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Electron-impact ionization cross section of neon (σ_{n+}, $n = 1$–5)

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Abstract. Multiple ionization cross sections of neon (Ne–Ne^{n+}, with $n = 1$–5) by electron impact have been measured with energies ranging from threshold up to 3000 eV, by a time-of-flight technique. A comparison with other experimental data is presented. The integrated oscillator strengths (M^2_{n+}) for the processes have been determined showing a good agreement with previous reported data.

1. Introduction

Obtaining the absolute ionization cross section of atomic and molecular species separated between their charge states, presents a serious experimental challenge (Bruce and Bonham 1992, Tarnovsky and Becker 1992, Bonham *et al* 1991, Kieffer and Dunn 1966). Such information may be needed for many fundamental applications in different technological and scientific areas. Nevertheless, accurate measurements of σ_{n+} for neon multi-ionization are still scarce in the literature and the discrepancies, very often, exceed the combined uncertainties. Some effort has been made to establish more accurate data, mainly for noble gases. In spite of this, there are still large differences between the data for diverse experimental groups, both in magnitude and slope. One of the best reviews of the different experiments on ionization cross section has been given by Kieffer and Dunn (1966). Systematic discrepancies can be found in measurements performed by groups using different experimental approaches, such as effusive gas beam, direct measurement, mass spectrometers and static gas target, which has motivated some authors to study the discrepancies (Bruce and Bonham 1992, Tarnovsky and Becker 1992).

From the theoretical point of view, the picture is also unsatisfactory. Diverse works have been dedicated to deriving a formula that calculates the ionization cross sections (McGuire 1971, Saxon 1973, Knapp and Schulz 1974, Wallace *et al* 1973, Deutsch and Märk 1987, Bethe 1930, Inokuti 1971, Inokuti *et al* 1978). Bethe, using a Born approximation, has presented a preliminary expression (Bethe 1930, Inokuti 1971) and, although limited in its application, it shows a good agreement in slope with the experimental values for a single ionization process. The conditions for the validity of the Bethe theory are the applicability of the Born approximation and the negligible effect of exchange contribution between the projectile and the target electron. Through the Bethe–Born formulae it is possible to establish a correlation between the cross section of inelastic electron impact and photoabsorption data (Inokuti 1971).

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Multiple ionization can be produced mainly by two processes: inner-shell ionization with subsequent secondary electron ejection; and outer-shell ionization with simultaneous electron ejection. The reaction channel can be investigated with the aid of the photoionization data (Van der Wiel *et al* 1969, Inokuti 1971, Inokuti *et al* 1978, Rudd 1991).

$$\sigma_{n+} = 4\pi a_0^2 (R/E)(M_{n+}^2 \ln(E/R) + \gamma_{n+}(R/E) + C_{n+}) \tag{1}$$

where E is the incident energy, a_0 is the first Bohr radius of hydrogen, R is the Rydberg energy, and γ_{n+} and C_{n+} are constants depending on the gas target. The matrix element squared M_{n+}^2 is obtained by integrating the generalized oscillator strength for the processes considered (Inokuti 1971).

The present work was done using a time-of-flight (TOF) charge/mass spectrometer which measured the neon ions formed by electron impact in the 140–3000 eV energy range. The absolute values were achieved, through normalization, by using the Ne total-ionization cross section from Rapp and Englander-Golden data (1965). Although our measurements have allowed the resolution of the Ne^{20} and Ne^{22} isotopes, all cross sections in this paper have been obtained by adding both intensities.

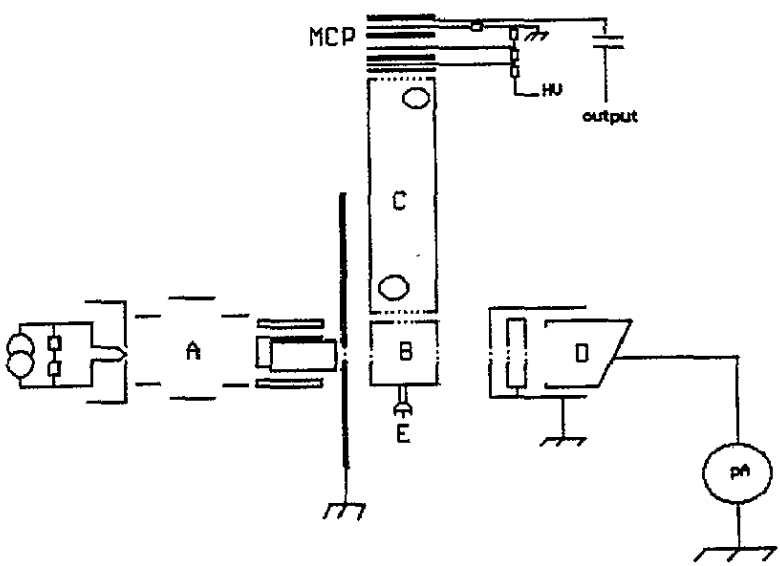

Figure 1. A schematic view of the experimental set-up: A, electron gun; B, gas target; C, time-of-flight tube; D, Faraday cup; E, pressure gauge.

2. Experimental apparatus

A detailed description of the apparatus and technique used in this paper has been given before (Almeida *et al* 1994), but see also figure 1. The experimental conditions are briefly as follows: a pulsed electron beam in the 90–3000 eV energy range was obtained from an electrostatically-focused gun. The beam entered a 3 cm long gas cell through a pair of diaphragms (1.5 and 2 mm diameter) filled by research grade gas (99.99% purity) to pressure below 10^{-4} Torr, which ensured single-collision conditions. After passing the cell, the electron beam was monitored into a Faraday cup coupled to a picoammeter. The secondary electron emission was efficiently prevented by a guard ring kept at −70 V. Typical

Table 1. The ratios $R_n = \sigma_{n+}/\sigma_+$ for $n = 2$–5 measured at 2 keV impact energy. The associated uncertainties are at the top of each column. The uncertainty of R_5 from Schram *et al* (1966) is about 20%.

R_n	Present work	Ziesel (1965)	Nagy *et al* (1980) 5%	Van der Wiel *et al* (1969) 10%	Gaudin and Hagemann (1967) 10%	Schram *et al* (1966) 10%
R_2	$(4.35 \pm 0.02) \times 10^{-2}$	$(4.4 \pm 0.2) \times 10^{-2}$	3.50×10^{-2}	5.98×10^{-2}	4.43×10^{-2}	3.42×10^{-2}
R_3	$(2.65 \pm 0.06) \times 10^{-3}$	$(2.7 \pm 0.3) \times 10^{-3}$	2.27×10^{-3}	4.93×10^{-3}	2.73×10^{-3}	1.87×10^{-3}
R_4	$(1.46 \pm 0.11) \times 10^{-4}$	$(1.75 \pm 1.15) \times 10^{-4}$	—	3.61×10^{-4}	1.58×10^{-4}	1.03×10^{-4}
R_5	$(1.10 \pm 0.21) \times 10^{-5}$	—	—	—	—	$4.8 \times 10^{-6*}$

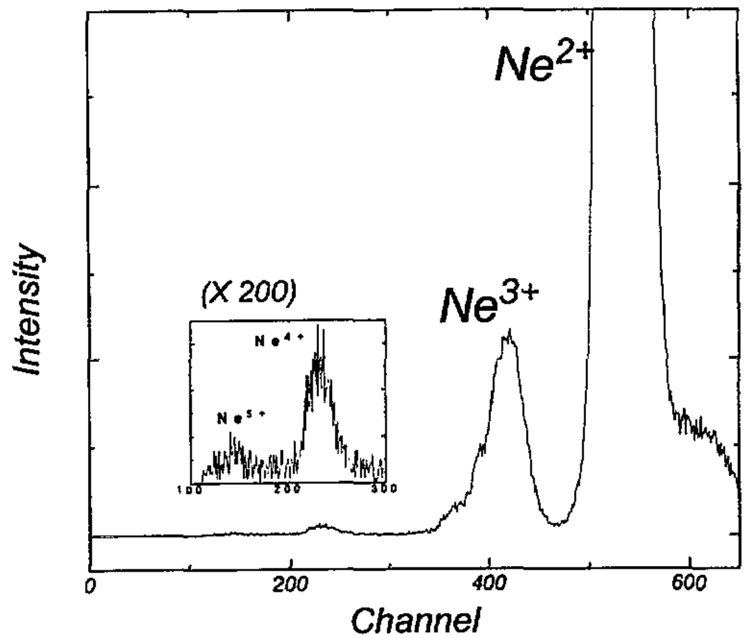

Figure 2. The ionic abundance at 2.2 keV incident energy.

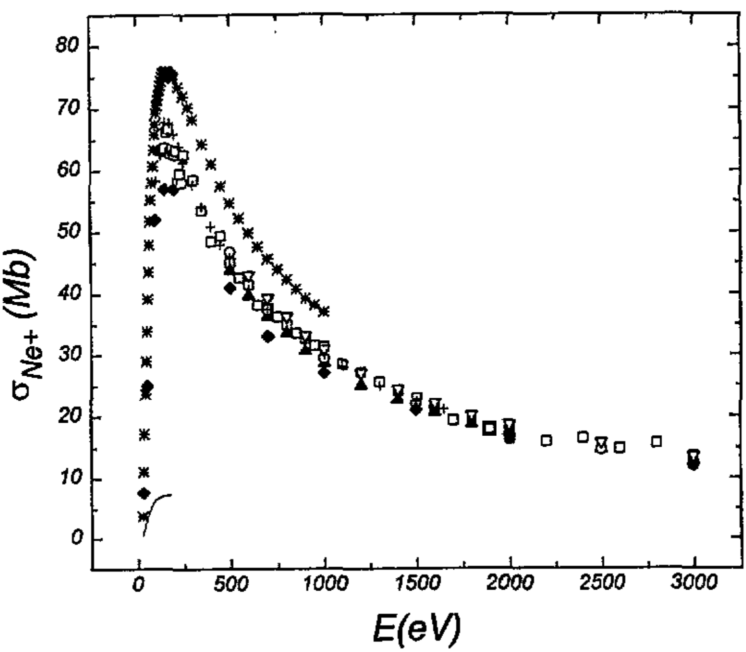

Figure 3. The electron-impact ionization cross section, σ_{1+}, as a function of the incident energy: □, present data; ○, Nagy *et al* (1980); *, Krishnakumar and Srivastava (1988); +, Gaudin and Hagemann (1967); ●, Van der Wiel *et al* (1969); ▲, Schram *et al* (1966); ▽, Schram *et al* (1965); ◆, Adamczyk *et al* (1966); ——, Stephan *et al* (1980).

incident currents were in the range 1–50 pA (DC equivalent) and each pulsed every 10 μs

Table 2. The partial-ionization cross section of neon by electron collision. The uncertainties are described in the text.

Energy (eV)	σ_{1+} (Mb)	σ_{2+} (Mb)	σ_{3+} (10^{-2} Mb)	σ_{4+} (10^{-3} Mb)	σ_{5+} (10^{-4} Mb)
140	63.2	1.34	—	—	—
150	63.7	2.28	—	—	—
160	66.3	2.43	—	—	—
170	66.8	2.69	—	—	—
180	62.9	2.98	3.5	—	—
190	63.4	3.26	4.0	—	—
200	62.6	3.41	4.3	—	—
210	63.2	3.24	8.3	—	—
220	58.1	3.44	9.9	—	—
230	59.5	3.12	10.8	—	—
240	58.0	3.34	9.4	—	—
250	62.6	3.29	12.2	—	—
260	—	—	14.4	—	—
270	—	—	11.7	—	—
280	—	—	14.9	—	—
300	58.5	3.16	14.2	—	—
350	53.5	3.22	16.0	—	—
400	48.5	3.02	16.3	2.78	—
450	49.4	2.73	14.5	2.99	—
500	45.1	2.50	15.7	4.70	—
550	42.6	2.36	15.5	3.73	—
600	41.5	2.23	12.7	3.60	—
650	38.1	2.12	12.0	3.31	—
700	37.6	2.10	11.3	2.97	—
750	36.2	1.92	11.0	2.63	—
800	34.9	1.88	10.2	2.30	—
850	33.5	1.69	9.1	2.58	—
900	32.7	1.61	8.5	—	—
950	31.5	1.50	8.3	2.19	—
1000	31.3	1.44	7.8	2.21	0.21
1100	28.4	1.33	7.5	2.45	0.22
1200	27.1	1.25	7.5	2.84	—
1300	25.5	1.14	6.5	2.65	—
1400	24.1	1.06	6.0	3.10	—
1500	22.9	1.00	5.6	3.47	1.73
1600	21.1	0.94	5.1	2.95	—
1700	19.3	0.93	5.3	3.32	1.79
1800	19.1	0.86	—	—	—
1900	17.9	0.85	—	2.59	—
2000	17.7	0.77	4.7	2.58	1.94
2200	16.0	0.79	4.4	2.35	2.31
2400	16.5	0.69	3.7	—	—
2600	14.8	0.61	3.3	—	—
2800	15.7	0.61	3.3	1.96	2.78
3000	13.7	0.64	3.4	2.45	—

at a 0.5% duty cycle. The acquisition time was typically 2 h per experimental point.

The ionic states present in the target were extracted by a 50 V cm^{-1} pulsed electrical field (during 5 μs) and transmitted through a time-of-flight (TOF) Wiley–McLaren-type (Wiley and McLaren 1955) to a set of micro-channel plates. The rise-time of the extraction pulse is coincident with the fall-time of the incident electron bunch.

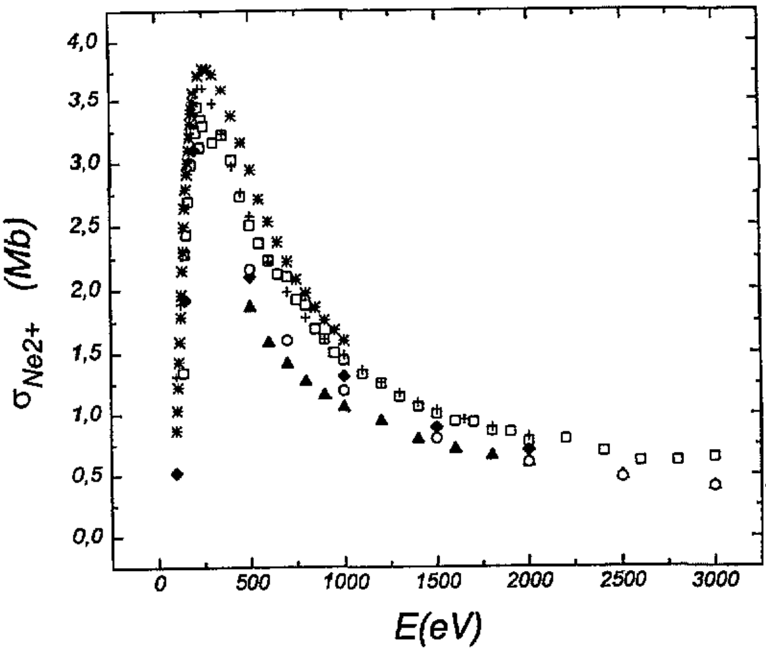

Figure 4. The electron-impact ionization cross section, σ_{2+}, as a function of the incident energy: □, present data; ○, Nagy *et al* (1980); $*$, Krishnakumar and Srivastava (1988); +, Gaudin and Hagemann (1967); ▲, Schram *et al* (1966).

The ions leave the target through a 0.7 cm diameter hole drilled in the cell wall, where an 82% transparent molybdenum grid was used to define the extraction field. Then they are accelerated across a 0.5 cm gap before entering the free-field region. Both ends of the TOF tube are closed by the Mo mesh. The drift region is pumped out through four ports (each of 0.5 cm diameter) drilled in the tube. A large optical TOF was adopted to ensure maximum ion detection. In order to optimize the TOF focusing properties, the ionic trajectories were performed with the aid of the SIMION program (Dahl and Delmore 1987).

During all the experiments the pressure inside the collision chamber was kept so low that the probability of an incident electron undergoing more than one collision along its journey across the target was negligible. The single-collision regimen was checked at each incident energy considered. The initial growth rate of the ratio I^{n+}/I^{-} is linear, I^{n+} being the ionic current detected for the n species and I^{-} the electron current (see Almeida *et al* 1994). For a fixed incident energy the ratio can be expressed as

$$I^{n+}/I^{-} = \varepsilon\pi(P)\sigma_{n+} \tag{2}$$

where $\pi(P)$ is the number of target particles per square centimetre which is proportional to the gas cell pressure P and ε is the full efficiency of ionic collection. Figure 2 shows a typical spectrum obtained at 2.2 keV incident energy.

Special attention has been paid to the incomplete collection and detection of the ions. The dependence of the transmission through the TOF spectrometer on the ionic charge could vary with the localization, mainly for highly-charged ions. Simulation by the program SIMION has shown, that under our experimental conditions, all extracted ions fly through trajectories parallel to the TOF tube axis. Therefore, the ionic loss fraction, by geometric effects, is independent of the charge state.

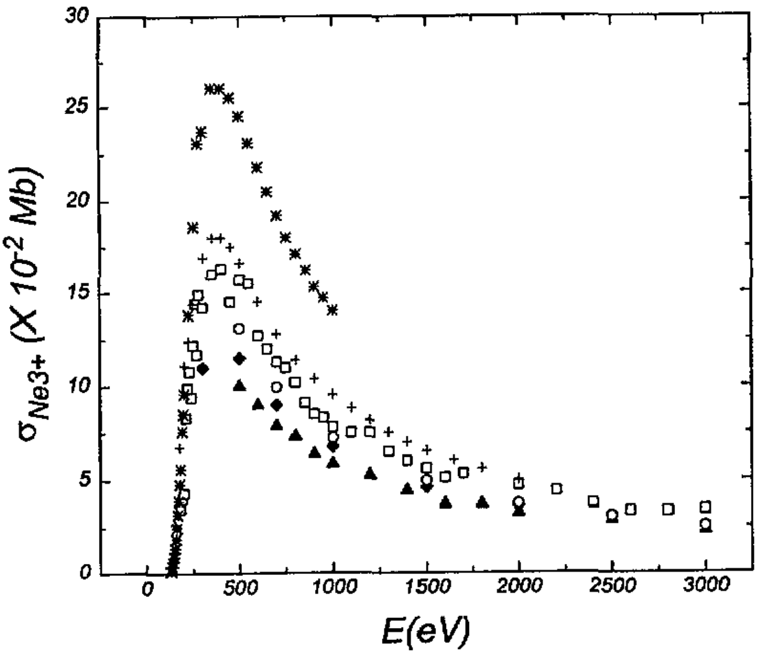

Figure 5. The electron-impact ionization cross section, σ_{3+}, as a function of the incident energy: □, present data; ○, Nagy *et al* (1980); ∗, Krishnakumar and Srivastava (1988); +, Gaudin and Hagemann (1967); ▲, Schram *et al* (1966).

The most decisive problem is due, basically, to the electron capture by the ion in collisions with the background gas. In our case, the ion loss during the flight up to the detector was reduced because of the short TOF length (4 cm) and the low pressure inside the chamber. Along the ionic trajectory (about 50 mm in total length) the ions fly from a pressure of less than 10^{-4} Torr inside the gas cell up to a pressure of 10^{-7} Torr in the detection region. The electron-capture cross section at 50 eV, estimated through the Landau–Zener model (Olson and Salop 1976), is in the order of 10^{-15} cm^2 for Ne^{5+} ions (the worst case). Therefore less than 1% of the ions are removed from their initial charge state so the effect of incomplete ion collection is covered by the total uncertainty.

We adopted both suggestions from Bruce and Bonham (1992) during the measurements, i.e. observation of the discrimination level (constant fraction discriminator) and the ratio σ_{2+}/σ_{+}. A discussion about the precautions considered in this work has been described before (Almeida *et al* 1994).

To consider the efficiency of the detector for different charge states, the accelerating potential in front of the micro-channel plate was varied between 3 and 4 kV and the ratios $R_n = \sigma_{n+}/\sigma_{+}$ for n = 2–5 changed by about 4% (less than the total uncertainty).

In our case, the determined ratios are generally in good agreement with previous reported data (Van der Wiel *et al* 1969, Gaudin and Hagemann 1967, Ziesel 1965, Nagy *et al* 1980, Schram *et al* 1966, Adamczyk *et al* 1966) for 2 keV impact energy (table 1). Hence, we can conclude that the dependence of ε on the ionic species is small for the geometry and detection system adopted, and therefore can be taken as constant for all states studied.

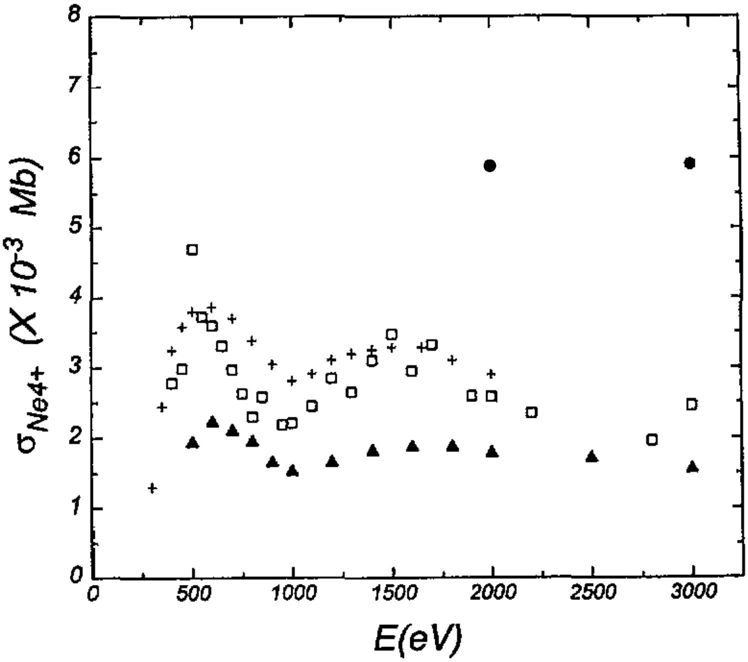

Figure 6. The electron-impact ionization cross section, σ_{4+}, as a function of the incident energy: □, present data; +, Gaudin and Hagemann (1967); ●, Van der Wiel *et al* (1969); ▲, Schram *et al* (1966).

3. Results and discussion

All data were determined through the ratio of the ion abundance, which is free from uncertainties due to absolute pressure measurements and fitting procedure. Subsequently, they have been normalized using the values of Rapp and Englander-Golden (1965). We considered the total-ionization cross section as $\sigma_{\text{tot}} = \sum_n n\sigma_{n+}$ and $I^{\text{tot}} = \sum_n nI^{n+}$.

The total errors in the present values of the normalized ionization cross section (NICS) have been estimated by considering the uncertainties involved in the measurement of the quantities used in the normalization procedure. The statistical counting uncertainties for I^{n+}/I^{tot} (n = 1–5) are approximately 0.1%, 0.3%, 2%, 6% and 16%, respectively, for each electron impact energy. We used an unmonochromatized electron gun and the energy spread of the incident electron beam was around 2 eV. The data from Rapp and Englander-Golden (1965) are reliable within 7%. Considering standard error reduction for independent measurements, the overall uncertainty of the present NICS is about 8%, 8%, 9%, 14%, 21% for σ_{n+} with n = 1–5, respectively. The results are presented in table 2.

The normalized ionization cross section, σ_{n+}, for electron collisions on neon can be compared, in figures 2–6, to the previous experimental results in the literature, ranging from threshold to 3000 eV.

There is a good set of measurements for σ_{1+} and σ_{2+} in the literature (Gaudin and Hagemann 1967, Ziesel 1965, Nagy *et al* 1980, Schram *et al* 1966, Adamczyk *et al* 1966, Schram *et al* 1965, Krishnakumar and Srivastava 1988, Stephan *et al* 1980). For σ_{1+} (figure 3), the present results agree well, both in slope and magnitude, with values from Gaudin and Hagemann (1967), Nagy *et al* (1980), Schram *et al* (1966) and from Van der Wiel *et al* (1969); however, they are up to 25% lower than those of Krishnakumar and

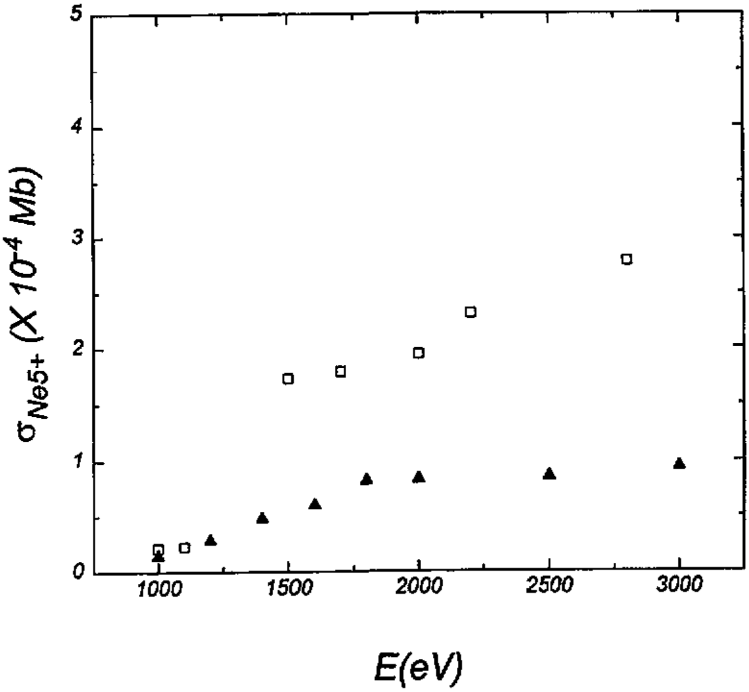

Figure 7. The electron-impact ionization cross section, σ_{5+}, as a function of the incident energy: □, present data; ▲, Schram *et al* (1966).

Srivastava (1988). A good accordance has been achieved for σ_{2+} (figure 4) between our results and those of Gaudin and Hagemann (1967) and Nagy *et al* (1980), nevertheless they are about a factor 1.5 times higher than Schram *et al* (1966), for energies up to 2 keV.

For σ_{3+} (figure 5), around the maximum region only ($200 < E < 1500$ eV), some relevant discrepancies have been found; our data agree well with the values from Gaudin and Hagemann (1967), Nagy *et al* (1980); but they are about 1.6 times lower than those from Krishnakumar and Srivastava (1988). The shapes of the cross sections measured by Krishnakumar and Srivastava (1988) are generally in good agreement with the literature; however the absolute values are usually larger. This discrepancy has been attributed to ionic extraction efficiency and transmission losses (Bonham *et al* 1991).

A feature, starting at about 1050 eV, in the σ_{4+} curve (figure 6) was originally observed by Ziesel (1965) and later confirmed by Schram *et al* (1966) and Gaudin and Hagemann (1967). This feature is assigned to a shake-off process and has been discussed by Gaudin and Hagemann (1967) and Schram *et al* (1966). For σ_{4+} no remarkable discrepancies have been found. Our data agree with the data from Gaudin and Hagemann (1967) and they are about 50% higher than those of Schram *et al* (1966).

For σ_{5+}, the only results (figure 7) found in the literature, in the present range of incident energy, are from Schram *et al* (1966). The present data are higher by a factor of 2 than those of Schram *et al* (1966). This significant difference cannot be covered by the combined uncertainties.

The asymptotic expression for electron collisions derived from equation (1), with $\gamma_{n+} = 0$ for energy higher than the maximum cross section, was fitted to the experimental data and is shown by the Fano–Bethe plot of figure 8. The parameters M_{n+}^2 and C_{n+} were

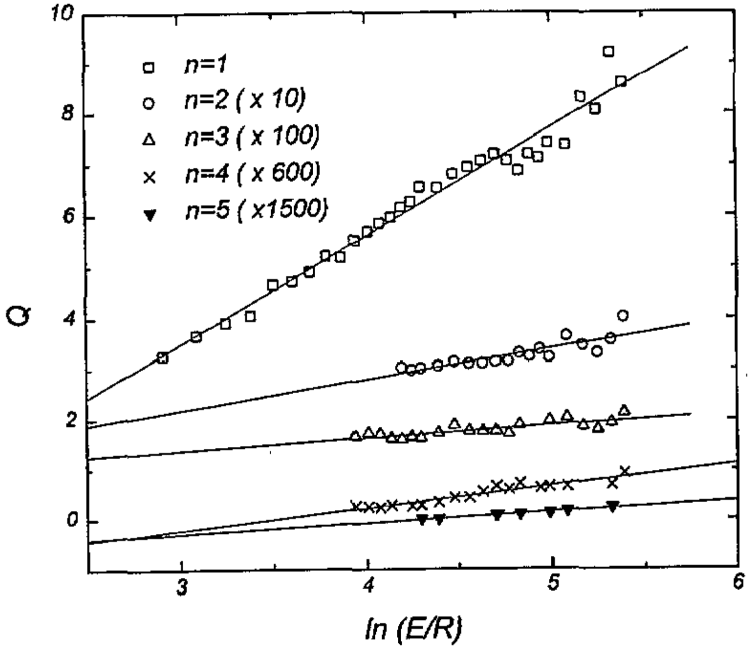

Figure 8. A Fano–Bethe plot for the process e + Ne ⇒ Ne^{n+} + $(n+1)$e with $n = 1$–5. The quantity Q is defined as $\sigma_{n+}E/(R4\pi a_0^2)$.

determined by adjusting a straight line to the asymptotic value of our data using a least-squares method. The values of M_{n+}^2 are presented in table 3, with data presented from Van der Wiel *et al* (1969) and Schram *et al* (1966).

Table 3. The integrated oscillator strength (M_{n+}^2).

n	This work	Van der Wiel *et al* (1969)	Schram *et al* (1966)
1	2.06 ± 0.31	1.85	1.82
2	$(4.6 \pm 0.7) \times 10^{-2}$	4.9×10^{-2}	8.8×10^{-3}
3	$(2.1 \pm 0.6) \times 10^{-3}$	5.2×10^{-3}	1.0×10^{-3}
4	$(7.9 \pm 2.5) \times 10^{-4}$	5.2×10^{-4}	3.6×10^{-4}
5	$(1.5 \pm 1.0) \times 10^{-5}$	—	1.6×10^{-5}

Our results for the single-ionization cross section, shown to be proportional to $(\ln E)/E$, confirmed that it is strongly dominated by an optically-allowed process. In contrast, σ_{2+} and σ_{3+} have a $1/E$ dependence for most of the spectra, and are therefore dominated by two- and three-electron emission, respectively. σ_{4+} and σ_{5+} show a competition between direct ionization and the inner-shell process as suggested by oscillation in the Fano plot, see Gaudin and Hagemann (1967).

The present results for σ_{n+}, with $n = 1$–4, have shown a good agreement with data from the literature. For $n = 5$ some discrepancies in magnitude have been found. Nevertheless, no systematic discrepancy or regions could be identified (over the impact energy range), associated with either different experimental procedures or groups, as mentioned by Bruce and Bonham (1992). This observation is particularly different from a previous study for argon (Almeida *et al* 1994). Following the observations from Becker *et al* (1989) and measurements from Samson *et al* (1992), the spectrum of ejected electrons from neon is shifted towards the high incident-energy region with respect to argon. Therefore, the argon atom is excited with higher population of the autoionizing states for energies above the maximum cross section, so should be more sensitive to transmission length. Long lifetime states may decay before reaching the detection system.

Acknowledgments

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