different sampling intervals.

(*f*) An improvement in the method of correcting for the dead time was instituted. While the new method (to be discussed in detail by R. Jones in a forthcoming paper) would seem to be superior on philosophical grounds, we do not expect the uncertainty in the final results to be altered in a significant way over that estimated in the KB work.

The experimental data were collected under conditions closely approximating those given by KB unless otherwise stated below. Alternate measurements of the secondary electron distribution without gas (100 s) and with gas (200 s) were made and the separate results summed by computer. The separate intensities with and without gas were accumulated until the section with the least statistical accuracy had accumulated more than 2×10^3 counts in the channel with minimum count rate. The temperature was measured before and after each experiment and the pressure was monitored continuously. Several runs of this type were made and it was noted that the standard deviation between them was the same as the statistical error in a single run. The data were then processed according to the procedures outlined in KB.

3. Error Analysis

The method used by KB to estimate their errors was very conservative. Each known source of systematic error was varied one at a time by a significant amount above its estimated uncertainty. In this way important error sources were identified and realistic estimates for the uncertainties assessed.

In this study the major improvement in the estimate of the uncertainty in the cross section was brought about by a careful calibration of the laboratory's two absolute MKS capacitance manometers. This was accomplished by use of an all-glass vacuum system consisting of a small volume ($\sim$1 l.) attached to a closed U-tube mercury manometer, of special large bore construction, by means of a valve. This volume was also connected through valves to an ion gauge for residual vacuum measurement, to a gas inlet system and to a second larger volume ($\sim$10 l.) which was in turn connected to the MKS gauge to be calibrated and, via a valve, to a vacuum pump. The ratio of the small to large volume was established by filling the small volume to 700–800 mmHg (1 mmHg = 133 Pa) with argon and then expanding the gas into the larger volume. From the pressure change, as recorded by the mercury manometer, the volume ratio could be established. Next the valve between the two volumes was closed and the small volume isolated from all its other connections. The large volume was then evacuated and isolated from the vacuum pump. The gas in the small volume was then allowed to expand into the larger volume. The valve between the two volumes was then closed and the large volume pumped out. The expansion process was repeated until the gas pressure in the larger bulb was reduced to the measurable range of the MKS gauge. One further expansion made it possible to determine the volume ratio from the MKS pressure measurements by assuming only that the MKS gauges were linear in their highest pressure ranges. Repeated determinations of the volume ratio, by using the mercury manometer, led to an average value with a standard deviation of 0·1%. The two MKS gauges

gave average values with standard deviations of 0·05%. The standard deviation for the average of these three ratios was 0·07%.

Continued expansion cycles were carried out to the 0·1 mTorr (1 Torr = 133 Pa) range to establish calibration curves for the two gauge heads. Both gauge heads were calibrated at room temperature to avoid thermal transpiration. Both gauges showed a linear 1 : 1 correspondence between true pressure and gauge readings well within the overall estimated uncertainty in the calibration procedure of $\pm 0{\cdot}6\%$ (1σ). One gauge was calibrated at 49°C and was found to read 2·9% high with an error estimate of $\pm 0{\cdot}6\%$. This agrees within 1·8% of the value used by KB for the thermal transpiration correction and is within their error estimates. A more detailed discussion of the calibration procedure including an analysis of all error sources will be published elsewhere.

The errors in the cross-section experiment can be conveniently classed as follows: multiplicative, such as errors in pressure, temperature or cell length; additive, such as gas effects at the source altering the intensity of the secondary electron spectrum with time, drifts in the secondary electron intensity caused by other than background gas, for example by changes of graphite coverage due to electron beam bombardment, and correction for instrumental dead time; and cross-section shape errors caused by aperture scattering, wall scattering, background noise, forward scattering into the exit aperture, gas impurities and uncertainties in the energy scale.

Besides the error in the pressure measurement, estimated above to be $\pm 0{\cdot}6\%$, the existence of a pressure gradient in the absorption cell can also lead to a serious error in the cross section. We found that, with a 5 mm aperture on one end of our 38 cm absorption cell, and a 2 mm aperture on the other end, a pressure gradient across the cell of 13% could be developed using hydrogen. A reading made at the centre of the cell only could be in error by as much as 6% under such circumstances. With 2 mm apertures at both ends of the cell the pressure gradient was 1·3% for hydrogen. It was also discovered that the pressure measured when all three sampling ports were opened was the same as the average of the three separate pressure measurements. Hence we expect that, by measuring the average cell pressure by having all three measuring ports open, our error in the pressure measurement from this source will be less than 0·5%. The uncertainty in the temperature was determined to be less than 0·3% by use of a thermocouple. The uncertainty in the cell length from direct measurement is 0·1% (see KB). A maximum error might be established by considering the ratio of twice the aperture diameter to the cell length or 1%. However, because we match the gas pressure outside the cell during blank runs, we adopt an estimate of 0·5% for the cell length uncertainty.

The additive errors have been dealt with in two ways. First the cross section was determined with a graphite target and then with an aluminium one. No discernible difference could be observed. The cross section was measured with cycle times of 80 s without gas and 480 s with gas. Again no difference above the counting statistics could be observed. The experiment which changes target sources should show up any major gas-dependent effects. The variation in cycle time should reveal any time variations caused by changes in the secondary emission rate or shape with ejected-electron energy that take place over a time scale of a minute.

The final test is of course the reproducibility of the measurement. Any serious random variations of the secondary electron spectrum in time will cause the average deviation of several runs to exceed the counting statistics for a single run. This

will be especially noticeable in regions where the secondary electron spectrum has its maximum slope. This occurs in our experiments at an energy of about 30 eV. In fact at one time significant irreproducibility of the experiment ($\pm 6\%$) in just this way was observed and traced to a broken ground connection between the emitting target and vacuum chamber. The results reported here show no evidence of errors of this type within the counting statistics. The dead-time correction was measured to be less than 3% and this is applied to the data. The error from this source is estimated to be 0·2%.

The major shape errors were dealt with as follows. Calculations were carried out for the effect of aperture scattering from the entrance and exit apertures. The most important error contribution comes from secondary ejected-electron distributions produced when the elastic line, which is by far the most intense feature in the secondary distribution, scatters off an aperture. By assuming that the aperture-produced secondary distribution has the same shape as the primary distribution, a 1% aperture-scattering contribution can be shown to yield a cross section that is too large above 1 eV and too small below 1 eV for our typical experimental conditions. The maximum error in the total cross section was one tenth of the aperture-scattering contribution. An upper bound for this error source was established by measuring the cross section of SF_6. In SF_6 there is a prominent resonance at 11·87 eV as shown by Kennerly *et al.* (1979). The secondary distribution produced by aperture scattering at the entrance to the absorption cell will then show this same resonance shifted to 14 eV. Careful measurements on SF_6 with 0·3% statistics in the region of interest failed to detect the presence of the shifted resonance. Analysis of this test indicates that the intensity of secondary electrons arising from aperture scattering is less than 1% of the intensity from the intended source. It should be noted that the maximum error in the cross section will be ten times smaller than this according to our calculations. The exit-aperture scattering cannot be tested for in this way but there is no reason to expect it to be significantly different in magnitude to the entrance case. Further, it can be shown that 0·2 eV electrons from the exit aperture will contribute to the primary spectrum at 50 eV. This means that the total exit-aperture contribution to our experimental range of 0·8–50 eV will come from the aperture-ejected distribution between 0 and 0·2 eV. We feel that a conservative estimate for the maximum contribution from each aperture is $\pm 0{\cdot}1\%$ below 25 eV and $\pm 0{\cdot}3\%$ from the exit aperture above 25 eV.

Forward scattering through the exit aperture can lead to a significant reduction in the measured cross section, especially at higher energies. We carried out detailed calculations of this effect for our geometry by integrating assumed elastic- and inelastic-scattering contributions over the accessible scattering angles for each point in the absorption cell along the path of the incident electron pulse. Both Born estimates of the angular dependence and experimental ones were employed. The results were model-independent within an order of magnitude and the maximum error at 60 eV was found to be 1%, due almost entirely to loss of inelastically scattered electrons. We have concluded that errors from this source are less than 0·5% in the main energy range of interest.

The error contribution from wall scattering was estimated to be equal to or less than that from aperture scattering based on simple geometric arguments, assuming specular reflection of the electrons from the cell wall. When the baffles used to reduce wall scattering were eliminated altogether, significant changes in cross section were observed.

Table 1. Error sources and magnitudes

Source	Estimated magnitude	Notes
	Multiplicative errors	
Existence of possible pressure gradient	±0·5%	Measured
Absolute pressure measurement	±0·6%	Measured
Temperature	±0·3%	Measured
Cell length	±0·5%	Estimated
	Additive errors	
Time-dependent effects[A]	±1%	Estimated[B]
Counting statistics	±2·5% (0·8–2 eV) ±0·8% (2–10 eV) ±1·7% (10–25 eV) ±3·0% (25–50 eV)	Random error calculated (per experiment)
Dead time	±0·20% (0·8–2 eV) ±0·22% (2–10 eV) ±0·36% (10–25 eV) ±0·56% (25–50 eV)	Estimate of error in measured value of 3%
	Shape errors	
Scattering from entrance aperture	±0·1%	Measured
Scattering from exit aperture	+0·1% (0·8–25 eV) +0·3% (25–50 eV)	Estimated from entrance aperture scattering
Wall scattering	±0·1%	Estimated
Forward scattering	+0·5% (2–25 eV) +0·8% (25–50 eV)	Estimated from model calculation
Background noise	±1·1% (0·8–2 eV) ±0·11% (2–10 eV) ±0·13% (10–25 eV) ±0·26% (25–50 eV)	Calculated from an estimated 10% uncertainty in the background correction
Gas impurities	−0·1%	Estimated
Time base linearity	±0·03% (0·8–2 eV) ±0·04% (2–10 eV) ±0·05% (10–25 eV) ±0·07% (25–50 eV)	Calibrated[C]
Energy scale bench mark (uncertainty in time of flight)	±0·1% (0·8–2 eV) ±0·3% (2–10 eV) ±0·7% (10–25 eV) ±1·4% (25–50 eV)	Random error estimated from ability to determine centre of gravity of argon elastic line
Uncertainty in origin of scattered electrons	±0·03% (0·8–2 eV) ±0·10% (2–25 eV) ±0·15% (25–50 eV)	Ratio of measured course width to flight distance
Uncertainty in incident energy	±0·02%	Calibrated voltage source for electron gun
Contact potential	±0·06% (0·8–10 eV) ±0·03% (10–50 eV)	Estimated 10 meV shift in electron energy

[A] Variations in intensity of secondary electron source.
[B] Random error estimated from reproducibility of experiment.
[C] Manufacturer's error estimate in calibration apparatus.

Background noise involves the possibility that electrons could enter the cell at times when the pulsed beam was turned off. This could happen if backscattered electrons from the incident 2 keV electron beam, in its resting state between sweeps across the pulsing aperture, could rescatter and enter the target chamber. This possibility was checked by including a second pulsing section in the gun chamber of a similar apparatus. In this way we could produce a pulse in the first sweep and then sweep the pulse across a second and final aperture. Most electrons escaping through the first aperture would not be able to escape through the second. Careful experiments showed no detectable difference between results using the single- and double-pulsed modes with 0·3% statistical accuracy.

Gas impurity errors were handled by assuming the worst possible case. The purity of the gas was given by the manufacturer to be better than 0·01%. If the impurity is assumed to be all nitrogen then it would make a contribution to the cross section at the 2·4 eV resonance line of about 0·06% and about the same at 50 eV. In both cases the cross section would appear to be too large. We have adopted 0·1% as the maximum possible error in this case.

Uncertainties in the energy scale were assigned as follows:

(i) The time scale calibration was taken as ±0·05% in time per channel.

(ii) The uncertainty in the time-of-flight of the energy bench mark, the elastic line position in argon scattering, was taken as ±1 ns for a 2 μs full-scale experiment.

(iii) The uncertainty in the origin of scattered electrons in determining the bench mark was taken as ±0·2%.

(iv) The uncertainty in the energy of the incident electron source was taken as ±0·1%.

(v) Voltage scale shifts from contact potentials were assumed to be less than 10 meV.

It should be noted that we have a check on the bench-mark position which is independent of the error source (iv). In the case of argon scattering it is possible to observe a fluorescent photon-decay peak with a sharp onset on the high-energy side of the elastic line. This feature was found to yield an energy scale in agreement with the use of the elastic line.

The uncertainty sources and the magnitude of the resulting uncertainties in the cross section are summarized in Table 1. In the case of additive and shape errors, which are functions of energy, the maximum error for each energy region is presented.

Table 2. Overall error estimates

Energy range (eV)	Coherent error sum (%)	Incoherent error sum (±1σ) (%)
0·8–2	±6·04	±3·08
2–10	±4·55	±1·75
10–25	±5·19	±2·40
25–50	±7·29	±3·75

In Table 2 the overall error estimates are summarized. The column labelled 'coherent error sum' is a direct sum of the absolute value of all listed errors except those which are clearly random from one experiment to another. The three random

error sources were added in quadrature and the result added to the coherent sum. The column labelled 'incoherent error sum' is the square root of the sum of the squares of all errors.

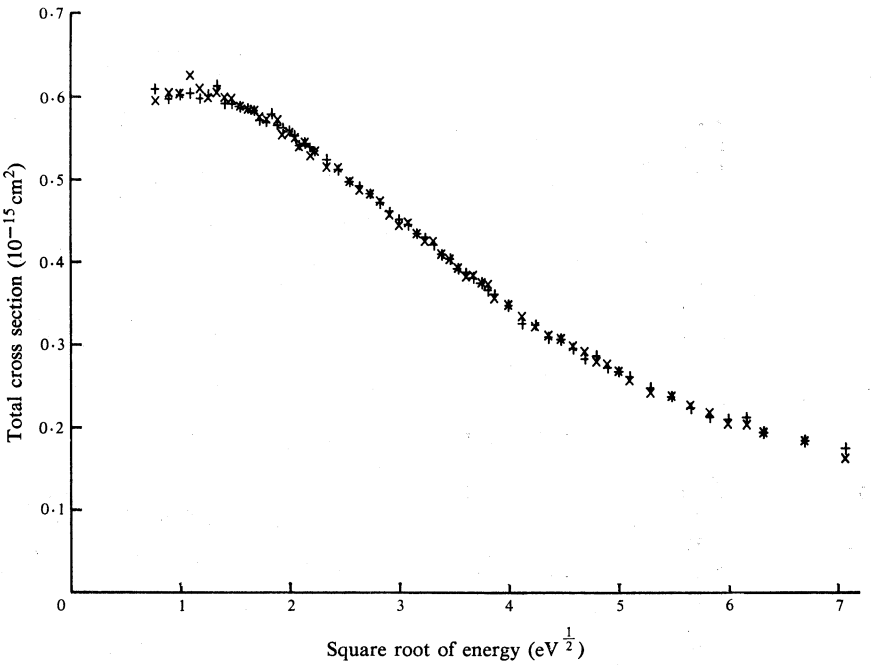

Fig. 2. Total cross section for helium as a function of the square root of the incident electron energy. Three separate determinations are indicated: pluses and stars, present results; crosses, the KB results.

4. Present Results and Comparisons with Recent Data

In Fig. 2 our two separate cross-section determinations (pluses and stars) are compared with the previously published KB results (crosses). The agreement confirms the earlier work. In Table 3, the average of the present experiments is compared with the KB results and all available theoretical and experimental results either appearing since KB or unknown to them at the time of their publication. In general the agreement is excellent, however, a number of comments need to be made.

Two new theoretical studies, one by Nesbet (1979) (N) and the other by O'Malley *et al.* (1979) (O) have appeared which still contain a number of approximations. However, both authors have now put forward error estimates for these approximations and both results purport to be 1% or better. The Kauppila *et al.* (1977) (K) results, as commented on earlier, have no clear error prediction, however, a recent study by Charlton *et al.* (1980) (C) claiming to use an identical apparatus gives an uncertainty estimate of $\pm 4\%$. It must be pointed out, however, that these authors reported the existence of a gas-dependent cell constant which was chosen to make their results match those of KB at 50 eV. Hence in some sense their work is not a pure absolute determination, although presumably their error estimate includes an uncertainty due to this adjustment. Their results do show a systematic difference in shape from the other results.

Table 3. Comparison of total cross section results

Energy (eV)	Total cross section (Å²)							
	This work[A]	KB[B]	N[C]	K[D]	B[E]	C[F]	G[G]	O[H]
0·8	5·96							6·19[I]
1·0	6·02	6·23	6·12				6·2	6·20[I]
1·2	6·10							6·11[J]
1·4	6·00							
1·6	5·97							
1·8	6·05							
2·0	5·94	6·06	6·03			5·46		
2·2	5·93							
2·4	5·89		5·95	5·89				
2·6	5·85							
2·8	5·84					5·57		5·85[J]
3·0	5·75	5·78	5·82			5·55		
3·2	5·74							
3·4	5·71		5·73	5·68		5·40		5·72
3·6	5·64							
3·8	5·55							
4·0	5·55	5·50	5·60			5·39		
4·2	5·50							
4·4	5·40		5·51	5·53				
4·6	5·42					5·34		
4·8	5·32							
5·0	5·34	5·25	5·38			5·23		5·34[J]
5·5	5·15							
6·0	5·11	5·04	5·15					
6·5	4·99							
7·0	4·89	4·83	4·94					
7·5	4·82							
8·0	4·72	4·64	4·75					
8·5	4·60							4·55[J]
9·0	4·48	4·46	4·57					
9·5	4·44							
10·0	4·33	4·30	4·39			4·14		
10·5	4·27							
11·0	4·18							4·17[J]
11·5	4·08							
12·0	4·01	3·96	4·06					
12·5	3·92							
13·0	3·85							
13·5	3·79							
14·0	3·72	3·69	3·76					
14·5	3·64							
15·0	3·57					3·43		
16·0	3·45	3·43	3·51		3·43			3·47[J]
17·0	3·28				3·29			
18·0	3·20	3·22	3·27		3·24			
19·0	3·08				3·16			
20·0	3·04	3·03			3·04	2·94		
21·0	2·93				2·95			
22·0	2·86	2·86			2·87			
23·0	2·80				2·79			
24·0	2·72	2·71			2·71			
25·0	2·68				2·64			

Table 3 (*Continued*)

Energy (eV)	Total cross section (Å²) This work[A]	KB[B]	B[E]	C[F]	Energy (eV)	Total cross section (Å²) This work[A]	KB[B]	B[E]	C[F]
26·0	2·58	2·57	2·58		36·0	2·04			
28·0	2·42	2·44	2·46		38·0	2·03			
30·0	2·36	2·36	2·37	2·31	40·0	1·93	1·95	1·95	2·01
32·0	2·26				45·0	1·82	1·81	1·83	
34·0	2·12				50·0	1·66	1·68	1·73	1·68

[A] Accuracy estimated to be within ±3·8% (1σ) over entire range.
[B] Kennerly and Bonham (1978). Uncertainties estimated at ±3%.
[C] Nesbet (1979). Variational phase shift theory. Accuracy estimated at ±1%.
[D] Kauppila *et al.* (1977). This work was intended (T. S. Kauppila *et al.*, personal communication) to provide a standard for determining positron cross sections. Error estimate is probably ~4% (see Note F).
[E] Blaauw *et al.* (1980). All measured points are estimated to have an accuracy of ±4%.
[F] Charlton *et al.* (1980). Similar apparatus to that used in Note D. A cell constant k was obtained by normalizing to data in Note B at 50 eV. Accuracy estimated at ±4%.
[G] Gus'kov *et al.* (1978). Results reported from 0·025 to 1·0 eV. Error level is not clear but from error discussion it is apparently not better than ±10%.
[H] O'Malley *et al.* (1979). Modified R-matrix theory. Uncertainty is estimated to be less than 0·8% for all values.
[I] These interpolated values have an uncertainty of ±0·05 originating in the interpolation process.
[J] Interpolation of original values with an error of better than 1%.

The higher energy results of Blaauw *et al.* (1980) (B) with an estimated error of 4% are shown. It is worth mentioning that this experiment used two different absorption cell lengths to reduce the error in the cell length definition and also employed a velocity filter at higher energy to eliminate the contribution from inelastic scattering through the forward aperture. The very low energy time-of-flight measurements by Gus'kov *et al.* (1978) (G) add one point at 1·0 eV to our range of interest. This is also a time-of-flight experiment and, although no specific estimate of overall uncertainty appeared, the error discussion would indicate that the measurements are not more accurate than ±10%. Their lower data down to 0·025 eV seems to be in excellent agreement with swarm results and theory.

The final conclusion is that the latest experimental and theoretical efforts seem to be converging to the same limit with agreement well below the 3% level. In the interest of completeness it should be pointed out that Dalba *et al.* (1979) reported an experimental determination of the cross section which, in the authors' words, is in only 'fair agreement' with the present results. Further, a number of theoretical estimates of the total cross section for helium above 20 eV exist in the literature but in our view most, if not all, of these yield results that are too crude to produce a fruitful comparison with the present data.

In closing we should mention that a number of improvements in our current experiment are desirable and possible. Use of a variable-length absorption cell can eliminate end effects and effectively eliminate any significant error in the definition of the cell length. Also, the possible existence of time-dependent effects can be monitored and reduced by recording the results of each separate measurement in the computer and analysing each separately for variations from the average. It should be possible to do this by adding some mass storage capability to the control

computer. Crompton *et al.* (1965) have demonstrated the ability to measure contact potential differences and to prepare highly uniform surfaces, suggesting that the problem of contact potentials can be reduced significantly.

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