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Total electron-impact ionization cross sections of helium

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Abstract
By accurate measurement of total cross section ratios for electron-impact ionization and photoionization, total electron-impact ionization cross sections of He were determined. Relative standard uncertainties as low as 1.6 to 2% in the electron energy range from 100 to 4000 eV were achieved using published cross section data for photoionization. Results are discussed in terms of theoretical predictions and by comparison with former experimental results. The data are in excellent agreement with the results by Rejoub *et al* (2002 *Phys. Rev.* A **65** 042713) and represent an accurate and reliable database for testing theoretical models.

1. Introduction

Electron-impact ionization (EI) and photoionization (PI) of He are two important processes in atomic physics that have been investigated intensively for many years. From a theoretical point of view, He is an ideal candidate for testing different theoretical models developed for complex many-electron atoms because it represents the simplest closed-shell structure. The ionization process of He is not affected by inner-shell effects. Contributions of double ionization and autoionization from doubly excited states are only small. Moreover, from an experimental point of view, He is of considerable interest due to the need for an accurate and reliable cross-section database of He ionization cross sections required in many fields of applied research to model plasmas, controlled thermonuclear fusion and atmospheres.

Numerous measurements of total ionization cross sections of He have been reported in the literature for EI and PI since the 1930s. However, the situation as regards precise cross-section data differs for the two ionization processes, which is closely connected with the different experimental techniques applied.

In the case of EI, two different methods and respective techniques were used for absolute measurements of ionization cross sections of He. Briefly, the commonly used method is based on the ionization of a static target gas by an electron beam and registration of ions by a particle detector. This method was utilized by a number of experimental groups including Smith (1930), Asundi and Kurepa (1963), Rapp and Englander-Golden (1965), Schram *et al* (1965, 1966), Gaudin and Hagemann (1967), Nagy *et al* (1980), and Rejoub *et al* (2002). A crossed-beam method, incorporating a fast neutral target beam instead of the static gas, was used by Montague *et al* (1984) and Wetzel *et al* (1987). As shown in reviews (e.g., Kieffer and Dunn (1966), Märk and Dunn (1985), Becker and Tarnovsky (1995)), in both cases the main contributions to the experimental uncertainties of EI cross sections arise from the absolute measurements of (a) the number of impact electrons, (b) the interaction path length accepted from the ion detector, (c) the ion detection efficiency and thus the number of ions created, and (d) the target atom density at a pressure of less than 10^{-2} Pa, which is typical for EI experiments. In the experiments employing the cross-beam technique, the latter problem is replaced by the problem of neutral-beam flux measurements. In order to avoid these problems, some groups (Adamczyk *et al* 1966, Van der Wiel *et al* 1969, Stephan *et al* 1980, Krishnakumar and Srivastava 1988, Shah *et al* 1988) paid great attention to studying relative dependences of EI cross sections on the electron energy, followed by normalization to previously published absolute data. The accuracy of those cross section data is not generally better than those directly obtained. The lowest relative uncertainty of EI cross sections for He recently reported by Rejoub *et al* (2002) is 5%. It was achieved using the most modern experimental techniques which allowed the authors to minimize the contributions arising from the absolute measurements of (b), (c) and (d). Other absolute cross-section data obtained in the past have quoted relative uncertainties ranging from 6% to 15% and differ from each other by up to 40%.

In the case of PI, the application of both the absorption cell technique and the double ionization chamber technique allow the problems (a) to (d) to be avoided completely (Samson 1976). Moreover, the gas pressure for these techniques is in the order of 100 Pa, i.e. four orders of magnitude higher than for EI experiments. Therefore, the application of precision oil manometers and capacitor manometers allows the target gas pressure to be measured with a relative uncertainty of less than 1% (Samson and Yin 1989). Thus, the total PI cross sections can be measured with a significantly better accuracy than the total EI cross sections, if a spectrally pure radiation source is used.

Reviews on total PI cross sections were given by Marr and West (1976) and Henke *et al* (1993).[4] The two groups have evaluated published experimental data available and presented recommended values for PI cross section of He with relative uncertainties of about 3%. Besides, several new studies of PI cross sections were reported which were not included in these reviews. Samson *et al* (1994) measured the total PI cross section of He using the double ionization chamber. In the VUV spectral range, the relative uncertainty of the measured cross sections was obtained to be as low as 1% at a photon energy ranging from threshold to 48 eV, increasing to 2% at a photon energy of 120 eV. Earlier, Chan *et al* (1991) measured PI cross sections from threshold to 180 eV by the use of the dipole (e, e) electron impact method. The two sets of data as well as the previously recommended data are in excellent agreement in the VUV spectral range. Finally, by compiling the previously published data, Bizau and Wuilleumier (1995) have tabulated recommended data for the total PI cross section of He with a relative uncertainty ranging from 1% at photon energies below 80 eV and 3% at a photon energy of 300 eV. A high reliability of the PI cross section data in the VUV spectral range is

[4] See also the data at http://www-cxro.lbl.gov/optical_constants/.

also proved by theory. As shown by Samson and co-authors (1994) who reviewed a number of calculations available, the agreement between the experimental and theoretical results is within 1 to 3% in the VUV spectral range (see figures 2 and 3 in their article).

On the other hand, many calculations for the EI cross sections of He and other rare gases were directed to improve collision theory. Total EI cross sections were calculated by Fursa and Bray (1995, 1997) using a sophisticated convergent close coupling (CCC) method. This method usually provides sufficiently accurate results. However, it is computationally intensive and there are some disagreements and questions in particular cases. Therefore, usage of the Born approximation for ionizing collisions, which is less computationally intensive, is still necessary. This is why many variants of the Born approximation have been developed to calculate the EI cross sections (Peach 1966, 1971, Bell and Kingston 1969, McGuire 1971, Omidvar *et al* 1972, Knapp and Schulz 1974, McCarthy and Stelbovics 1983, Moores 2001, Bartlett and Stelbovics 2002). From a practical point of view, semiclassical methods are also of interest due to the simplicity of the equations. Among these methods, two approaches based on a combination of the classical binary-encounter theory with the Born–Bethe approximation were reported recently by Margreiter *et al* (1994), Kim and Rudd (1994) and Kim *et al* (2000).[5]

Thus, the improved theoretical data for EI cross sections of He require a higher level of confidence for experimental data as achieved for PI. Measurements which provide an accuracy within 1 to 2% are required in a wide electron energy range. In this context we have measured in the present work total EI cross sections of He with relative uncertainties below 2% in the electron energy range from 100 to 4000 eV. This was achieved by using a method recently applied for measurements of total EI cross sections of other rare gas atoms (Sorokin *et al* 1998, 2000). The method is based on the accurate measurement of ratios of total cross sections for EI and PI, followed by the determination of the total EI cross sections using the measured cross-section ratios and published total PI cross section data. In addition, we also present results of a calculation for the EI cross section of He performed in the Born approximation using the program ATOM (Shevelko and Vainshtein 1993, Vainshtein and Shevelko 1996). The data are compared with the experimental and theoretical data published in the past.

2. Experiment

The ratios of total EI and PI cross sections were measured in the photon energy range from 25 to 30 eV at the normal incidence monochromator (NIM) beamline in the radiometry laboratory of the Physikalisch-Technische Bundesanstalt at the electron storage ring BESSY II (Richter *et al* 2001). The reflection optics of this beamline contained a 1 m normal incidence 15° McPherson-type monochromator equipped with a premirror and a diffraction grating, both of spherical geometry and with an Os coating for higher reflectance. At its output, a photon flux of up to 10^{11} s^{-1} and a resolving power $\lambda/\Delta\lambda$ of approximately 70 is provided.

The apparatus used for the cross-section measurements (see figure 1) as well as the experimental procedure were discussed in detail previously (Sorokin *et al* 1998, 2000). Briefly, the apparatus consists of an ionization chamber, an ion detector, an electron gun, a removable Faraday cup for electron current measurements and a photodetector calibrated against an electrical substitution radiometer (ESR) for photon flux measurements (Richter *et al* 2001, 2003). The He of 99.996% purity homogeneously fills the ionization chamber. During the measurements the He pressure is maintained at certain levels in the range between 1×10^{-3} Pa and 1×10^{-2} Pa. The operation of the apparatus is based on the successive ionization of the target gas by monoenergetic electrons of energy E and by monochromatized synchrotron

[5] See also the BEB database at http://physics.nist.gov/PhysRefData/Ionization/.

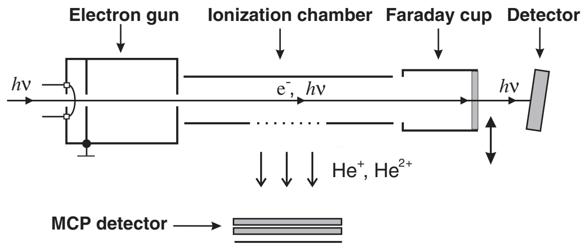

Figure 1. Schematic diagram of the apparatus.

radiation of photon energy $h\nu$, and on the comparison of the corresponding ion yields by using a microchannel plate (MCP) detector. The design of the apparatus ensures equivalent conditions for EI and PI as regards the gas density and the electric field distribution within the ionization chamber as well as the collection and detection efficiency of ions. In this case, the ratio of the total EI cross section $\sigma_e(E)$ to the total PI cross section $\sigma_{ph}(h\nu)$ is expressed as

$$\frac{\sigma_e(E)}{\sigma_{ph}(h\nu)} = \frac{1}{\eta_{ph}(h\nu)} \frac{f_e/I_e}{f_{ph}/I_{ph}}. \tag{1}$$

I_e and I_{ph} denote the current of Faraday cup and photodetector, respectively, f_e and f_{ph} are the MCP detector count rates for ions generated by electron and photon impact, respectively, and $\eta_{ph}(h\nu)$ is the quantum efficiency of the photodetector. The absolute determination of the quantities on the right-hand side of equation (1) as well the analysis of the respective contributions to the total relative uncertainties of the cross-section ratios has been described in detail earlier (Sorokin *et al* 2000). Therefore, only special features inherent to the present measurement will be discussed in the following.

First, in the photon energy range above the ionization threshold of He ($h\nu > 24.6$ eV) the photon flux at the output of the NIM beamline is rather low, decreasing from 6×10^{10} s^{-1} at a photon energy of 25 eV down to 8×10^9 s^{-1} at a photon energy of 30 eV. Because of the low photon flux and as a result of the low photodetector current, the trap detector which was utilized in our earlier work to suppress backward reflection of photons from the detector could not be used in the present work due to its high dark current. Therefore, single photodiodes of two different types, namely a silicon p–n junction photodiode manufactured at the Ioffe Physico-Technical Institute (Goldberg *et al* 1999) and PtSi–n-Si Schottky barrier photodiodes manufactured at the Swiss Federal Institute of Technology (Solt *et al* 1996) were used for photon flux measurements. In order to eliminate reflection of photons backward to the ionization chamber, the photodiode used in individual cross-section measurements was turned with respect to the incident photon beam by several degrees (figure 1). Typical values of the photocurrent ranged from 100 pA to 1 nA, depending on the photon flux and type of the photodiode. The dark current of the p–n photodiode was always less than 0.3 pA, whereas that of the PtSi–n-Si photodiode was in the range of 30 pA, remaining stable within 3 pA during individual cross-section measurements. The dark current was subtracted from the total current, resulting in the true photodiode-signal current. The dark current correction leads to a contribution to the total relative standard uncertainty of our cross-section measurements in the range from 0.1 to 3%.

Second, during the PI measurements in the photon energy range from 25 to 30 eV, the ion count rate as well as the photodiode current were affected by false light. In the first case, low-energy stray light with photon energies below the ionization threshold of He (i.e. for

$h\nu < 24.6$ eV) does not ionize He at all and thus, only second-order radiation and high-energy stray light with photon energies above the ionization threshold of He (i.e. for $h\nu > 24.6$ eV) contributed to the ion count rate. This contribution was found to be less than 1% by comparing the count rate at the photon energy of 25 eV and the remaining count rate at a photon energy of 24.2 eV, i.e. at photon energies slightly above and below the ionization threshold of He. To check the contribution of false light to the photodiode current, a gas filter 4 m in length integrated into the beamline and filled with He at a pressure of up to 25 Pa was used. By differential pumping using glass capillary arrays of 1 mm thickness and 50 μm tube diameter, the filter was separated from neighbouring vacuum chambers (Richter *et al* 2001). It cuts off radiation with photon energies above the ionization threshold of He and was transparent for radiation with lower photon energies except for those absorbed by intertube webs of the glass capillary assembly. Thus, measuring the decrease of the photodiode current at certain photon energies above and below the ionization threshold of He as the pressure in the gas filter was increased from background to 25 Pa, the contribution of the low-energy stray light and the contribution of the second-order radiation and high-energy stray light was determined, respectively. The latter contribution was found to be less than 1%, whereas that for the low-energy stray light was found to range from 3% at a photon energy of 25 eV to 20% at a photon energy of 30 eV, depending on the type of photodiode. The respective contributions were subtracted from the total ion count rate and photodiode current. This correction procedure leads to a contribution to the relative standard uncertainty of the measured cross-section ratios ranging from 0.6 to 1.5%.

Next, during calibration of the photodiode, its current and the radiant power measured by the ESR were also affected by false light, leading to a distortion of the measured quantum efficiency of the photodiode and, as a result, of the measured cross-section ratios. The contribution of the false light to the photodiode current was described above. In the case of radiant power measurements, an operation of the ESR in combination with the gas filter was complicated because of the initially low photon flux and its additional reduction due to absorption in the glass capillary assembly. Therefore, the contribution of false light to the total radiant power was determined through the respective contribution to the photodiode current. For this, the measured spectral dependence of the photodiode quantum efficiency and the spectral distribution of the false light were used. Assuming a predominance of second-order radiation in the high-energy false light, an upper limit for the contribution of the latter to the total radiant power was estimated to be less than 1%. Since the photodiode quantum efficiency is proportional to the ratio between the photodiode current and the radiant power, the contribution of the high-energy false light to the photodiode quantum efficiency was estimated to be negligible. In order to obtain a corresponding contribution of the low-energy stray light, its spectral distribution was determined. It was carried out by measuring the successive decrease of the photodiode current down to zero at certain photon energies above the ionization threshold of He, as different filters with absorption edges ranging from 24.6 to 11 eV were successively introduced into the beamline. The photodiode quantum efficiency in this spectral rage was taken into account. To perform these measurements we used the p–n photodiode, which has the lowest dark current, the gas filter filled with He, Ne and Ar at a pressure of 25 Pa, and a MgF_2 filter 2 mm thick. It was found that the contribution of the low-energy stray light to the total radiant power measured by the ESR ranged from 4% at a photon energy of 25 eV to 26% at a photon energy of 30 eV. Taking into account these data and the respective contributions to the photodiode current, the photodiode quantum efficiency was corrected and its true value was obtained ranging from 4.6 electron–hole pairs per incident photon at a photon energy of 25 eV to 6.1 at a photon energy of 30 eV for the p–n photodiode. Respective quantum efficiencies for PtSi–n-Si photodiodes were approximately 1.5 times less.

Table 1. Obtained total cross section ratios for electron-impact ionization and photoionization of He. The relative standard uncertainties are indicated in parentheses.

Photon energy $h\nu$ (eV)	$\frac{\sigma_e(E=1000\,\text{eV})}{\sigma_{ph}(h\nu)}$
25	1.725 (1.2%)
26	1.829 (1.2%)
27	1.932 (1.4%)
28	2.038 (1.6%)
29	2.149 (1.9%)
30	2.284 (2.9%)

Table 2. Contributions to the relative standard uncertainty of the ratios of the total cross sections for electron-impact ionization and photoionization of helium at 1000 eV electron energy and photon energies $h\nu$ ranging from 25 eV to 30 eV, as obtained for different photodiodes.

		Contributions to the relative uncertainty of total cross-section ratios (%) $25\text{ eV} \leqslant h\nu \leqslant 30\text{ eV}$		
Number	Source of uncertainty	p–n diode		PtSi–n-Si diodes
1[a]	Current of the impact electrons		0.2	
2[a]	Energy of the impact electrons		0.1	
3	Number of the impact photons			
	Photodiode current		0.1	
	Dark current correction	0.1		0.3–3.0
	Photodiode quantum efficiency	0.4–2.0		0.8–2.5
4[a]	Energy of the impact photons		0.2	
5[a]	Count rate measurements:			
	Counting statistics		0.5	
	Background correction		0.2	
	Linearity of detector		0.5	
6	False light contribution	0.6–1.5		0.8–1.5
7[a]	Equivalence of interaction path lengths		0.1	
8[a]	Equivalence of ion collection efficiencies		0.5	
9[a]	Equivalence of ion detection efficiencies		0.1	
10[a]	Gas pressure stability		0.1	
11[a]	Effects by secondary electrons		0.3	
	Total relative uncertainty (sum in quadrature)	1.2–2.7		1.5–4.3

[a] The discussion was presented earlier (Sorokin *et al* 1998, 2000).

The correction procedure concerning false light leads to an additional contribution to the relative standard uncertainty of the measured cross-section ratios ranging from 0.4 to 2.5%.

3. Results and comparison with other experimental data

Ratios $\sigma_e(E)/\sigma_{ph}(h\nu)$ of total cross sections for EI and PI of He were measured at an electron energy E of 1000 eV and six photon energies $h\nu$ between 25 and 30 eV in three different periods within 1.5 years by using different photodiodes (see chapter 2). All sets of data agreed within the combined relative uncertainties. The average values of the ratios are presented in table 1. The contributions to the total relative standard uncertainties of the ratios partly discussed above and in more detail earlier (Sorokin *et al* 1998, 2000) are summarized in table 2.

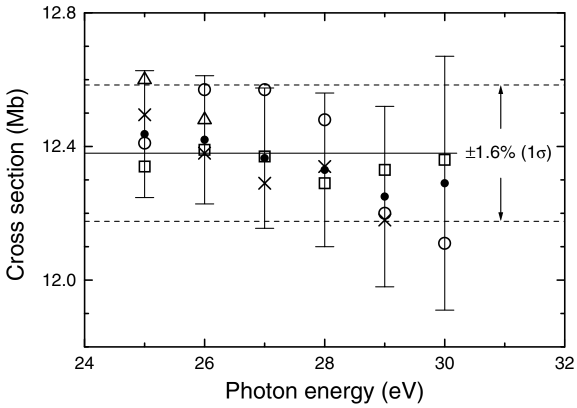

Figure 2. Total electron-impact ionization cross sections of He at an electron energy of 1000 eV obtained from cross-section ratios measured at different photon energies by multiplication with total photoionization cross section values reported by Samson *et al* (1994). □: data obtained using a silicon p–n junction diode and ○, ×, △: data obtained using different PtSi–n-Si diodes by three independent measurement periods within 1.5 years, ●: average data obtained using the cross-section ratios given in table 1. The continuous line represents the average value. Bars represent the relative uncertainties mentioned in section 3.

Total EI cross section data for 1000 eV electron energy were deduced from the measured ratios by multiplication with the absolute total PI cross sections reported by Samson *et al* (1994) with a relative standard uncertainty of 1%. The deduced total EI cross section values are plotted in figure 2. The relative uncertainties arise from the relative uncertainties of the measured ratios and the relative uncertainty of the absolute total PI cross sections. All values for $\sigma_e(E = 1000\ \text{eV})$ obtained at different photon energies by using different photodiodes are in excellent agreement. Averaging of these values results in a total EI cross section of He $\sigma_e(E = 1000\ \text{eV}) = 12.38$ Mb with a relative standard uncertainty of 1.6%. This value was used to convert the relative energy dependence $\sigma_e(E)/\sigma_e(E = 1000\ \text{eV})$, determined with a relative uncertainty less than 1.2%, on an absolute scale. The data are given in table 3. $\sigma_e(E)/\sigma_e(E = 1000\ \text{eV})$ was measured by comparing ion count rates normalized to the impact-electron current at the reference energy of 1000 eV and at electron energies E between 100 and 4000 eV.

Figure 3 compares our results with published experimental data obtained by direct absolute measurements. Former measurements normalized to the work of others are omitted. The early measurements of Smith (1930) and Asundi and Kurepa (1963) are not shown either in figure 3 because they used McLeod vacuum gauges uncorrected for the mercury pumping effect (Kieffer and Dunn 1966) and, thus, their results seem to be inaccurate. The fractional deviation of the published data from the present data and relative uncertainties for all sets of data are also shown to facilitate comparison. The results of Rejoub *et al* (2002), Nagy *et al* (1980), Gaudin and Hagemann (1967) and Schram *et al* (1965, 1966) correspond, like ours, to total ionization cross sections σ_e as the sum of single σ^+ and double σ^{2+} ionization cross sections for the creation of singly and doubly charged He ions, respectively. The measurements of Rapp and Englander-Golden (1965) provide so-called gross ionization cross sections σ_{gross}, i.e. the charged-weighted sum of the single and double ionization cross sections. The data were obtained by using an electron-beam-static-gas technique. Wetzel *et al* (1987) and Montague *et al* (1984) using a crossed electron-beam-fast-neutral-beam technique measured single ionization cross sections. Since the double EI ionization cross section of He stays

Table 3. Total electron-impact ionization cross section values $\sigma_e(E)$ of He and relative standard uncertainties.

Electron energy E (eV)	$\sigma_e(E)$ (Mb)	Relative standard uncertainty (%)
100	33.23	2.0
105	33.41	2.0
110	33.53	1.9
115	33.61	1.9
120	33.64	1.9
125	33.80	1.9
130	33.71	1.9
135	33.60	1.9
140	33.46	1.8
150	33.24	1.8
160	32.92	1.8
170	32.56	1.8
180	32.21	1.8
200	31.20	1.8
225	29.85	1.8
250	28.60	1.7
300	26.46	1.7
350	24.47	1.7
400	22.79	1.7
450	21.27	1.7
500	20.00	1.7
550	18.87	1.7
600	17.75	1.7
650	16.82	1.7
700	16.01	1.7
750	15.26	1.7
800	14.57	1.7
850	13.96	1.7
900	13.40	1.7
950	12.90	1.7
1000	12.38	1.6
1100	11.53	1.7
1200	10.80	1.7
1300	10.13	1.7
1400	9.59	1.7
1500	9.09	1.7
1600	8.67	1.7
1700	8.26	1.7
1800	7.91	1.7
1900	7.55	1.7
2000	7.25	1.7
2500	6.053	1.7
3000	5.204	1.7
3500	4.559	1.7
4000	4.077	1.7

below 0.5% of the single ionization cross sections (see, e.g., Rejoub *et al* (2002), Schram *et al* (1966)), the single and gross ionization cross sections differ from the total ones by less than 0.5%.

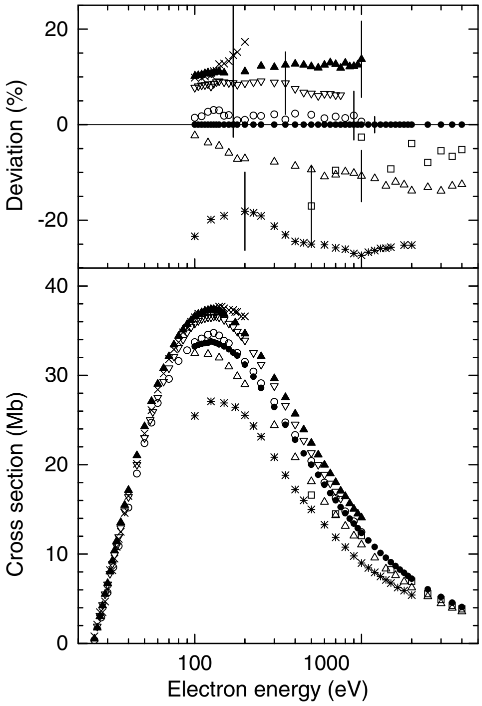

Figure 3. Total electron-impact ionization cross sections of He. ●: present data, ○: Rejoub *et al* (2002), ×: Wetzel *et al* (1987), ▽: Montague *et al* (1984), □: Nagy *et al* (1980), ∗: Gaudin and Hagemann (1967), △: Schram *et al* (1965, 1966), ▲: Rapp and Englander-Golden (1965). The upper plot shows the fractional deviation of the published experimental data from the present data. Bars represent the relative standard uncertainties of the present and published data.

We omit a description of experimental techniques and examination of experimental work with respect to possible error sources responsible for discrepancies which are clearly revealed by figure 3. It has been done many times in review articles (e.g., Kieffer and Dunn (1966), Märk and Dunn (1985)) as well as in experimental works (e.g., Straub *et al* (1995), Sorokin *et al* (1998), (2000)). As a general result it follows that our results as regards both, the relative energy dependence and absolute values, are in an excellent agreement with those of Rejoub *et al* (2002) who measured ionization cross sections with quoted relative uncertainties of 5% in the electron energy range from the ionization threshold to 1000 eV. The results of other experimental groups disagree with ours. It should be mentioned that our earlier data for Ne, Ar, Kr and Xe and those of Rejoub *et al* (2002) also agree within the combined relative standard uncertainties confirming the reliability of both data sets obtained by two completely different methods. Rejoub *et al* (2002) have applied a traditional method and modern experimental techniques which allowed them to minimize contributions to the uncertainty arising from absolute measurements of the target gas density, the ion detector and collection efficiency and the interaction path length. Our measurements, based on the comparison with photoionization, allowed us to eliminate these sources of uncertainty. Therefore, the data reported here in combination with those reported by Rejoub *et al* (2002) for the low electron energy range represent an accurate and reliable cross-section database of ionization cross section data. It may be used for testing theoretical models in a wide electron energy range from threshold

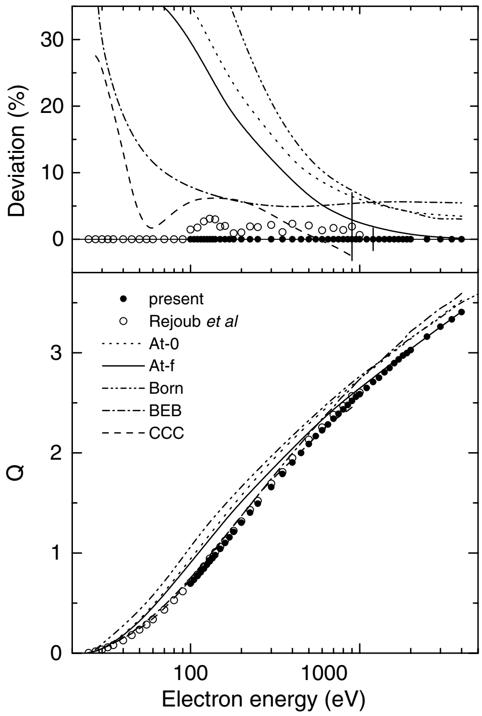

Figure 4. Total electron-impact ionization cross sections of He represented as $Q = \sigma_e(E)E/(4\pi a_0^2 R_y)$. Curves labelled 'At-0' and 'At-f' are present Born calculations performed using the ATOM code (Shevelko and Vainshtein 1993, Vainshtein and Shevelko 1996). The calculation denoted by Born, BEB and CCC are due to McGuire (1971), Kim and Rudd (1994), Kim *et al* (2000) and Fursa and Bray (1995, 2000), respectively. Experimental data: ● present, ○ Rejoub *et al* (2002). The upper plot shows the fractional deviation of the theoretical data from the present experimental data (above 100 eV) and from the data of Rejoub *et al* (below 100 eV). Bars represent the relative standard uncertainties of the experimental data.

to keV-energies where the Born approximation should successfully describe the process of electron–atom ionization.

4. Comparison with theory

From a theoretical point of view, the problem of atomic ionization by electron impact includes two aspects: the treatment of the collision process and approximation of the atomic wavefunction for the initial state. The 'collision part' can be considered in the Born approximation which is valid at large energies of the projectile. Here we used the semiempirical code ATOM (Shevelko and Vainshtein 1993, Vainshtein and Shevelko 1996) with a fitting energetic parameter equal to the ionization potential to calculate single ionization cross sections of the ground state of He. Comparison of the calculated data (the curve is labelled 'At-0') with the experimental data is given in figure 4 where a graph of $Q = \sigma_e(E)E\big/\big(4\pi a_0^2 R_y\big)$ against E is shown in a logarithmic scale. In the keV-energy range, both, the theoretical and experimental data represent straight lines with almost the same positive slope which is in accordance with the Bethe–Born approximation for an optically allowed transition (Inokuti 1971), and differ from each other by about 5%. Better agreement between calculated and experimental data is achieved when a fitting energetic parameter is chosen to provide a correct oscillator strength for the resonance transition $1s^2$–$1s2p^1P$ (the curve is labelled 'At-f'). For lower energies, the Born approximation generally fails. As an example, one of the early Born calculation performed by McGuire (1971) is also shown in figure 4 which agrees with our 'At-0' calculation in the keV-energy range and rise more rapidly with decreasing electron energy.

Ionization cross sections of the He atom were also calculated recently using the semiclassical Binary–Encounter–Bethe (BEB) model (Kim and Rudd 1994, Kim *et al* 2000 (see also footnote 5)) as well as using the sophisticated convergent close coupling method (Fursa and Bray 1995, 1997). The comparison of the results is presented in figure 4. Both calculations provide a level of agreement with the experimental data within 8% at electron energies above 100 eV, while they also overestimate the latter at lower energies.

5. Summary

Ratios of total EI cross sections to total PI cross sections of He were measured at an electron energy of 1000 eV and photon energies between 25 and 30 eV at the NIM beamline in the radiometry laboratory of the Physikalisch-Technische Bundesanstalt at the electron storage ring BESSY II. Relative standard uncertainties as low as 1.2–2.9% for the cross-section ratios were achieved. The measurements yield a common scale of total cross sections for EI and PI. Using the measured ratios and well-known PI cross sections, we deduced total EI cross sections of He with the lowest relative standard uncertainty of 1.6% at an electron energy of 1000 eV and of less than 2% at all other energies ranging from 100 to 4000 eV. Our data for total EI cross sections of He are found to be in excellent agreement with the recent results of Rejoub *et al* (2002) who measured EI cross sections with quoted relative uncertainties of 5% in the electron energy range from the ionization threshold to 1000 eV using a traditional method and modern experimental techniques. Therefore, both sets of data represent an accurate and reliable database of ionization cross sections of He in a wide electron energy range from threshold to keV-energies.

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