Absolute optical oscillator strengths for the electronic excitation of atoms at high resolution. II. The photoabsorption of neon

W. F. Chan, G. Cooper, X. Guo,* and C. E. Brion
Department of Chemistry, The University of British Columbia, 2036 Main Mall, Vancouver, British Columbia, Canada V6T 1Z1
(Received 18 June 1991)

A recently developed high-resolution dipole (e,e) method [W. F. Chan, G. Cooper, and C. E. Brion, Phys. Rev. A **44**, 186 (1991)] for the measurement of absolute optical oscillator strengths (cross sections) for electronic excitation of free atoms and molecules has now been applied to photoabsorption and photoionization processes for neon in the energy range 16–250 eV. The absolute scale is obtained by Thomas-Reiche-Kuhn (TRK) sum-rule normalization of the Bethe-Born converted electron-energy-loss spectrum. The measured absolute photoabsorption oscillator strengths for discrete electronic transitions of neon from the ground state to the $2s^22p^5ns$ and $2s^22p^5nd(^2P_{3/2,1/2})$ manifolds are compared where previously reported experimental data are available. Measurements of the absolute optical strength in the photoionization continuum up to 250 eV are compared with other experimental and theoretical data. Absolute optical oscillator strengths in the 40–55-eV region of the $2s2p^6np$ and $2s^22p^43lnl'$ autoionizing resonances are also reported.

PACS number(s): 32.70.Cs, 32.30.Dx, 32.80.Fb

I. INTRODUCTION

Absolute optical oscillator strengths for discrete and continuum electronic excitation of neon are important quantities in such areas as radiation physics, plasma physics, and astrophysics. For instance, Auer and Mihalas [1] have used Ne I oscillator strength data to reevaluate the abundances of neon in the B stars. Recently there has also been strong interest in the energy levels and oscillator strengths of neonlike systems because of their application in the development of soft-x-ray lasers [2]. Discrete oscillator strengths also provide a sensitive test for atomic-structure calculations, since the simple LS and j-j coupling schemes are not strictly applicable for neon and some sort of intermediate-coupling scheme must be used instead [3]. In contrast to the situation for helium, the photoionization cross-section maximum of neon is not at threshold, showing a significant departure from hydrogenic behavior due to more prominent electron correlations. Cooper [4] has calculated the oscillator-strength distribution for the outer atomic subshell of neon by assuming an electron moving in an effective central potential similar to the Hartree-Fock potential. McGuire [5], approximating the Herman-Skillman central field with a series of straight lines, has computed the photoionization cross section of neon with the continuum orbitals calculated from the approximate potential. Kennedy and Manson [6], utilizing Hartree-Fock wave functions with complete exchange, Luke [7], employing a multiconfiguration close-coupling method for the wave functions, Burke and Taylor [8], using the R-matrix theory, and Amus'ya, Cherepkov, and Chernsheva [9], applying the random-phase approximate with exchange (RPAE) method, have also calculated photoionization cross sections for neon. Relativistic random-phase-approximation (RRPA) calculations carried out by Johnson and Cheng [10] showed that relativistic effects are small in neon and gave results in good agreement with the nonrelativistic RPAE of Amus'ya, Cherepkov, and Chernsheva [9]. Parpia, Johnson, and Radojevic [11] have also reported the photoionization cross sections of the outer shells of neon using the relativistic time-dependent local-density approximation (RTDLDA) method which is closely related to the RRPA method of Johnson and Cheng [10]. Although the calculated values are much improved with the inclusion of electron correlation, some discrepancies ($>15\%$) still exist between the experimental [12–21] and theoretical [4–11] photoionization cross sections in certain energy ranges. Experimental total photoabsorption and photoionization measurements in the continuum performed using the Beer-Lambert law [12–18] show good agreement with each other in terms of the shape (i.e., relative cross section). However, the various reported values of the absolute cross sections in the continuum show substantial differences ($\sim 10\%$), probably due to difficulties in obtaining sufficiently precise measurements of the sample target density in a "windowless" far-uv system. In addition, inadequately accounted for contributions from stray light and/or higher-order radiation will affect measured cross sections. Lee and Weissler [12] and Ederer and Tomboulian [13] have measured the photoabsorption cross section of neon using discharge-lamp line sources in the energy ranges 15.5–54 and 20–155 eV, respectively. Lee and Weissler [12] recorded the absorption photometrically in a grazing-incidence vacuum spectrograph. Ederer and Tomboulian [13] have made measurements combining the conventional photographic recording method with a Geiger-Müller counter for selected wavelengths. Samson [14,15] has designed an extremely effective double-ion chamber technique which is capable of measuring very accurate photoionization cross sections using either line or continuum sources. Using this apparatus Samson [14,15] has reported measurements for

neon in the range 21.6–310 eV. Saxon [22] reviewed the limited neon photoabsorption data available in 1973 and provided a sum-rule analysis which suggested that the measured cross sections were reasonably accurate. Wuilleumier and Krause [23] derived $2p$, $2s$, and $1s$ subshell partial photoionization cross sections by combining photoelectron branching-ratio studies using x-ray line sources with existing total photoabsorption measurements. In addition, contributions from multiple ionization were estimated [23]. With the advance of synchroton radiation (SR), an intense and continuous light source became available for measuring the photoionization cross sections of atoms and molecules up to high energies. However, with SR sources very careful work is required to correct for the effects of contributions from stray light and higher-order radiation on absolute cross-section measurements [24–26]. Watson [16] obtained photoionization cross sections for neon in the 60–230-eV photon-energy range. West and Marr [17] not only used synchroton radiation to make absolute absorption measurements for neon over the range 36–310 eV but also gave a critical evaluation of existing published cross-section data and obtained recommended weighted-average values [18] throughout the vacuum ultraviolet and x-ray regions. Electron-impact-based techniques [19–21] have also been employed to obtain photoionization cross sections of neon. By approximating the generalized oscillator strength [$f(K,E)$ where K is the momentum transfer and E is the energy] as the optical oscillator strength [$f^0(E)$] using an impact energy 500–1000 eV and collecting the inelastically scattered electrons at small angles, Kuyatt and Simpson [19] converted the electron-energy-loss spectrum of neon (up to 100-eV energy loss) to a *relative* photoabsorption cross-section curve. Using high electron-impact energy (10 keV) and the calculated scattering geometry of the beam to obtain the relative Bethe-Born factor, electron-energy-loss results at small momentum transfer have been converted to relative photoionization cross sections for neon by Van der Wiel [20]. Van der Wiel and Wiebes [21] have also studied multiple photoionization of neon using the same method. The relative optical oscillator strength data obtained by the electron-impact methods described above were normalized using a literature value of the absolute photoabsorption cross-section value at a single energy.

Apart from the difficulty of measuring an accurate sample density, Beer-Lambert law photoabsorption measurements for the discrete excitation region of neon may also be subject to serious errors due to so-called "line-saturation" (i.e., bandwidth) effects [27–30] since the neon valence-shell ($2p$) electronic transitions have extremely narrow natural linewidths [31–40]. These effects are most significant when the cross section is large and where the bandwidth of the incident radiation is greater than the natural linewidths of the spectral lines being measured. In such situations the oscillator strength (cross section) may be much smaller (by as much as an order of magnitude) than the true value unless careful measurements are made as a function of pressure [28,30]. Detailed discussions and quantitative assessments of "line-saturation" effects have been given in Refs. [28,30]. Other experimental methods for optical oscillator strength determination which avoid the line-saturation problems include profile analysis [31,41], self-absorption [42–44], total absorption [32], and lifetime measurements [30–40], as well as the completely independent approach afforded by electron-impact-based methods using electron-energy-loss spectroscopy [27,28,45–47]. These various optical and electron-impact methods have been used in earlier reported work to obtain absolute optical oscillator strengths for neon in the discrete region, but the measurements have been mainly restricted to the 16.671 eV (f_1) and 16.848 eV (f_2) resonance lines corresponding to the [$2s^22p^6 \rightarrow 2s^22p^5(^2P_{3/2,1/2})3s$] transitions. Korolev, Odinstov, and Fursova [31] measured the transition probability of the f_2 line from the natural-broadening profile while Lewis [41] studied the pressure-broadening profile and gave the oscillator strengths for both the f_1 and f_2 resonance lines. The relative self-absorption method was used by Jongh and Eck [42] to measure the oscillator strength of the f_2 resonance line using the calculated oscillator strength of the helium $1\,^1S \rightarrow 2\,^1P$ line as a reference. Westerveld, Mulder, and Van Eck [43] and Tsurubuchi, Watanabe, and Arikawa [44] used the absolute self-absorption method to determine the oscillator strengths of the f_1 and f_2 resonance lines. Aleksandrov *et al.* [32] employed the total-absorption method to obtain oscillator strengths for various lines in the 20–80-nm (15.5–62-eV) range. Radiative lifetimes for some of the resonance transitions of neon have been determined using (a) a pulsed-electron source for excitation and studying the resulting photon-decay curve [33,34]; (b) the beam-foil method [35,36]; (c) the level-crossing technique [37]; (d) the phenomena of hidden alignment [38]; (e) relaxation upon polarized laser irradiation in a magnetic field [39,40]. Knowing the branching ratios for the resonance lines, the obtained lifetimes can then be converted to the optical oscillator strengths for the respective transitions. In electron-impact-based studies, Geiger [45] obtained the sum of the absolute photoabsorption oscillator strengths for the f_1 and f_2 resonance lines at low resolution by measuring both the electron elastic-scattering cross section and the small-angle inelastic-scattering cross section at very high impact energy (25 keV) and normalizing on known absolute values of the elastic-scattering cross section. Later Geiger [46] obtained the ratio (f_2/f_1) of the oscillator strengths of the resonance lines using a high-resolution electron-energy-loss spectrometer, and by combining the value obtained from the low-resolution spectrometer with this ratio he obtained values for the individual oscillator strengths for the two resonance lines. The electron-impact method has also been employed by Natali, Kuyatt, and Mielczarek [47] to measure the discrete optical oscillator-strength distribution of neon. The unpublished results of Natali, Kuyatt, and Mielczarek are quoted in Refs. [43,48].

A variety of discrete oscillator-strength calculations have been reported for neon. Cooper [4], employing a one-electron central potential model, Kelly [49], using the Slater approximation to the Hartree-Fock method, and Amus'ya [50], applying the RPAE method, have cal-

culated the oscillator strengths for transitions from the ground state of neon to the $2s^22p^5(^2P_{3/2,1/2})ns$ and nd states. Other calculations of the oscillator strengths for individual transitions from the ground state to various $2s^22p^5(^2P_{3/2})ns$ and nd states, and also to $2s^22p^5(^2P_{1/2})ns'$ and nd' states, have likewise been reported, but in most cases these are only for the transitions to the $2s^22p^5(^2P_{3/2})3s$ (f_1) and $2s^22p^5(^2P_{1/2})3s'$ (f_2) states. The oscillator strengths of the f_1 and f_2 resonance lines were calculated by Gold and Knox [51] using the Hartree-Fock equation based on experimental energies and dipole-matrix elements computed from theoretical atomic wave functions. Gruzdev [3], using the techniques of intermediate coupling and the values of the transition integral obtained from the Coulomb approximation, has reported the oscillator strengths for the f_1 and f_2 resonance lines. Aymar, Fenueille, and Klapisch [52] calculated Ne I transition probabilities and lifetimes with the introduction of an effective operator for the angular part of the wave functions and a parametrized central potential for the radial part of the wave functions. Gruzdev and Loginov [53] carried out the calculation of the radiative lifetimes of several levels of neon with a many-configuration approximation using Hartree-Fock self-consistent-field wave functions. Albat and Gruen [54] have reported the excitation cross section of the lowest resonance level of neon using a configuration-interaction (CI) calculation based on the orthogonal set of orbitals obtained from a ground-state Hartree-Fock calculation. The time-dependent Hartree-Fock equations were also employed by Stewart [55,56] to study the excitation energies and bound-bound oscillator strengths for atoms isoelectronic with neon over a wide range of energies. Aleksandrov *et al.* [32] not only reported the measurements for the discrete oscillator strengths of neon by the total-absorption method, but have also calculated the oscillator strengths for the same discrete lines of neon based on an intermediate-coupling scheme with the electrostatic, spin-orbit, and effective interactions included in the energy matrices. An examination of the various experimental [31–44] and theoretical [3,4,49–56] studies reveals a considerable spread in oscillator-strength values for a given transition, even in the case of the intense f_1 and f_2 resonance lines of neon.

Electron-energy-loss experiments at low resolution utilizing the virtual photon field of a fast electron inelastically scattered at negligible momentum transfer have been used extensively in this laboratory as the basis of dipole (e,e), $(e,2e)$, and $(e,e+\text{ion})$ spectroscopies for the determination of absolute oscillator strengths for molecular processes, particularly in the continuum region [57,58]. Some recent applications are shown in Refs. [27,28,59–63]. Recently, we have reported a highly accurate, electron-impact method [27,28] for obtaining absolute photoabsorption oscillator strengths for discrete excitation processes over a wide spectral range at high resolution. The method [28] involves absolute measurements obtained using a high resolution [0.048-eV full width at half maximum (FWHM)] dipole (e,e) spectrometer in conjunction with a lower resolution ($\sim$1-eV FWHM) instrument. In this previous work (part I of the present series) helium was used to check the accuracy of the high-resolution method [28]. Excellent agreement was found between experiment and theory for the He $1\,^1S \rightarrow n\,^1P$ ($n=2$–7) series as well as in the photoionization continuum and doubly excited-state resonance regions [27,28]. The high-resolution dipole (e,e) method is now applied to the electronic transitions for neon. In the present paper we also report measurements of the absolute photoabsorption continuum oscillator strengths up to 250 eV. The absolute scale has been obtained by Thomas-Reiche-Kuhn (TRK) sum-rule normalization and is thus completely independent of any direct optical measurement. The absolute (photoabsorption) oscillator strengths for the dipole-allowed electronic transitions of neon from the $2p^6$ subshell to lower members of the $2s^22p^5ns$ and $2s^22p^5nd$ ($^2P_{3/2,1/2}$) manifolds have been obtained by using the high-resolution dipole (e,e) spectrometer and normalization on the low resolution results in the smooth continuum region. The present measurements are compared with other published experimental and theoretical data. Absolute optical oscillator strengths have also been obtained in the energy range 43–55 eV in the region of the Beutler-Fano autoionization resonance profiles arising from processes involving single excitation of a valence $2s$ electron as well as processes due to double excitation of $2p$ electrons.

II. EXPERIMENTAL METHOD

The experimental procedures used are similar to those employed in earlier reported measurements for helium [27,28]. Briefly, a low-resolution ($\sim$1-eV FWHM) dipole (e,e) spectrometer, employing high-impact energy (8000 eV) and zero-degree ($\theta=0°$) scattering angle (the acceptance angle is 1.4×10^{-4} sr) was used to obtain electron-energy-loss measurements for the valence shell of neon in the energy ranges 15.7–25, 25–50, 50–120, and 120–250 eV at intervals of 0.1, 0.5, 1, and 2 eV, respectively. Relative optical oscillator strengths were obtained by transforming the electron-energy-loss data using the known Bethe-Born conversion factor of the spectrometer (see Ref. [28] and details below). Extrapolation of a least-square fit to the data of a function of the form AE^{-B} (E is energy and A and B are constants) in the 60–250-eV region was utilized to estimate the portion of the relative oscillator strength from 250 eV to infinity. The absolute scale was then established by TRK sum-rule normalization of the entire spectral area to 8.34. This type of extrapolation procedure and absolute scale determination has earlier been shown to be extremely effective [57–63].

The high-resolution dipole (e,e) spectrometer described in Refs. [28,64] was used to obtain electron-energy-loss spectra of neon at an impact energy of 3000 eV and a mean scattering angle of 0° (the acceptance angle is 3.0×10^{-5} sr) in the energy-loss ranges 15–60 eV at a resolution of 0.048-eV FWHM and 15–100 eV at resolutions of 0.072- and 0.098-eV FWHM. The intensity of the high-resolution electron-energy-loss spectrum for neon at each energy loss in the smooth continuum region above 25 eV was divided by the absolute optical oscillator strengths recorded for neon using the low-resolution di-

pole (e,e) spectrometer as described above. This quotient was then fitted in the energy region 25–60 eV to a function $F(E)$ of the form

$$F(E)=\frac{(a+cE)}{E}\ln\left[1+\frac{\theta_0^2}{x^2}\right], \quad (1)$$

where a and c are constants, $x=E/E_0$ (E_0 is the impact energy, E is the energy loss), and $\theta°$ is the half-angle of acceptance emanating from the collision region as seen by the electron analyzer and detector system [28]. $F(E)$ is equal to $1/B_{\mathrm{HR}}$, where B_{HR} is the Bethe-Born conversion factor of the high-resolution spectrometer. The values obtained for B_{HR} are in excellent agreement with the results of an earlier determination using similar procedures involving measurements for helium [28]. The average of the two determinations now provides increased statistical precision and will be used in the present and all future high-resolution absolute oscillator-strength work [65] using the high-resolution dipole (e,e) spectrometer. The functional form of this averaged B_{HR} provides increased reliability when extrapolated down to 5 eV. The excellent agreement between our earlier reported measurement for helium ($1\,^1S\rightarrow n\,^1P$, $n=2$–7)

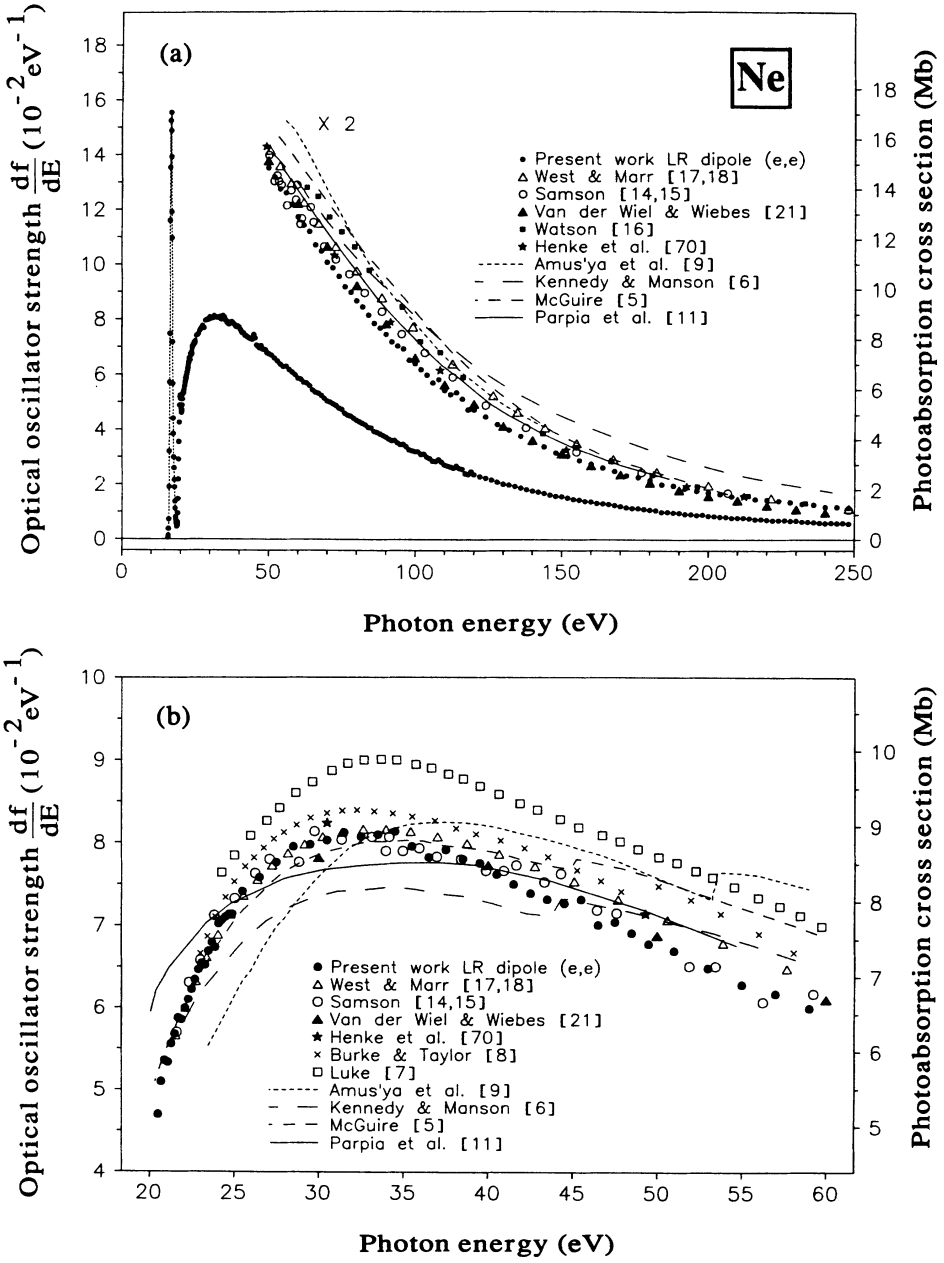

FIG. 1. Absolute oscillator strengths for the photoabsorption of neon measured by the low-resolution dipole (e,e) spectrometer (FWHM=1 eV). (a) 15.7→250 eV compared with other experimental [14–18,21,70] and theoretical [5,6,9,11] data. (b) Expanded view of the 20→60-eV energy region compared with other experimental [14,15,17,18,21,70] and theoretical [5–9,11] values. Note the offset vertical scale.

TABLE I. Absolute optical oscillator strengths for neon obtained using the low-resolution dipole (e,e) spectrometer (21.6–250 eV).

Energy (eV)	Oscillator strength (10^{-2} eV^{-1})	Energy (eV)	Oscillator strength (10^{-2} eV^{-1})	Energy (eV)	Oscillator strength (10^{-2} eV^{-1})
21.6	5.75	36.5	7.83	80.0	4.33
21.7	5.88	37.0	7.90	81.0	4.28
21.8	5.82	37.5	7.92	82.0	4.22
21.9	5.86	38.0	7.86	83.0	4.16
22.0	5.98	38.5	7.80	84.0	4.07
22.1	6.00	39.0	7.73	85.0	4.06
22.2	6.05	39.5	7.76	86.0	3.92
22.3	6.10	40.0	7.72	87.0	3.89
22.4	6.15	40.5	7.62	88.0	3.84
22.5	6.22	41.0	7.52	89.0	3.78
22.6	6.25	41.5	7.50	90.0	3.72
22.7	6.35	42.0	7.42	91.0	3.65
22.8	6.40	42.5	7.39	92.0	3.59
22.9	6.47	43.0	7.35	93.0	3.60
23.0	6.60	43.5	7.32	94.0	3.51
23.1	6.55	44.0	7.29	95.0	3.44
23.2	6.55	44.5	7.27	96.0	3.46
23.3	6.52	45.0	7.45	97.0	3.37
23.4	6.73	45.5	7.32	98.0	3.25
23.5	6.69	46.0	7.06	99.0	3.22
23.6	6.77	46.5	7.01	100.0	3.19
23.7	6.80	47.0	6.96	101.0	3.18
23.8	6.82	47.5	7.04	102.0	3.09
23.9	6.74	48.0	6.91	103.0	3.10
24.0	6.97	48.5	6.91	104.0	2.99
24.1	7.02	49.0	6.89	105.0	2.94
24.2	7.05	49.5	6.78	106.0	2.84
24.3	7.07	50.0	6.75	107.0	2.83
24.4	7.07	51.0	6.70	108.0	2.90
24.5	7.11	52.0	6.59	109.0	2.81
24.6	7.13	53.0	6.49	110.0	2.71
24.7	7.14	54.0	6.37	111.0	2.67
24.8	7.18	55.0	6.29	112.0	2.63
24.9	7.14	56.0	6.30	113.0	2.59
25.0	7.22	57.0	6.17	114.0	2.67
25.5	7.42	58.0	6.08	115.0	2.58
26.0	7.46	59.0	5.99	116.0	2.55
26.5	7.58	60.0	5.86	117.0	2.39
27.0	7.67	61.0	5.83	118.0	2.36
27.5	7.76	62.0	5.71	119.0	2.46
28.0	7.69	63.0	5.69	120.0	2.36
28.5	7.95	64.0	5.59	122.0	2.28
29.0	7.99	65.0	5.43	124.0	2.23
29.5	7.98	66.0	5.35	126.0	2.17
30.0	8.09	67.0	5.31	128.0	2.09
30.5	8.03	68.0	5.24	130.0	2.02
31.0	8.05	69.0	5.13	132.0	1.99
31.5	8.13	70.0	5.03	134.0	1.93
32.0	8.08	71.0	4.99	136.0	1.88
32.5	8.08	72.0	4.93	138.0	1.82
33.0	8.06	73.0	4.88	140.0	1.77
33.5	8.10	74.0	4.78	142.0	1.73
34.0	8.00	75.0	4.73	144.0	1.69
34.5	8.14	76.0	4.59	146.0	1.62
35.0	8.08	77.0	4.52	148.0	1.58
35.5	7.96	78.0	4.48	150.0	1.57
36.0	7.88	79.0	4.41	152.0	1.52

TABLE I. (*Continued*).

Energy (eV)	Oscillator strength (10^{-2} eV^{-1})	Energy (eV)	Oscillator strength (10^{-2} eV^{-1})	Energy (eV)	Oscillator strength (10^{-2} eV^{-1})
154.0	1.46	188.0	0.981	220.0	0.724
156.0	1.44	190.0	0.971	222.0	0.700
158.0	1.39	192.0	0.929	224.0	0.703
160.0	1.38	194.0	0.915	226.0	0.706
162.0	1.32	196.0	0.887	228.0	0.678
164.0	1.31	198.0	0.906	230.0	0.684
166.0	1.29	200.0	0.857	232.0	0.649
168.0	1.25	202.0	0.848	234.0	0.649
170.0	1.21	204.0	0.826	236.0	0.635
172.0	1.16	206.0	0.823	238.0	0.614
174.0	1.14	208.0	0.786	240.0	0.596
176.0	1.13	210.0	0.792	242.0	0.612
178.0	1.11	212.0	0.791	244.0	0.595
180.0	1.08	214.0	0.771	246.0	0.607
182.0	1.06	216.0	0.736	248.0	0.581
184.0	1.00	218.0	0.740	250.0	0.572
186.0	1.00				

and very high level calculations [27,28] indicates that the high-resolution dipole (e,e) method produces highly accurate absolute optical oscillator strengths.

The high-resolution electron-energy-loss spectra of neon were multiplied by the averaged B_{HR} function, obtained as described above, to obtain relative optical oscillator-strength spectra which were then normalized in the smooth continuum region at 25 eV using the absolute data determined with the low-resolution spectrometer. A short-range electron-energy-loss spectrum at a medium resolution of 0.098-eV FWHM in the energy region 40–55 eV, showing details of autoionization structures in the inner valence and the doubly excited-state resonance regions of neon, was also measured. It was then converted to the relative optical spectrum using the averaged B_{HR} factor for this resolution, obtained as described above. This relative spectrum was finally normalized in the smooth continuum region at 55 eV using the corresponding absolute data obtained from the low-resolution spectrometer.

For all the above measurements, the effects of the small contributions from background gases remaining at the base pressure of the spectrometers (typical 2×10^{-7} Torr) were removed by subtracting the signal when the neon pressure was quartered. The energy scale for the spectra measured using the low-resolution spectrometer was calibrated using the discrete excitation peak corresponding to the $2s^2 2p^5(^2P_{1/2})3s'$ state of neon (16.850 eV [66]) while the high-resolution spectra were calibrated by admitting helium simultaneously with the neon sample and referencing the $1\,^1S \rightarrow 2\,^1P$ transition of helium which occurs at 21.218 eV [67]. The sample of neon gas (Matheson; 99.99% purity) showed no measurable indication of impurities according to the high-resolution electron-energy-loss spectra.

III. RESULTS AND DISCUSSION

A. Low-resolution measurements of the photoabsorption oscillator strengths for neon up to 250 eV

A relative photoabsorption spectrum of neon was obtained by Bethe-Born conversion of the electron-energy-loss spectrum measured with the low-resolution dipole (e,e) spectrometer from 15.7 to 250 eV. This was then least-squares fitted to the function AE^{-B} over the energy range 120–250 eV, and extrapolation of the formula gave the relative photoabsorption oscillator strength for the valence shell from 250 eV to infinity. The fit gave $B=1.959$ and the fraction of the total valence-shell oscillator strength above 250 eV was estimated to be 17.6%. The total area was then TRK sum-rule normalized to a value of 8.34, corresponding to the number of valence electrons of neon (eight) plus a small correction (0.34) for Pauli excluded transitions [68,69]. Figure 1(a) shows the resulting absolute optical differential oscillator strengths for the photoabsorption of neon below 250 eV. Also shown in Fig. 1(a) are previously reported theoretical and experimental data from the literature [5,6,9,11,14–18,21,70]. Figure 1(b) is an expanded view (on an offset vertical scale) of the spectrum in the energy

region 20–60 eV, where in addition to previous experimental data [14,15,17,18,21,70], theoretical oscillator strengths from Refs. [5–9,11] are also shown for comparison. Numerical values of the absolute photoabsorption oscillator strengths of neon obtained in the present work from 21.6 to 250 eV are summarized in Table I.

From Figs. 1(a) and 1(b), it can be seen that the presently reported Bethe-Born converted, TRK sum-rule normalized results obtained from the low-resolution spectrometer are generally in quite good quantitative agreement with the photoionization measurement of Samson [14,15], the compilation data of Henke *et al.* [70], and the earlier electron-impact-based measurements by Van der Wiel and Wiebes [21]. The data of Samson [14,15] and Henke *et al.* [70] are slightly higher than the present work in the energy region 60–150 eV, while the results reported by Van der Wiel and Wiebes [21] are lower at energies above 180 eV. The photoionization oscillator strengths for neon measured by Watson [16] in the energy range 60–230 eV are larger than all other reported exper-

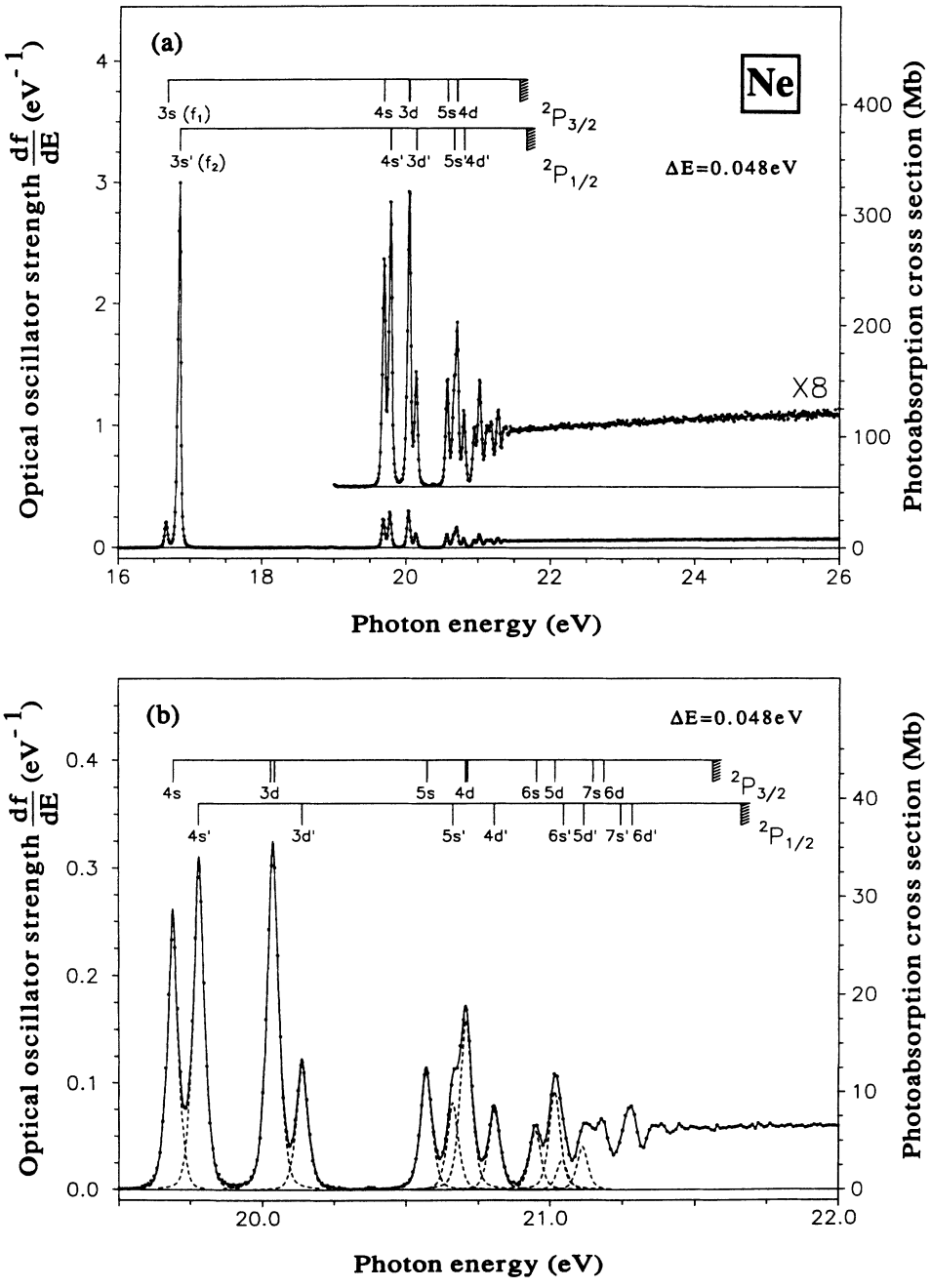

FIG. 2. Absolute oscillator strengths for the photoabsorption of neon measured by the high-resolution dipole (e,e) spectrometer (FWHM=0.048 eV). Assignments are from Ref. [66]. (a) 16→26 eV. (b) 19.5→22 eV with deconvoluted peaks shown as dashed lines.

imental data below ~200 eV but are in better agreement at higher energies. West and Marr [17] measured photoionization cross sections for neon in the energy range 36–310 eV using synchroton radiation and gave a critical evaluation of several published cross-section data (including the data of Samson [14,15] and Watson [16]) which they used to obtain "best-weighted-average" values [18] throughout the vacuum ultraviolet and x-ray spectral regions. However, the West and Marr measured and compiled values [17,18] are significantly higher than the present data and than the other experimental data from Samson [14,15], Henke *et al.* [70], and Van der Wiel and Wiebes [21] in the energy range 35–200 eV.

The calculated photoionization cross sections for neon generally show great differences in absolute values between calculations using the dipole-length and dipole-

TABLE II. Theoretical and experimental determinations of the absolute optical oscillator strengths for the $2s^22p^6 \rightarrow 2s^22p^5(^2P_{3/2,1/2})3s$ discrete transitions of neon. (Estimated uncertainties in experimental measurements are shown in parentheses.)

	Oscillator strength for transition from $2s^22p^6 \rightarrow 2s^22p^5m$ where $m =$	
	$(2P_{3/2})3s$ (f_1)	$(2P_{1/2})3s'$ (f_2)
(a) Theory		
Amus'ya (1990) [50]		0.163[a]
Kelly (1964) [49]		0.188[a]
Cooper (1962) [4]		0.163[a]
Aleksandrov *et al.* (1983) [32]	0.0106	0.141
Stewart (1975) [55]		0.159
Albat and Gruen (1974) [54]	0.0113	0.149
Gruzdev and Loginov (1973) [53]	0.0106	0.139
Aymar, Feneuille, and Klapisch (1970) [52]		
(a) Dipole length	0.0121	0.161
(b) Dipole velocity	0.0100	0.130
Gruzdev (1967) [3]	0.035	0.160
Gold and Knox (1959) [51]		
(a) Wave function	0.011	0.110
(b) Semiempirical	0.012	0.121
(b) Experiment		
Present work [(HR dipole (e,e)]	0.0118	0.159
	(0.0006)	(0.008)
Tsurubuchi, Watanabe, and Arikawa (1990) [44]	0.0122	0.123
(Absolute self-absorption)	(0.0006)	(0.006)
Aleksandrov *et al.* (1983) [32]	0.012	0.144
(Total absorption)	(0.003)	(0.024)
Westerveld, Mulder, and Van Eck (1979) [43]	0.0109	0.147
(Absolute self-absorption)	(0.0008)	(0.012)
Bhaskar and Luiro (1976) [37]	0.0122	0.148
(Lifetime: Hanle effect)	(0.0009)	(0.014)
Knystautas and Drouin (1974) [35]	0.0078	0.161
(Lifetime: beam foil)	(0.0008)	(0.011)
Irwin, Livingston, and Kernahan (1973) [36]		0.158
(Lifetime: beam foil)		(0.006)
Natali, Kuyatt, and Mielczarek (1973) [47]	0.012	0.158
(Electron impact)		
Jongh and Eck (1971) [42]		0.134
(Relative self-absorption)		(0.010)
Kazantsev and Chaika (1971) [38]	0.0138	
(Lifetime: hidden alignment)	(0.0008)	
Geiger (1970) [45,46]	0.009	0.131
(Electron impact)	(0.002)	(0.026)
Lawrence and Liszt (1969) [33]	0.0078	0.130
(Lifetime: delay coincidence)	(0.0004)	(0.013)
Lewis (1967) [41]	0.012	0.168
(Pressure-broadening profile)	(0.002)	(0.002)
Korolev, Odinstov, and Fursova (1964) [31]		0.160
(Natural-broadening profile)		(0.014)

[a]Total oscillator strength (f_1+f_2).

velocity forms. However, the dipole-length data have better agreement with the experimental values than the dipole-velocity data. The dipole-length data of McGuire [5] using the Hartree-Fock-Slater approach with the Herman-Skillman central field show good agreement with the present experimental values from the $2p$ ionization threshold to 35 eV but are significantly higher in the region 35–210 eV. Kennedy and Manson [6], employing Hartree-Fock functions with complete exchange, have also reported calculations of the photoionization cross section of neon from the $2p$ ionization threshold up to 400 eV. Their dipole-length data [6] give lower results below the $2s$ threshold and become much higher at higher energies when compared with the present experimental values. Both the McGuire [5] and Kennedy and Manson [6] data show a lower calculated $2s$ threshold energy than other theoretical [8] and experimental [71,72] work. The dipole-length data calculated using a Hartree-Fock core as reported by Luke [7] [see Fig. 1(b)] are considerably higher than all other reported experimental and theoretical data. The R-matrix theory dipole-length results of Burke and Taylor [8] show good agreement with the experimental values at the $2p$ ionization threshold but agreement becomes worse at higher energies, although below the $2s$ ionization threshold there is less than a 10% difference with the experimental values [note the offset intensity scale in Fig. 1(b)]. Amus'ya, Cherepkov, and Chernsheva [9], using the RPAE method, report very close agreement between the dipole-length and dipole-velocity results. However, the RPAE calculation [9] shows a shift of several electron volts from experiment in the photoionization cross-section maximum and also the energy of the $2s$ ionization threshold for neon. The predicted oscillator strength [9] is also considerably larger than experiment in the energy region 40–100 eV. Since the values calculated by Johnson and

TABLE III. Theoretical and experimental determinations of the absolute optical oscillator strengths for the discrete transitions of neon (19.5–20.9 eV). (Estimated uncertainties in experimental measurements are shown in parentheses.)

	Oscillator strength from $2s^2 2p^6 \rightarrow 2s^2 2p^5 m$ where m is							
	$(^2P_{3/2})4s$	$(^2P_{1/2})4s'$	$(^2P_{3/2})3d$	$(^2P_{1/2})3d'$	$(^2P_{3/2})5s$	$(^2P_{1/2})5s'$	$(^2P_{3/2})4d$	$(^2P_{1/2})4d'$
(a) Theory								
Amusy'ya (1990) [50][a]		0.028		0.021				
Kelly (1964) [49][a]		0.029		0.036		0.008		0.025
Cooper (1962) [4][a]		0.026		0.037		0.009		0.020
Aleksandrov *et al.* (1983) [32]	0.0124	0.0160	0.0176	0.0064	0.0060	0.0043	0.0091	0.0041
Stewart (1975) [55]		0.0260	0.0238					
Gruzdev and Loginov (1973) [53][b]	0.0121	0.0164		0.0081	0.0058	0.0046		
Klose (1969) [34]								
(i) IC and HFS						0.0032		
(ii) IC and CF						0.0037		
Klose (1969) [75]								
(i) IC and HFS		0.0156						
(b) Experiment								
Present work [HR dipole (e,e)]	0.0129	0.0165	0.0186	0.006 65	0.006 37	0.004 61	0.009 44	0.004 39
	(0.0006)	(0.0008)	(0.0009)	(0.000 33)	(0.000 32)	(0.000 23)	(0.000 47)	(0.000 22)
Aleksandrov *et al.* (1983) [32]	0.0145	0.0185	0.0222	0.0082	0.0083	0.0049	0.0147	0.005
(Total absorption)	(0.0035)	(0.006)	(0.0046)	(0.0029)	(0.0031)	(0.0017)	(0.0036)	(0.002)
Westerveld, Mulder, and Van Eck (1979) [43]	0.0128	0.0153		0.0064	0.0061	0.0042		
(Absolute self-absorption)	(0.0010)	(0.0012)		(0.0005)	(0.0005)	(0.0003)		
Ducloy (1973–1974) [40]		0.0153						
(Lifetime: laser irradiation)		(0.0030)						
Natali, Kuyatt, and Mielczarek (1973) [47]	0.013	0.016	0.017	0.006	0.006	0.0043	0.0085	0.0043
(Electron impact)								
Klose (1970) [34]						0.0040		
(Lifetime: delayed coincidence)						(0.0003)		
Lawrence and Liszt (1960) [33]								
(Lifetime: delayed coincidence) (1)	0.0086	0.0130	0.0217	0.0064	0.0057	0.0042		
	(0.0010)	(0.0020)	(0.0022)	(0.0010)	(0.0010)	(0.0010)		
(2)[c]	0.0134	0.0178		0.0068	0.0062	0.0048		
	(0.0010)	(0.0025)		(0.0010)	(0.0010)	(0.0010)		
Decomps and Dumont (1968) [39]		0.0164				0.005 98		
(Lifetime: laser irradiation)		(0.0020)				(0.000 23)		

[a]Summed oscillator strength as indicated.

[b]Lifetime data converted by Westerveld, Mulder, and Van Eck [43] to oscillator strengths using transition probabilities reported in Refs. [73] and [74].

[c]Recalculated by Westerveld, Mulder, and Van Eck [43] using branching ratios reported in Refs. [53], [73], and [74].

Cheng [10] using the RRPA method show good agreement with those calculated by Amus'ya, Cherepkov, and Chernsheva [9] using the nonrelativistic RPAE method, only values from Amus'ya, Cherepkov, and Chernsheva [9] are shown on Fig. 1. Except in the region near the maximum, the values calculated by Parpia, Johnson, and Radojevic [11] using the RTDLDA method show better agreement with experiment than the other theoretical data [5–10].

B. High-resolution measurements of the photoabsorption oscillator strengths for the discrete transitions of neon below the $2p$ ionization threshold

High-resolution electron-energy-loss spectra of neon at resolutions of 0.048-, 0.072-, and 0.098-eV FWHM in the energy range 16–26 eV were multiplied by the appropriate B_{HR} functions for the high-resolution dipole (e,e) spectrometer (see Sec. II) to obtain relative optical oscillator-strength spectra which were then normalized in the smooth continuum region at 25 eV using the absolute data of Table I, as determined in the present work with the low-resolution spectrometer. Figure 2(a) shows the typical absolute differential optical oscillator-strength spectrum of neon over the range 16–26 eV at an energy resolution of 0.048-eV FWHM. Figure 2(b) is an expanded view of the spectrum in the energy region 19.5–22 eV showing the dipole-allowed electronic transitions from the $2s^2 2p^6$ configuration of neon to members of the $2s^2 2p^5(^2P_{3/2,1/2})ns$ and nd manifolds. Very small peaks, barely visible at 18.96 and 20.38 eV, represent contributions from the dipole-forbidden $2s^2 2p^6 \rightarrow 2s^2 2p^5(^2P_{3/2,1/2})3p$ and $4p$ transitions, respectively. These nondipole transitions which occur because of the finite but very small momentum transfer (<0.01 a.u.) are all less than 0.3% of the f_2 peak. The positions and assignments [66] of the various members of the nl and nl' series are indicated on Fig. 2. Above 19 eV the peaks have been deconvoluted as indicated [Fig. 2(b)] to obtain the separate oscillator strengths for the various transitions. Since the peak energies of the $nd[\frac{1}{2}]$ and $nd[\frac{3}{2}]$ states which converge to the same $^2P_{3/2}$ limit are very close, especially at higher n values, the two transitions have been treated as a single peak in the deconvolution.

For peaks in the experimental spectrum which can be completely resolved, such as the f_1 and f_2 resonance lines [i.e., the $3s$, $3s'$ lines, Fig. 2(a)], integration of the peak areas provides a direct measure of the absolute optical oscillator strengths for the individual discrete electronic transitions. For the higher-energy peaks which cannot be completely resolved absolute oscillator strengths have been obtained from the deconvoluted peak areas as shown in Fig. 2(b). The accuracy of the presently developed method is confirmed by the consistency of the oscillator strengths determined for given transitions at the three different resolutions. The results obtained from the analysis of the spectrum at the highest resolution (0.048-eV FWHM) are given in Tables II–IV. The uncertainties are estimated to be $\sim 5\%$ for the lower energy resolved transitions and $\leq 10\%$ for those such as $6s$, $6s'$, $5d$, and $5d'$ at higher energies due to additional errors involved in deconvoluting the peaks. Also shown in Tables II–IV are the absolute oscillator-strength values for several discrete electronic transitions of neon reported in various other experimental [31–47] and theoretical [4,32,49–55] studies.

It can be seen (Table II) that there is very little variation in the oscillator-strength values for the f_1 resonance line calculated by different theoretical approaches (0.010–0.012) and these results [3,32,51–54) correspond closely with the presently reported experimental value (0.0118). However, for the f_2 resonance line there is substantial variation in the calculated oscillator strengths (0.110 to 0.161). The dipole-length result reported by Aymar, Feneuille, and Klapisch [52], the result of Gruzdev [3], and the calculation by Stewart [55] all show good agreement with the presently reported experimental value (0.159) for f_2. Other theoretical calculations [32,51–54] for the f_2 resonance line give lower oscillator strengths. Cooper [4], Kelly [49], and Amus'ya [50] have reported calculated summed $(nl+nl')$ oscillator strengths for

TABLE IV. Theoretical and experimental determinations of the absolute optical oscillator strengths for the discrete transitions of neon (20.9–21.2 eV). (Estimated uncertainties in experimental measurements are shown in parentheses.)

	Oscillator strength from $2s^2 2p^6 \rightarrow 2s^2 2p^5 m$ where m is				Total to
	$(^2P_{3/2})6s$	$(^2P_{1/2})6s'$	$(^2P_{3/2})5d$	$(^2P_{1/2})5d'$	ionization
	(a) Theory				
Kelly (1964) [49][a]		0.003		0.018	
Cooper (1962) [4][a]		0.004		0.011	
Aleksandrov *et al.* (1983) [32]	0.0031	0.0018	0.0050	0.0024	
	(b) Experiment				
Present work [HR dipole (e,e)]	0.003 30	0.001 56	0.005 43	0.002 29	0.292
	(0.000 30)	(0.000 16)	(0.000 54)	(0.000 23)	(0.015)
Aleksandrov *et al.* (1983) [32]	0.0045	0.003			
(Total absorption)	(0.0019)	(0.001)			
Natali, Kuyatt, and Mielczarek (1973) [47] (Electron impact)					0.277

[a]Summed oscillator strength as indicated.

transitions from $2s^22p^6$ to several $2s^22p^5(^2P_{3/2,1/2})ns$ or nd states. For the $2p\rightarrow(3s+3s')$ transitions (Table II), the summed absolute optical oscillator strengths (i.e., f_1+f_2) calculated by Cooper [4] and Amus'ya [50] are slightly lower while the value of Kelly [49] is slightly higher than the presently reported summed result (0.171). For higher-energy transitions (Tables III and IV) such as $2p\rightarrow(4s+4s')$, all three calculations [4,49,50] give good agreement with the present work, while for the $2p\rightarrow(5s+5s')$ and $2p\rightarrow(6s+6s')$ transitions the data of Cooper [4] and Kelly [49] are slightly lower. For the $2p\rightarrow(3d+3d')$, $2p\rightarrow(4d+4d')$, and $2p\rightarrow(5d+5d')$ transitions the Cooper [4] and Kelly [49] data are significantly higher while the Amus'ya [50] data for the $2p\rightarrow(3d+3d')$ transitions are slightly lower when compared with the present experimental results. The calculated f_2 value reported by Gruzdev [3] using intermediate-coupling techniques is consistent with the present reported value while the f_1 value is much higher than all the other values quoted in Table II. The calculated data reported by Aleksandrov *et al.* [32] using an intermediate-coupling scheme are more comprehensive and comparison with the presently reported experimental data is possible for individual transitions up to the $6s$, $6s'$, $5d$, and $5d'$ states as shown in Tables II–IV. Immediately it can be seen that the calculated data of Aleksandrov *et al.* [32] are in good agreement with the presently reported values except for the f_1 and f_2 values for which their data are slightly lower. Gruzdev and Loginov [53] have calculated the radiative lifetimes of several transitions of neon using an intermediate-type coupling and the Hartree-Fock self-consistent-field method. Westerveld, Mulder, and Van Eck [43] have converted the lifetime data of Gruzdev and Loginov [53] to oscillator-strength values using transition probabilities reported by Gruzdev and Loginov in Refs. [73,74] and these values show good agreement with the present work for oscillator-strength values of the $4s$, $4s'$, $5s$ and $5s'$ lines and are slightly higher for the $3d'$ line. Stewart [55], using fully coupled time-dependent Hartree-Fock equations, has reported calculated oscillator-strength values for the $4s'$ and $3d$ lines which are considerably higher than the present experimental results. Klose [34], using intermediate coupling and a Hartree-Fock-Slater (IC-HFS) calculation, and intermediate coupling and the central-field (IC-CF) approximation, has reported two oscillator-strength values for the $5s'$ line but both values are considerably lower than the presently reported experimental value. In a second paper, Klose [75] reported an oscillator strength for the $4s'$ line from an IC-HFS calculation which is slightly lower than the present experimental result.

Turning now to a consideration of the various experimental results, it can be seen from Tables II–IV that the presently reported data are in very good agreement over the whole discrete region with the earlier electron-impact-based results of Natali, Kuyatt, and Mielczarek [47]. The latter unpublished results [47] have been quoted in Refs. [43] and [48]. The high-resolution data by Aleksandrov *et al.* [32], using the total absorption method, have rather large uncertainties and agreement with the present data is good for the f_1 and f_2 resonance lines but generally poorer for the higher transitions. The measured absolute oscillator strengths [32] for the discrete transitions at higher energy are significantly higher than those determined in the present work (see Tables III and IV). The self-absorption method was used by three groups [42–44] and the reported values range from 0.123 to 0.147 for the absolute oscillator strength of the f_2 resonance line. All these values are lower than the present value of 0.159. Agreement between different groups using the self-absorption method is generally better for the f_1 resonance line where the value of Tsurubuchi, Watanabe, and Arikawa [44] is consistent with the present work, and that obtained by Westerveld, Mulder, and Van Eck [43] is slightly lower but still within the quoted uncertainties. Westerveld, Mulder, and Van Eck [43] have also measured the oscillator strengths for the transitions from the ground state to the $2s^22p^5(^2P_{3/2})4s$ and $5s$, and also to the $2s^22p^5(^2P_{1/2})4s'$, $5s'$, and $3d'$ states and these results all show very good agreement with the present work.

Lifetime measurements using various experimental procedures [33–40] show good agreement for the absolute oscillator strength of the f_2 resonance line with the present data, with the exception of Ref. [33] which is $\sim$20% lower. For the f_1 resonance line the result of Kazantsev and Chaika [38] is somewhat higher and the values reported by Knystautas and Drouin [35] and by Lawrence and Liszt [33] are much lower than most other reported values which are in close agreement with the present work. In the case of discrete transitions at high energy (Table III), the Lawrence and Liszt [33] values are slightly lower than the present work except for the transition to the $2s^22p^5(^2P_{3/2})3d$ and $2s^22p^5(^2P_{1/2})3d'$ states. Westerveld, Mulder, and Van Eck [43] have reevaluated the lifetime data of Lawrence and Liszt [33] using the transition probabilities calculated by Gruzdev and Loginov [53,73,74], and it is noteworthy that the reevaluated oscillator-strength values are in all cases in better agreement with the present work. The absolute oscillator strength for the $5s'$ line determined by Klose [34] using a delayed coincidence method is slightly lower than the present value, while that determined by Decomps and Dumont [39] is $\sim$33% higher. For the $4s'$ line, the values of Decomps and Dumont [39] and Ducloy [40] are both consistent with the presently reported experimental measurement.

With the use of a high-resolution electron-impact spectrometer, Geiger [46] measured the intensity ratio of the f_2/f_1 resonance lines giving a value consistent with the ratio derived from the present data. However, the total absolute optical oscillator-strength sum for the two resonance lines obtained [46] from Geiger's earlier work [45], which was normalized on the elastic electron-scattering cross section, is about 20% lower than the presently reported value. The absolute oscillator strengths obtained from line-profile analysis for f_1 and f_2 by Lewis [41] and for f_2 by Korolev, Odinstov, and Fursova [31] are in good agreement (see Table II) with the present work. Finally, the total discrete oscillator-strength sum up to 21.616 eV, which is the middle point between the $^2P_{3/2}$ and $^2P_{1/2}$ ionization thresholds of neon, has been deter-

mined in the present work to be 0.292 compared with estimates of 0.277 reported by Natali, Kuyatt, and Mielczarek [47] and 0.4 reported by West and Marr [17]. The latter value would seem to be too high.

C. High-resolution photoabsorption oscillator strengths in the 40–55 eV region of the autoionizing excited-state resonances

The spectroscopy (i.e., the energy levels) of the autoionizing excited-state resonance of neon, involving excitation of a $2s$ electron and also the double excitation of $2p$ electrons, has been studied in some detail experimentally [32,72,76]. However, prior to the present quantitative work no detailed high-resolution absolute intensity measurements have been reported for neon in this region. Similar absolute intensity measurements in the double excitation region for helium in excellent agreement with theory [77] have recently been reported from this laboratory for helium [28]. In the present study, the electron-energy-loss spectrum in the 40–55-eV energy region was measured with the use of the high-resolution dipole (e,e) spectrometer at a resolution of 0.098-eV FWHM. This was then converted to a relative optical oscillator-strength spectrum by multiplying with the B_{HR} function (see Sec. II). Normalization was performed in the smooth continuum region at 55 eV using the absolute optical oscillator-strength data given in Table I, as determined by the low-resolution dipole (e,e) spectrometer. The present high-resolution absolute dipole oscillator strengths (solid circles) are shown in Fig. 3. The few photoionization (absolute) data points earlier reported by Samson [14,15] in this region are seen from Fig. 3 (open circles) to be reasonably consistent with the present high-resolution dipole (e,e) results.

In Fig. 3, the energies (± 0.005 eV) of the maxima of the transitions corresponding to excitation of the $2s$ electrons to np subshells with $n=3$ to 6, and the double excitation transition of $2p$ electrons to the $3s3p$ configuration of neon have been determined in the present work to be 45.550, 47.127, 47.677, and 47.975, and 44.999 eV, respectively. These energy values are in good agreement with the high-resolution experimental studies reported by Codling, Madden, and Ederer [72] and by Aleksandrov *et al.* [32], as well as with the multiconfiguration close-coupling calculations of Luke [7]. For peaks observed at higher energies in the present work, the assignments and energy positions of the excited-state resonances shown in Fig. 3 are those given in the photoabsorption data reported by Codling, Madden, and Ederer [72]. A small peak (X) at 43.735 eV has not been reported in previous photoabsorption measurements [32,72,76] but it should be noted that the published spectra in all of these measurements did not extend below 44 eV. However, a threshold electron-impact study by Brion and Olsen [78] and a lower electron-impact energy (400 eV) study of the ionization continuum of neon by Simpson, Chamberlain, and Mielczarek [79] also detected a peak at ~43.7 eV and it was suggested that this was probably due to excitation to the $2s2p^6 3s$ state, which had earlier been reported [80] to be at 43.65 eV. However, it seems unlikely that the formally dipole-forbidden transition $2s^2 2p^6 \rightarrow 2s2p^6 3s$ would be so prominent at the very low momentum transfer (0.014 a.u.) corresponding to the present experimental conditions of high-impact energy (3 keV) and 0° mean-scattering angle. This peak at 43.735 eV is also too high in energy to be due to any double-scattering processes involving below-edge outer-valence processes.

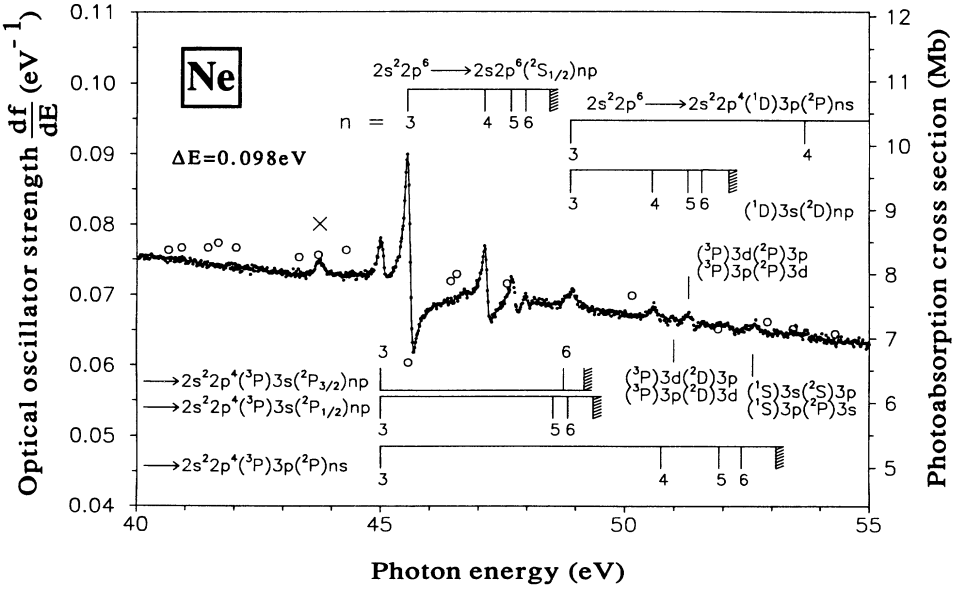

FIG. 3. Absolute oscillator strengths for the photoabsorption of neon in the autoionizing resonance region 40→55 eV (FWHM=0.098 eV) measured by the high-resolution dipole (e,e) spectrometer. Solid circles are this work and open circles are photoionization data reported by Samson [14,15]. Assignments are from Ref. [72]. Note the offset vertical scale.

IV. CONCLUSIONS

This work is a continuation of the application of the recently developed high-resolution dipole (e,e) technique for measuring absolute optical oscillator strengths for atoms and molecules throughout the discrete and continuum regions. The present absolute data for neon, unlike the direct optical measurements, are subject to the stringent constraints of the TRK sum rule and are thus considered to be of high accuracy. Optical oscillator strengths for the discrete transitions involving valence $2p$ electrons and also for the photoionization continuum up to 250 eV have been measured for neon. The presently reported results were compared with theory and also with earlier reported experimental data, all of which are less comprehensive than the present work. The accuracy of the earlier unpublished electron-impact data of Natali, Kuyatt, and Mielczarek [47] at lower impact energy (i.e., large momentum transfer) in the discrete region is confirmed. Unlike the situation for helium, theoretical calculations for the absolute oscillator strengths of neon in both the discrete and continuum regions show a wide spread of values. The present data provide a critical test for these quantum mechanical calculations throughout the spectrum and especially for the valence $2p$ discrete electronic excitations such as the f_1 and f_2 resonance lines. High-resolution absolute optical oscillator strengths have been obtained for the autoionizing excited state and doubly excited-state resonance region (40–55 eV) involving $2s$ excitation and double excitation and it is hoped that these measurements will stimulate calculation in this region.

ACKNOWLEDGMENTS

Financial support for this project was provided by the Natural Sciences and Engineering Research Council of Canada and by the Canadian National Networks of Centres of Excellence Programme (Centre for Molecular and Interfacial Dynamics). One of us (W.F.C.) gratefully acknowledges support from the University of British Columbia. Financial support from the World Laboratory (Lausanne) is acknowledged by X. Guo.

*Permanent address: University of Science and Technology of China, Hefei, People's Republic of China.

[1] L. H. Auer and D. Mihalas, Astrophys. J. **184**, 151 (1973).
[2] R. C. Elton, *X-Ray Lasers* (Academic, Orlando, 1990).
[3] P. F. Gruzdev, Opt. Spektrosk. **22**, 313 (1967) [Opt. Spectrosc. (USSR) **22**, 170 (1967)].
[4] J. W. Cooper, Phys. Rev. **128**, 681 (1962).
[5] E. J. McGuire, Phys. Rev. **175**, 20 (1968).
[6] D. J. Kennedy and S. T. Manson, Phy. Rev. A **5**, 227 (1972).
[7] T. M. Luke, J. Phys. B **6**, 30 (1973).
[8] P. G. Burke, and K. T. Taylor, J. Phys. B **8**, 2620 (1975).
[9] M. Ya. Amus'ya, N. A. Cherepkov, and L. V. Chernsheva, Zh. Eksp. Theor. Fiz. **60**, 160 (1971) [Sov. Phys.—JETP **33**, 90 (1971)].
[10] W. R. Johnson and K. T. Cheng, Phys. Rev. A **20**, 978 (1979).
[11] F. A. Parpia, W. R. Johnson, and V. Radojevic, Phys. Rev. A **29**, 3173 (1984).
[12] P. Lee and G. L. Weissler, Proc. R. Soc. London Ser. A **220**, 71 (1953).
[13] D. L. Ederer and D. H. Tomboulian, Phys. Rev. **133A**, 1525 (1964).
[14] J. A. R. Samson, J. Opt. Soc. Am. **55**, 935 (1965).
[15] J. A. R. Samson, Adv. At. Mol. Phys. **2**, 177 (1966); in *Corpuscles and Radiation in Matter I,* edited by Editors, Handbuch der Physik (Springer-Verlag, Berlin, 1982), p.147.
[16] W. S. Watson, J. Phys. B **5**, 2292 (1972).
[17] J. B. West and G. V. Marr, Proc. R. Soc. London Ser. A **349**, 397 (1976).
[18] G. V. Marr and J. B. West, At. Data Nucl. Data Table **18**, 497 (1976).
[19] C. E. Kuyatt and J. A. Simpson, *Proceedings of the Third International Conference on the Physics of Electronic and Atomic Collisons, London, 1963,* edited by M. R. C. McDowell (North-Holland, Amsterdam, 1964), p. 191.
[20] M. J. Van der Wiel, Physica **49**, 411 (1970).
[21] M. J. Van der Wiel and G. Wiebes, Physica **54**, 411 (1971).
[22] R. P. Saxon, Phys. Rev. A **8**, 839 (1973).
[23] F. Wuilleumier and M. O. Krause, Phys. Rev. A **10**, 242 (1974).
[24] M. H. Hecht and I. Lindau, J. Electron. Spectrosc. Relat. Pheonom. **35**, 211 (1985).
[25] D. M. P. Holland, M. A. MacDonald, and M. A. Hayes, Chem. Phys. **142**, 291 (1990).
[26] N. Saito, I. Suzuki, H. Onuki, and M. Nishi, Rev. Sci. Instrum. **60**, 2190 (1989).
[27] W. F. Chan, G. Cooper. K. H. Sze, and C. E. Brion, J. Phys. B **23**, L523 (1990).
[28] W. F. Chan, G. Cooper, and C. E. Brion, Phys. Rev. A **44**, 186 (1991).
[29] S. Brodersen, J. Opt. Soc. Am. **44**, 22 (1954).
[30] R. D. Hudson, Rev. Geophys. Space Phys. **6**, 305 (1971).
[31] F. A. Korolev, V. I. Odintsov, and E. V. Fursova, Opt. Spektrosk. **16**, 555 (1964) [Opt. Spectrosc. (USSR) **16**, 304 (1964)].
[32] Y. M. Aleksandrov, P. F. Gruzdev, M. G. Kozlov, A. V. Loginov, V. N. Makhov, R. V. Fedorchuk, and M. N. Yakimenko, Opt. Spektrosk. **54**, 7 (1983) [Opt. Spectrosc. (USSR) **54**, 4 (1983)].
[33] G. M. Lawrence and H. S. Liszt, Phys. Rev. **178**, 178 (1969).
[34] J. Z. Klose, Phys. Rev. **188**, 45 (1969).
[35] E. J. Knystautas and R. Drouin, Astron. Astrophys. **37**, 145 (1974).
[36] D. J. G. Irwin, A. E. Livingston, and J. A. Kernahan, Can. J. Phys. **51**, 1948 (1973).
[37] N. D. Bhaskar and A. Lurio, Phys. Rev. A **13**, 1484 (1976).
[38] S. Kazantsev and M. Chaika, Opt. Spektrosk. **3**, 510 (1971) [Opt. Spectrosc. (USSR) **3**, 273 (1971)].
[39] B. Decomps and M. Dumont, IEEE J. Quantum Electron. **QE-4**, 916 (1968).
[40] M. Ducloy, Ann. Phys. (Paris) **8**, 403 (1973).

[41] E. L. Lewis, Proc. Phys. Soc. **92**, 817 (1967).
[42] J. P. De. Jongh and J. Van Eck, Physica **51**, 104 (1971).
[43] W. B. Westerveld, Th. F. A. Mulder, and J. Van Eck, J. Quant. Spectrosc. Radiat. Tranfer **21**, 533 (1979).
[44] S. Tsurubuchi, K. Watanable, and T. Arikawa, J. Phys. Soc. Jpn. **59**, 497 (1990).
[45] J. Geiger, Z. Phys. **177**, 138 (1964).
[46] J. Geiger, Phys. Lett. **33A**, 351 (1970).
[47] S. Natali, C. E. Kuyatt, and S. R. Mielczarek, unpublished observations as quoted in Refs. [43] and [48].
[48] J. Berkowitz, *Photoabsorption, Photoionization and Photoelectron Spectroscopy* (Academic, New York, 1979), p. 80.
[49] P. S. Kelly, J. Quant. Spectrosc. Radiat. Transfer **4**, 117 (1964).
[50] M. Ya. Amus'ya, *Atomic Photoeffect* (Plenum, New York, 1990), p. 170.
[51] A. Gold and R. S. Knox, Phys. Rev. **113**, 834 (1959).
[52] M. Aymar, S. Feneuille, and M. Klapisch, Nucl. Instrum. Methods **90**, 137 (1970).
[53] P. F. Gruzdev and A. V. Loginov, Opt. Spektrosk. **35**, 3 (1973) [Opt. Spectrosc. (USSR) **35**, 1 (1973)].
[54] R. Albat and N. Gruen, J. Phys. B **7**, L9 (1974).
[55] R. F. Stewart, Mol. Phys. **29**, 1577 (1975).
[56] R. F. Stewart, Mol. Phys. **30**, 745 (1975).
[57] J. W. Gallagher, C. E. Brion, J. A. R. Samson, and P. W. Langhoff, J. Phys. Chem. Ref. Data **17**, 9 (1988).
[58] C. E. Brion, Comments At. Mol. Phys. **16**, 249 (1985).
[59] W. Zhang, G. Cooper, T. Ibuki, and C. E. Brion, Chem. Phys. **137**, 391 (1989).
[60] G. Cooper, T. Ibuki, and C. E. Brion, Chem. Phys. **140**, 133 (1990).
[61] G. Cooper, T. Ibuki, and C. E. Brion, Chem. Phys. **140**, 147 (1990).
[62] E. B. Zarate, G. Cooper, and C. E. Brion, Chem. Phys. **148**, 277 (1990).
[63] E. B. Zarate, G. Cooper, and C. E. Brion, Chem. Phys. **148**, 289 (1990).
[64] S. Daviel, C. E. Brion, and A. P. Hitchcock, Rev. Sci. Instrum. **55**, 182 (1984).
[65] W. F. Chan, G. Cooper, G. R. Burton, X. Guo, and C. E. Brion (unpublished).
[66] C. E. Moore, *Atomic Energy Levels,* Natl. Bur. Stand. (U.S.) Circ. No. 467 (U.S. GPO, Washington, DC, 1949), Vol. **I**, p. 77.
[67] W. L. Wiese, M. W. Smith, and B. M. Glenon, *Atomic Transition Probabilities: Hydrogen through Neon,* Natl. Bur. Stand. Ref. Data. Ser., Natl. Bur. Stand. (U.S.) Circ. No. **4** (U.S. GPO, Washington, DC, 1966), Vol. I.
[68] J. A. Wheeler and J. A. Bearden, Phys. Rev. **46**, 755 (1934).
[69] J. L. Dehmer, M. Inokuti, and R. P. Saxon, Phys. Rev. A **12**, 102 (1975).
[70] B. L. Henke, P. Lee, T. J. Tanaka, R. L. Shimabukuro, and B. K. Fujikawa, At. Data Nucl. Data Tables **27**, 1 (1982).
[71] W. Lotz, J. Opt. Soc. Am. **60**, 206 (1970).
[72] K. Codling, R. P. Madden, and D. L. Ederer, Phys. Rev. **155**, 26 (1967).
[73] A. V. Loginov and P. F. Gruzdev, Opt. Spektrosk. **37**, 817 (1974) [Opt. Spectrosc. (USSR) **37**, 467 (1974)].
[74] P. F. Gruzdev and A. V. Loginov, Opt. Spektrosk. **39**, 817 (1975) [Opt. Spectrosc. (USSR) **39**, 464 (1975)].
[75] J. Z. Klose, J. Quant. Spectrosc. Radiat. Transfer **9**, 881 (1969).
[76] A. A. Wills, A. A. Cafolla, A. Svensson, and J. Comer, J. Phys. B **23**, 2013 (1990).
[77] J. A. Fernley, K. T. Taylor, and M. J. Seaton, J. Phys. B **20**, 6457 (1987).
[78] C. E. Brion and L. A. R. Olsen, J. Phys. B **3**, 1020 (1970).
[79] J. A. Simpson, G. E. Chamberlain, and S. R. Mielczarek, Phys. Rev. A **139**, 1039 (1965).
[80] K. Siegbahn, C. Nordling, G. Johansson, J. Hedman, P. F. Heden, K. Hamrin, U. Gelius, T. Bergmark, L. O. Werme, R. Manne, and Y. Baer, *ESCA: Applied to Free Molecules* (North-Holland, Amsterdam, 1969), p. 152.