

Energy levels and spectral lines of Ne VIII*

A.E. Kramida^{1,a} and M.-C. Buchet-Poulizac²

¹ National Institute of Standards and Technology, Gaithersburg, Maryland, 20899-8422, USA

² Laboratoire de Spectrométrie Ionique et Moléculaire, UMR CNRS no. 5579, Université Claude Bernard Lyon 1, Campus de la Doua, 69622 Villeurbanne Cedex, France

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Abstract. All experimental data on the valence-shell-excited and core-excited spectra of Li-like neon, including previously unpublished beam-foil spectroscopy data, have been compiled and critically evaluated. Seventeen spectral lines have been newly identified. Sets of recommended energy levels have been derived from the total list of observed lines and from selected results of theoretical and semi-empirical calculations. An accurate value of the ionization potential has been derived from existing theoretical calculations.

PACS. 32.10.Fn Fine and hyperfine structure – 32.10.Hq Ionization potentials, electron affinities – 32.30.Jc Visible and ultraviolet spectra – 31.15.Ct Semi-empirical and empirical calculations (differential overlap, Huckel, PPP methods, etc.) – 95.30.Ky Atomic and molecular data, spectra, and spectral parameters (opacities, rotation constants, line identification, oscillator strengths, gf values, transition probabilities, etc.)

1 Introduction

The spectrum of Li-like neon, which has the ground configuration $1s^2 2s$, was first studied in the early 1960s in connection with controlled fusion research, since neon is widely used as an admixture to hot deuterium plasmas. Several studies using high-temperature discharge plasmas [1–10] yielded most of the known spectral lines of Ne VIII involving valence-electron excitation. The Ne VIII spectrum also attracts much attention in astrophysics, mainly due to its presence in the Sun (see [11] and references therein). Introduction of the beam-foil spectroscopy method in the 1970s [12–24] made it possible to further extend knowledge of this spectrum and identify a number of lines involving excitation of an inner $1s$ electron. The inner-shell excited spectrum of Ne^{7+} was reviewed by Kramida and Ivanov [25]. Since then, several new experimental studies employing the beam-foil method [21–24, 26] and the electron-beam ion trap [27] have been published.

In the present work we compile and evaluate all previously published experimental data on Ne VIII, as well as some additional unpublished data, and construct a comprehensive set of energy levels based on these data.

2 Spectral lines involving excitation of the valence electron

The list of observed lines due to the $1s^2 nl - 1s^2 n'l'$ transitions in Ne VIII is given in Table I (see the *Supplementary Online Materials*). Wavelengths below 2000 Å are given in vacuum, otherwise in standard air. The observed vacuum wave numbers in the region above 2000 Å were derived from the wavelengths using the five-parameter formula of Peck and Reeder [28] for the refractive index of air. The first column of references contains references to the source of the measured wavelength. The second column lists all other sources where additional information for the lines was obtained. Below we discuss the observations made by different authors.

The resonance doublet $1s^2 2s \ ^2S_{1/2} - 1s^2 2p \ ^2P_{1/2,3/2}^\circ$ at about 770.4 Å and 780.3 Å was the first classified feature in the Ne VIII spectrum [1]. Bockasten et al. [2] measured the wavelengths of these two lines in the spectrum of a high-temperature discharge with uncertainties of 0.005 Å and 0.010 Å, respectively. Their measurement remains the most accurate in the literature.

The most comprehensive line list of Ne VIII in the grazing-incidence region was obtained in the work of Tondello and Paget [7], where the $2s - np$, $2p - ns$, and $2p - nd$ series were observed in emission up to large n values with a theta-pinch light source. Uncertainties of their measurements vary from ± 0.005 Å for strong isolated lines

* Two supplementary tables (Tabs. I and II) are only available in electronic form at <http://www.eurphysj.org>.

^a e-mail: Alexander.kramida@nist.gov

measured in several orders of diffraction to $\pm 0.02 \text{ \AA}$ for the weakest short-wavelength lines. Later, Hermansdorfer [29] independently measured some of these lines. However, his measurement uncertainty was worse than that of Tondello and Paget [7]. Energy levels belonging to these series can be derived from the line list of Tondello and Paget [7] with uncertainties of 30 cm^{-1} to 60 cm^{-1} for all $3s$, $3p$, $3d$, $4s$, $4d$, $4f$, and $5s$ terms and 60 cm^{-1} to 500 cm^{-1} for other terms¹.

Johnston and Kunze [6] observed the $3s - 3p$ doublet at 2820.7 \AA and 2860.1 \AA in a theta-pinch discharge with an uncertainty of $\pm 0.1 \text{ \AA}$. These lines determine the $3s - 3p$ separations with an uncertainty of 1.2 cm^{-1} .

Kunze [8] measured the two $3d - 4f$ lines at $292.38 \pm 0.04 \text{ \AA}$ and $292.47 \pm 0.04 \text{ \AA}$. Later works [9,10,12,13] have larger uncertainties or refer to Kunze [8] for these wavelengths. Wang et al. [30], on the basis of the calculated fine-structure intervals, suggested that the identification of these two lines in reference [8] is wrong. Although Wang et al. [30] refer to Druetta et al. [9] for the measured wavelengths, these wavelengths were actually taken from reference [8]. Based on a comparison of the calculated and measured wavelengths, Wang et al. [30] suggested that the 292.38 \AA line is a blend of the $J = 3/2 - 5/2$ and $J = 5/2 - 7/2$ transitions (predicted wavelengths $292.321 \pm 0.012 \text{ \AA}$ and $292.421 \pm 0.012 \text{ \AA}$ [30]), while the 292.47 \AA line is the $J = 5/2 - 5/2$ transition (predicted wavelength 292.447 \AA [30]). From the point of view of expected line intensities, this suggestion is unrealistic. According to our calculations with Cowan's computer codes [31], the transition rate (gA) of the $J = 5/2 - 5/2$ transition is smaller than that of the $J = 3/2 - 5/2$ and $J = 5/2 - 7/2$ transitions by a factor of at least 15. We conclude that the identifications in reference [8] are correct, but the measured wavelengths are in error by $+0.05 \text{ \AA}$.

Druetta et al. [9], using a theta-pinch source similar to that in [8], measured the wavelengths of the $3p - 4s$, $3p - 4d$, $3s - 4p$, $3d - 5f$, and $3p - 5s$ transitions in the region 199 \AA to 292 \AA with uncertainties ranging from 0.02 \AA to 0.06 \AA . Later work by Chang et al. [10] cites the wavelengths from [9] without source reference.

Buchet et al. [12] observed the $(4d - 5f) + (4f - 5g)$, $(4d - 6f) + (4f - 6g)$, $(5f - 6g) + (5g - 6h)$ and $(5f - 7g) + (5g - 7h)$ unresolved transition arrays at 633 \AA , 410 \AA , 1165 \AA , and 727 \AA ($\pm 2 \text{ \AA}$), respectively, using a beam-foil source. Their resolution was not sufficient to resolve the structure of these blended lines.

The work of Hardis et al. [32] was devoted to beam-foil spectroscopy of transitions in the core-excited Ne VII spectrum. To excite the spectrum, they used Ne^{2+} ion beams passing through thin carbon foils. In Figure 1 of their paper, they showed a portion of a spectrogram obtained at ion beam energy 7.2 MeV . At this beam energy, the Ne VIII spectrum can be excited as well. We identify

the leftmost peak on this picture as a blend of $5f - 9g$ and $5g - 9h$ transitions in Ne VIII. Using the known lines of Ne IV, V, VI, and VII as reference lines, we determined the wavelength of the above-mentioned Ne VIII line as $514.86 \pm 0.20 \text{ \AA}$.

With the beam-foil technique, Berry and Hardis [17] observed the region around 630 \AA in the second order of diffraction with much higher resolution than that of Buchet et al. [12]. They observed the $4f \text{ } ^2\text{F}_{5/2,7/2}^\circ - 5g \text{ } ^2\text{G}_{7/2,9/2}$ transitions as an unresolved peak at 632.7 \AA , and the $4d \text{ } ^2\text{D}_{3/2,5/2} - 5f \text{ } ^2\text{F}_{5/2,7/2}^\circ$ transitions as another peak at 631.5 \AA . The calculated wavelength of the hydrogenic $4f - 5g$ line of Ne VIII, 632.686 \AA , as well as a number of other lines from argon hollow cathode and nitrogen beam-foil spectra, were used by Berry and Hardis [17] to calibrate their spectrometer and derive the wavelengths of the observed lines of He-like Ne IX. According to our analysis, the line at 633.5 \AA was incorrectly identified in reference [17] as the $4f - 5d$ transition in Ne VIII. In fact, this line is due to the $2s2p^2(^4\text{P})3d \text{ } ^5\text{F}_5 - 2s2p^2(^4\text{P})4f \text{ } ^5\text{G}_6^\circ$ transition in Ne V ($633.74 \pm 0.10 \text{ \AA}$ [33]). It is the strongest line of Ne V in this region of the spectrum and could well be excited at the beam energy of 8 MeV used by Berry and Hardis [17]. The $4f - 5d$ transition in Ne VIII, as follows from our calculations with Cowan's codes, should be weaker than the neighboring $4f - 5g$ transition by a factor of 200 and thus can hardly be observed. We also identified two known Ne VI lines in the spectrograms presented by Berry and Hardis [17]. As given by Kramida et al. [34], they correspond to the $2s2p^2 \text{ } ^2\text{P}_{1/2} - 2p^3 \text{ } ^2\text{P}_{1/2}^\circ$ and $2s2p^2 \text{ } ^2\text{P}_{3/2} - 2p^3 \text{ } ^2\text{P}_{3/2}^\circ$ transitions at $638.074 \pm 0.005 \text{ \AA}$ and $641.231 \pm 0.005 \text{ \AA}$, respectively. Using these Ne V and Ne VI lines (observed in the second order of diffraction), as well as the Ne IX lines at $1248.104 \pm 0.010 \text{ \AA}$ and $1277.71 \pm 0.02 \text{ \AA}$ [35] (in the first order of diffraction) as reference lines, we derived the wavelengths of the Ne VIII lines from Figure 1 of Berry and Hardis [17] as $631.53 \pm 0.10 \text{ \AA}$ ($4d - 5f$), $632.49 \pm 0.20 \text{ \AA}$ ($4f \text{ } ^2\text{F}_{5/2}^\circ - 5g \text{ } ^2\text{G}_{7/2}$), and $632.86 \pm 0.20 \text{ \AA}$ ($4f \text{ } ^2\text{F}_{7/2}^\circ - 5g \text{ } ^2\text{G}_{9/2}$).

Barrette et al. [13] identified the $3s - 5p$, $3p - 5d$, $3d - 4p$, and $3d - 5p$ transitions in a beam-foil spectrum. Their uncertainty was $\pm 0.3 \text{ \AA}$ in the region 250 \AA to 300 \AA and $\pm 0.2 \text{ \AA}$ in the region 150 \AA to 200 \AA . Buchet et al. [14] and Buchet [15], also using the beam-foil method, re-measured the $3s - 5p$ and $3p - 5d$ lines with an uncertainty of $\pm 0.2 \text{ \AA}$ and identified the $3p - 6d$, $3d - 6f$, and $5g - 8h$ transitions. The latter transition was observed at $584 \pm 1 \text{ \AA}$ by Buchet [15]. Denis et al. [36] and Lembo et al. [19,20] observed the hydrogenic $n = 7 - 8$ and $n = 8 - 9$ transitions in beam-foil spectra. The assignment of the $1950 \pm 5 \text{ \AA}$ line to a $n = 6 - 7$ transition in Ne VIII [36] was erroneous because the more precise predicted positions of the lines belonging to this transition array (see discussion of Edlén's semiempirical formulas below) are $1932.0 \pm 0.2 \text{ \AA}$ ($6h - 7i$) and $1931.8 \pm 0.3 \text{ \AA}$ ($6g - 7h$). From observations made by Lembo et al. [19,20] by means of beam-foil spectroscopy,

¹ The customary unit cm^{-1} for energy levels, used here, is related to the SI unit for energy (joule) by $1 \text{ cm}^{-1} = 1.986 445 61(34) \times 10^{-23} \text{ J}$ [P.J. Mohr, B.N. Taylor, Rev. Mod. Phys. **77**, 1 (2005)].

the $n = 7 - 8$ and $n = 8 - 9$ energy differences can be determined with uncertainties ranging from $\pm 3 \text{ cm}^{-1}$ to $\pm 5 \text{ cm}^{-1}$.

In the beam-foil spectrum observed by Livingston et al. [18], the $(5f - 7g) + (5g - 7h)$ transition appeared as a single blended line. Its wavelength was not measured but calculated using semiempirical formulas from Edlén [37] and used as a reference for measurement of other lines.

We identified three previously unclassified lines at 2970.2 Å, 3319.4 Å, and 3433.7 Å observed in the beam-foil spectrum by Denis et al. [38] as the $7d - 8f$, $9s - 11p$, and $9p - 11d$ transitions in Ne VIII.

Ishii et al. [39], by using a beam-foil method, observed a group of lines between 3700 Å and 3900 Å. They identified these lines as belonging to the $n = 7 - 8$ transition array in Ne VII. In particular, they identified the line at $3726.5 \pm 1.0 \text{ Å}$ as the $2s7f \ ^3F^\circ - 2s8g \ ^3G_5$ transition in Ne VII. Lapiere and Knystautas [22] observed this line at similar experimental conditions and identified it as the $n = 11 - 15$ transition in Ne VIII. In the latter paper, the line was noted as blended. We adopted the more accurate wavelength from Ishii et al. [39].

In the experiment done by Gauntt and Danzmann [40], the $n = 9$ levels of Ne VIII were populated by means of single electron capture from atomic sodium by low-energy Ne^{8+} ions. At very low collision velocities, the s states were populated preferentially. This allowed Gauntt and Danzmann to identify the $8p \ ^2P_{1/2}^\circ - 9s \ ^2S_{1/2}$ and $8p \ ^2P_{3/2}^\circ - 9s \ ^2S_{1/2}$ lines near 4540 Å in addition to the $8f \ ^2F^\circ - 9g \ ^2G$ and $8g \ ^2G - 9h \ ^2H^\circ$ lines near 4340 Å. They used the wavelength of the hydrogenic $8hik - 9ikl$ line, 4341.92 Å in vacuum (air wavelength 4340.70 Å), calculated with a multiconfiguration Dirac-Fock code, as a reference. All other measured wavelengths of Ne VIII are given in reference [40] relative to this calculated vacuum wavelength. The air wavelength of this line measured by Lembo et al. [19,20] is $4340.9 \pm 0.6 \text{ Å}$. It is the best available experimental value for this wavelength. The uncertainty of the calculated wavelength is unknown. Therefore, we adjusted all Ne VIII wavelengths given by Gauntt and Danzmann [40] so that the wavelength of the $8hik - 9ikl$ line matches the measured one. The resulting wavelengths given in Table I (those with reference to Gauntt and Danzmann [40]) may possess a systematic shift of up to $\pm 0.6 \text{ Å}$. This unknown systematic error is much greater than the measurement uncertainties given by Gauntt and Danzmann [40] ($\pm 0.04 \text{ Å}$ to $\pm 0.06 \text{ Å}$).

In the beam-foil experiment of Lapiere and Knystautas [22] several tens of lines of Ne VIII were identified in the visible and ultraviolet regions. These lines are due to transitions between highly excited Rydberg levels. Lapiere and Knystautas gave wavelengths for these lines in vacuum with uncertainty $\pm 1 \text{ Å}$. In Table I, we give those wavelengths that are greater than 2000 Å converted to standard air. As noted in reference [22], identifications of the lines assigned to transitions corresponding to electron jumps from lower- L states to higher- L ones are questionable since these transitions are expected to have a very

small radiative decay rate. Besides the lines identified by Lapiere and Knystautas [22], we identified two lines at air wavelengths $2333.9 \pm 3 \text{ Å}$ and $3266.1 \pm 1.5 \text{ Å}$ in the spectrograms presented in their paper as the $n = 10 - 16$ and $n = 11 - 16$ transitions of Ne VIII, respectively.

Buchet-Poulizac et al. [24] observed the $nl - n'l'$ ($n = 3, 4$; $n' = 4$ to 10) transitions in the vacuum ultraviolet (VUV) region (195 Å to 400 Å) with uncertainties between $\pm 0.05 \text{ Å}$ and $\pm 0.25 \text{ Å}$. Wavelengths of these transitions are given in Figure 1 of their paper without classification. We made an additional analysis of the spectrograms obtained in that work and found several new lines of Ne VIII. For several lines, we improved previous measurements of other authors. For example, we determined the wavelength of the unresolved $3p - 5d$ doublet as $195.23 \pm 0.10 \text{ Å}$. The previously reported values for this wavelength were $195.3 \pm 0.2 \text{ Å}$ [13] and $195.0 \pm 0.2 \text{ Å}$ [14]. The $4d - 12f$ and $4f - 12g$ lines were found to be masked by a Ne VII line at 256.04 Å [41]. The $4p - 11d$ doublet is masked by a Ne VII line at 258.65 Å [41]. We identified the blended line at $262.32 \pm 0.25 \text{ Å}$ as unresolved $4d - 11f$ and $4f - 11g$ transitions. The $4s - 9p$ transition was found at $269.04 \pm 0.11 \text{ Å}$. The $4d - 10f$ and $4f - 10g$ lines are masked by the line at 271.11 Å belonging to the Ne VIII core-excited spectrum [24]. Similarly, the $4d - 9f$ and $4f - 9g$ lines are masked by the core-excited Ne VIII line at 283.74 Å [24]. We identified the lines at $297.12 \pm 0.05 \text{ Å}$, $303.65 \pm 0.05 \text{ Å}$, $332.08 \pm 0.10 \text{ Å}$, and $381.49 \pm 0.10 \text{ Å}$ as the unresolved $3d - 4p$, $4f - 8g$, $4p - 7d$, and $4s - 6p$ doublets, respectively. The line at 303.56 Å was previously assigned to the $2p3s \ ^3P_2^\circ - 2p4p \ ^3P_1$ transition in Ne VII [24]. However, it was found in reference [41] that it is actually due to the $4d - 8f$ transition in Ne VIII. We identified the blended line at $338.03 \pm 0.20 \text{ Å}$ as the unresolved $4d - 7f$ and $4f - 7g$ transitions.

In Table I, the relative intensities of the lines observed by different authors were converted to a uniform scale. The survey spectrograms of the extreme ultraviolet (EUV) region (60 Å to 120 Å) presented in Lapiere's thesis [42] were used to establish the relative intensities of the Ne VIII and Ne VII lines and construct the intensity scale consistent with the one used in the Ne VII compilation [41]. Our scale in this spectral region approximately corresponds to the scale of Tondello and Paget [7] multiplied by 30. For other spectral regions, we used the spectrograms in the publications to determine relative intensities of the lines. The values of relative intensities do not take into account variations of excitation conditions in different light sources and variations of detection sensitivity. They can be used only as a qualitative measure of relative strengths of the lines.

For completeness of the reference material we note that precise calculations of the hyperfine structure and isotopic shifts of the $1s^23s$ and $1s^24s$ states in Ne VIII were made by King [43]. Lifetimes were measured for a number of singly- and doubly-excited states in references [12, 13, 18, 26, 44].

3 Ionization potential

3.1 Experimental data

Tondello and Paget [7] determined the ionization potential (IP) of Ne VIII as $1928350 \pm 200 \text{ cm}^{-1}$. Lotz [45] gave a theoretical value of the IP as 1928439 cm^{-1} . Odabasi [46] calculated the IP to be $1928480.0 \text{ cm}^{-1}$, which compares well with Edlén's semiempirical result of $1928462.0 \text{ cm}^{-1}$ [47]. Later, Edlén [48] refined the experimental value to $1928471 \pm 52 \text{ cm}^{-1}$. Edlén compared this new result with the value 1928449 cm^{-1} calculated by means of his semiempirical formula derived from interpolation along the isoelectronic sequence [48].

Biémont et al. [49] systematically investigated the behavior of the differences between experimental values of IP s and those calculated ab initio by means of multiconfiguration Dirac-Fock approach along isoelectronic sequences. Their interpolated value for Ne VIII is $1928450 \pm 70 \text{ cm}^{-1}$.

As seen from Table I, the list of observed lines of Ne VIII is now significantly extended compared to what was available to Edlén [48]. Based on this line list, energy levels of Ne VIII can be derived with improved accuracy. The resulting energy levels, in turn, can be used to find a new experimental value of the IP . This derivation is described below.

We determined the optimized experimental energy levels given in Table 1 by means of the computer code LOPT [50]. It should be noted that most of the experimental levels with $n \geq 3$ are well defined relative to the lowest $n = 3$ level, $1s^23s^2S_{1/2}$, because they are connected by a number of lines having relatively low uncertainties. However, the connection of these excited levels with the ground state is still based on the same four VUV lines belonging to the $1s^22s - 1s^23p$ and $1s^22p - 1s^23d$ transitions ($\lambda = 98.115 \text{ \AA}$, 98.260 \AA , 102.911 \AA , and 103.085 \AA), measured by Tondello and Paget [7], that were used by Edlén [48]. The uncertainty of these four wavelengths is $\pm 0.005 \text{ \AA}$. Therefore, the position of the system of excited levels relative to the ground state may be affected by a systematic shift of up to $\pm 50 \text{ cm}^{-1}$ that might be present in the measurements of Tondello and Paget. In total, there are 49 $1s^2nl$ levels with $3 \leq n \leq 16$ having experimental uncertainties in the range 50 cm^{-1} to 100 cm^{-1} relative to the ground state. From each one of them, a separate value of the ionization limit can be derived using Edlén's polarization formula [37,48] for the nl ($l \geq 2$) levels and Edlén's semiempirical "screening" formulas [48] for the nl ($l \leq 1$) levels. Each of these values of the limit is expected to have approximately the same uncertainty as the level itself. The weighted mean of these values is equal to 1928454 cm^{-1} with a standard deviation of 23 cm^{-1} . This value differs by only 5 cm^{-1} from Edlén's semiempirical result, 1928449 cm^{-1} [48].

3.2 Theoretical results

Here we will discuss the results of the three theoretical studies [51–53] that we consider the most accurate.

Johnson et al. [51] calculated the ionization energies of lithium-like ions using relativistic many-body perturbation theory (RMBPT). Their calculations start from a Dirac-Fock basis and include second- and third-order Coulomb corrections, the lowest-order Breit interaction with retardation, and second-order Breit corrections. Their result for Ne VIII, not including the quantum-electrodynamic (QED) corrections, is 1928544 cm^{-1} .

Chung [52] performed extensive calculations of IP s for the lithium isoelectronic sequence, Li I through Ne VIII. His computational method is called "full core plus correlation" (FCPC). It employs a non-relativistic multiconfiguration interaction approach with optimized Slater-type wave functions. Relativistic and mass polarization effects were included using first-order perturbation theory. The QED contributions to the IP were calculated using an effective nuclear charge. In a subsequent publication Chung [54] noted that there was an error in the computer code for the QED energy correction used in reference [52]. In [54], the revised IP of Ne VIII (including the revised QED correction) is given as $1928462.6 \pm 5.6 \text{ cm}^{-1}$. The value without the QED correction is $1928538.69 \pm 0.32 \text{ cm}^{-1}$.

Chen et al. [53] used a relativistic configuration-interaction method with B-spline basis functions. Their result for the IP of Ne VIII (without QED corrections) is 1928550 cm^{-1} . As discussed in their work, the difference of 11 cm^{-1} between the results of Chen et al. [53] and Chung [54] is probably due to neglecting of higher-order relativistic corrections in Chung's method [52,54]. This suggests that the results of Johnson et al. [51] and Chen et al. [53] should be more accurate. The difference between the values given in the two latter papers is only 6 cm^{-1} . The energies of the $2s^2S_{1/2} - 2p^2P_{1/2,3/2}^{\circ}$ transitions computed by Chen et al. [53], 128152.1 cm^{-1} and 129802.5 cm^{-1} , are in excellent agreement with the experimental values, 128151.9 cm^{-1} and 129801.2 cm^{-1} , respectively. This allows us to conclude that the calculations of Chen et al. [53] are the most accurate. However, unlike the transition energies, the values of the IP are given by Chen et al. [53] without the QED corrections. Thus, we need to obtain these corrections from other sources.

The QED corrections to the IP s of Li-like ions were calculated by McKenzie and Drake [55]. A small error was found in their calculation procedure and corrected in reference [56]. Their value of the QED correction for the IP of Ne VIII is -103.4 cm^{-1} . This value does not include the finite nuclear size effects. However, these effects are negligible for Ne VIII [57]. The result of McKenzie and Drake can be compared with Chung's result, -71.6 cm^{-1} [54]. The large difference between these two calculations shows that the largest uncertainty in the theoretical values of the IP results from the QED corrections. Comparison with accurate experimental data on the IP s of Be II [58], C IV [59], and F VII [60] indicates that calculations of McKenzie and Drake [56] are more accurate than those of Chung [54]. In reference [56], evidence of the high quality of the calculations is provided by the good agreement of the calculated QED corrections for the $2s^2S_{1/2} - 2p^2P_{1/2}^{\circ}$ interval with

Table 1. Experimental energy levels (E) derived from observed spectral lines of Ne VIII compared to the calculated energies (E_c) derived from the adopted value of the ionization limit, 1928447 cm^{-1} and experimental value of the $2p \ ^2P_{1/2}^\circ - \ ^2P_{3/2}^\circ$ interval using Edlén's semiempirical formulas [37,48].

Configuration	Term	J	$E \text{ (cm}^{-1}\text{)}$	Unc. ^a (cm ⁻¹)	Num. obs. lines	$E_c \text{ (cm}^{-1}\text{)}$	$E - E_c \text{ (cm}^{-1}\text{)}$
$1s^2 2s$	2S	1/2	0.0	–	11	0.0	
$1s^2 2p$	$^2P^\circ$	1/2	128151.9	1.8	9	–	
$1s^2 2p$	$^2P^\circ$	3/2	129801.2	1.2	12	–	
$1s^2 3s$	2S	1/2	1099903.7	50	6	1099881.7	22.0
$1s^2 3p$	$^2P^\circ$	1/2	1134857.3	1.2	8	1134840.9	16.4
$1s^2 3p$	$^2P^\circ$	3/2	1135345.4	1.3	8	1135328.6	16.8
$1s^2 3d$	2D	3/2	1147366	40	7	1147347	19
$1s^2 3d$	2D	5/2	1147513	40	7	1147494	19
$1s^2 4s$	2S	1/2	1469644	30	5	1469616	28
$1s^2 4p$	$^2P^\circ$	1/2	1483875	60	7	1483912	–37
$1s^2 4p$	$^2P^\circ$	3/2	1484080	60	7	1484117	–37
$1s^2 4d$	2D		1489160	30	10	1489141	19
$1s^2 4f$	$^2F^\circ$	5/2	1489397	40	7	1489436	–39
$1s^2 4f$	$^2F^\circ$	7/2	1489429	40	7	1489467	–38
$1s^2 5s$	2S	1/2	1637420	60	5	1637460	–40
$1s^2 5p$	$^2P^\circ$		1644810	110	5	1644733	77
$1s^2 5d$	2D		1647370	80	6	1647317	53
$1s^2 5f$	$^2F^\circ$		1647485	40	5	1647490	–5
$1s^2 5g$	2G		1647505	40	5	1647511	–6
$1s^2 6s$	2S	1/2	1727700	500	1	1727579	221
$1s^2 6p$	$^2P^\circ$		1731736	60	4	1731748	–13
$1s^2 6dfgh$			1733300	60	12	1733332	–32
$1s^2 7s$	2S	1/2	1781489	60	3	1781495	–6
$1s^2 7p$	$^2P^\circ$		1784129	60	4	1784104	25
$1s^2 7d$	2D		1785058	60	8	1785036	22
$1s^2 7f$	$^2F^\circ$		1785124	50	4	1785103	21
$1s^2 7ghi$			1785135	50	4	1785115	20
$1s^2 8s$	2S	1/2	1816309	60	4	1816292	17
$1s^2 8p$	$^2P^\circ$	1/2	1818017.8	60	10	1818015	3
$1s^2 8p$	$^2P^\circ$	3/2	1818043.8	50	10	1818040	3
$1s^2 8d$	2D		1818672	50	6	1818655	17
$1s^2 8f$	$^2F^\circ$		1818709.9	60	6	1818701	9
$1s^2 8g$	2G		1818722.1	50	4	1818706	16
$1s^2 8hik$			1818727.8	60	5	1818709.7	18.5
$1s^2 9s$	2S	1/2	1840049.9	60	3	1840047	3
$1s^2 9p$	$^2P^\circ$		1841273	50	5	1841265	8
$1s^2 9d$	2D		1841720	60	5	1841702	18
$1s^2 9f$	$^2F^\circ$		1841753	50	8	1841734	19
$1s^2 9g$	2G		1841757.0	60	8	1841738	19
$1s^2 9h$	$^2H^\circ$		1841757.2	60	7	1841739.9	17.2
$1s^2 9ikl$			1841758.7	60	6	1841742	17
$1s^2 10s$	2S	1/2	1856930	80	1	1856983	–53
$1s^2 10p$	$^2P^\circ$		1857883	60	3	1857869	14
$1s^2 10d$	2D		1858200	70	1	1858187	13
$1s^2 10fghiklm$			1858234	50	6	1858215	19
$1s^2 11s$	2S	1/2	1869482	60	2	1869480	2
$1s^2 11p$	$^2P^\circ$		1870164	60	3	1870144	20
$1s^2 11d$	2D		1870377	60	3	1870383	–6
$1s^2 11fghiklmn$			1870433	60	6	1870404	29
$1s^2 12dfghiklmno$			1879685	60	3	1879675	10
$1s^2 13ghiklmnoq$			1886886	60	2	1886890	–4
$1s^2 14fghiklmnoqr$			1892640	60	3	1892615	25
$1s^2 15ghiklmnoqrt$			1897262	60	3	1897233	29
$1s^2 16hiklmnoqrtu$			1901043	60	2	1901013	30

^a Uncertainties of the $1s^2 2p \ ^2P_{1/2,3/2}^\circ$ and $1s^2 3s \ ^2S_{1/2}$ levels are given relative to the ground state. Uncertainties of all other levels are given relative to the $1s^2 3s \ ^2S_{1/2}$ level. To obtain the uncertainty of levels higher than $1s^2 3s \ ^2S_{1/2}$ relative to the ground state, one should combine the given uncertainty value with the uncertainty of the $1s^2 3s \ ^2S_{1/2}$ level, 50 cm^{-1} . Despite the large uncertainties, extra digits are necessary in some of the energy values in order to reproduce the observed level separations.

the values obtained by combining the measured transition frequencies with the calculations of Johnson et al. [51]. For $Z = 8$ through 11, the agreement is within 3×10^{-5} a.u. Since the value of the QED correction for the $2s \ ^2S_{1/2} - 2p \ ^2P_{1/2}^\circ$ transition energy is dominated by the QED correction to the $2s \ ^2S_{1/2}$ state, this implies that QED corrections to the latter state calculated by McKenzie and Drake [56] agree with experimental data on O VI, F IX, Ne VIII, and Na XI within 3×10^{-5} a.u., which corresponds to 7 cm^{-1} for Ne VIII. As discussed above, the non-QED part of the energy calculated by Chen et al. [53] is even more accurate than that calculated by Johnson et al. [51]. Therefore, we add the QED correction from McKenzie and Drake [56] to the IP value calculated without the QED corrections by Chen et al. [53] to obtain the adopted value 1928447 cm^{-1} for the IP of Ne VIII. Its total uncertainty should not exceed $\pm 15 \text{ cm}^{-1}$.

4 Valence-shell excited energy levels of Ne VIII

Using an accurate value of the IP , it is possible to derive the excitation energies of all the $1s^2nl$ states ($n \geq 3$) with higher accuracy than can be obtained from the level-optimization procedure based on fitting the observed lines (like the one used to obtain the first column of energy levels in Tab. 1). This derivation is described below.

As mentioned above, Edlén [48] published a list of Ritz formulas for the energies of the $2s - np$ and $2p - ns$ series of lithium-like ions, derived from interpolation along the isoelectronic sequence from Li I to Fe XXIV. To obtain the fine-structure splittings of the np states, we used the hydrogenic formula (see e.g. Denne et al. [61]):

$$\Delta E_H = R_z \alpha^2 Z_{\text{eff}}^4 / (n^3 l(l+1)),$$

where Z_{eff} is effective nuclear charge (for Ne VIII, $Z_{\text{eff}} = 8$), R_z is the Rydberg constant for the given ion (corrected for the finite nuclear mass), n is the principal quantum number, and l is the orbital angular momentum.

Excitation energies of all nl states with $n \geq 3$ and $l \geq 2$ were calculated using the following procedure.

The formula for the binding energy of the hydrogenic nl states can be found e.g. in Edlén's paper [37]:

$$T_H(n, l) = R_z (Z_{\text{eff}}/n)^2 [1 + (Z_{\text{eff}}\alpha/n)^2 (n/(l+1/2) - 3/4)],$$

where $R_z = 109737.318 - 60.200/M_z$ (see [48], footnote to Tab. III) is the Rydberg constant (M_z is the atomic weight). Additionally, Edlén [37] gave a set of semiempirical formulas for the core-polarization corrections $\Delta P(n, l)$. These formulas, slightly corrected in [48] using some new experimental data, were proved valid for $l \geq 3$ in the Na I isoelectronic sequence and for $n \geq 2$ for the Li I sequence. The binding energy of the nl states can be represented as the sum of $T_H(n, l)$ and $\Delta P(n, l)$ [37]. Using the adopted value of the IP (see previous section) and the hydrogenic formula for the fine-structure splittings given above, excitation energies of all nl states with $n \geq 3$, $l \geq 2$ can be calculated with high accuracy.

Wang et al. [30,62,63], using the same multiconfiguration approach as Chung [52,54], calculated the excitation energies of the $1s^2ns$, $1s^2np$, $1s^2nd$, and $1s^2nf$ ($n = 3, 4$ and 5) states. Wang et al. estimated their uncertainty as $\pm 10 \text{ cm}^{-1}$, but the arguments of Chen et al. [53] cited above (regarding the accuracy of calculations of Chung [52,54]) along with alternative theoretical data on the QED corrections [55,56] enlarge it to $\pm 30 \text{ cm}^{-1}$. Nevertheless, the excitation energies of Ne VIII calculated by Wang et al. [30,62,63] agree with those obtained from Edlén's semiempirical formulas [48] within $\pm 20 \text{ cm}^{-1}$.

An alternate way of checking the accuracy of Edlén's formulas is to compare their results with new experimental data on isoelectronic spectra. Tunklev et al. [59] determined the energy levels and ionization potential of C IV with uncertainties of $\pm 1.5 \text{ cm}^{-1}$. They combined all previously known data on this spectrum with new observations of beam-foil and tokamak emission spectra. Comparison of their table of energy levels with the values calculated by means of Edlén's formulas shows an excellent agreement. The rms deviation of calculated levels from experimental ones is 1.1 cm^{-1} . The largest deviations are 2.6 cm^{-1} for the $1s^24d \ ^2D$ ($J = 3/2$ and $5/2$) levels.

Engström [60] published a comprehensive analysis of the F VII spectrum by means of beam-foil spectroscopy. For this spectrum, the rms deviation of levels calculated with Edlén's formulas (using the value $1493632 \pm 5 \text{ cm}^{-1}$ for the IP of F VII [60]) from the experimental ones is 10 cm^{-1} . The mean deviation is $+6 \text{ cm}^{-1}$, indicating that the IP found by Engström [60] is probably too low by 6 cm^{-1} . It should be noted that the uncertainty of the IP value given in reference [60] ($\pm 5 \text{ cm}^{-1}$) does not take into account possible presence of a systematic shift in the short-wavelength lines corresponding to the $n = 2$ to $n = 3$ transitions. If we take this factor into account, the uncertainty of the IP should be raised to $\pm 30 \text{ cm}^{-1}$. Engström stated that the internal uncertainty of the energy levels found in his work is around 2 cm^{-1} . This estimate seems to be too low, since only a few long-wavelength lines observed in his spectrum had uncertainties below 4 cm^{-1} . The largest deviations between the levels calculated with Edlén's formulas and the measured ones listed in reference [60] are 18 cm^{-1} for the $4d$ levels. All wavelength deviations, except those for the long-wavelength $3s - 3p$ transitions, are statistically consistent with the measurement uncertainties quoted in reference [60].

Based on these comparisons, we conclude that Edlén's formulas [37,48] should be applicable to Ne VIII as well. Provided that an accurate value of the IP is used, uncertainties of levels calculated with these formulas should be lower than those of experimentally determined levels listed in Table 1 with only a few exceptions.

Table 2 provides a list of recommended values of energy levels of Ne VIII. The energies derived from experiment are the most accurate ones only for the states $1s^22p \ ^2P_{1/2,3/2}^\circ$ (their uncertainties are $\pm 1.6 \text{ cm}^{-1}$ and $\pm 0.8 \text{ cm}^{-1}$, respectively [2]). Also, the experimental values for the $1s^23s - 1s^23p$ (upper $J = 1/2$ and $3/2$) energy differences ($35441.8 \pm 1.3 \text{ cm}^{-1}$ and 34953.6 cm^{-1} ,

Table 2. Recommended energy levels of Ne VIII involving excitation of the valence electron.

Configuration	Term	J	Energy ^a (cm ⁻¹)	Unc. rel. ^b (cm ⁻¹)	Unc. ^c (cm ⁻¹)
1s ² 2s	² S	1/2	0.0	0.7	–
1s ² 2p	² P ^o	1/2	128151.9	1.6	1.6
1s ² 2p	² P ^o	3/2	129801.2	0.8	1.2
1s ² 3s	² S	1/2	[1099886.0] ^d	0.9	17
1s ² 3p	² P ^o	1/2	[1134839.5] ^d	1.2	18
1s ² 3p	² P ^o	3/2	[1135327.7] ^d	1.3	18
1s ² 3d	² D	3/2	[1147347]	20	21
1s ² 3d	² D	5/2	[1147494]	20	21
1s ² 4s	² S	1/2	[1469616]	13	19
1s ² 4p	² P ^o	1/2	[1483912]	10	24
1s ² 4p	² P ^o	3/2	[1484117]	10	30
1s ² 4d	² D	3/2	[1489104]	10	19
1s ² 4d	² D	5/2	[1489166]	10	20
1s ² 4f	² F ^o	5/2	[1489436]	10	21
1s ² 4f	² F ^o	7/2	[1489467]	10	22
1s ² 5s	² S	1/2	[1637460]	20	23
1s ² 5p	² P ^o	1/2	[1644664]	9	24
1s ² 5p	² P ^o	3/2	[1644768]	9	30
1s ² 5d	² D	3/2	[1647298]	5	24
1s ² 5d	² D	5/2	[1647330]	5	30
1s ² 5f	² F ^o	5/2	[1647480.7]	2.0	17
1s ² 5f	² F ^o	7/2	[1647496.7]	2.0	17
1s ² 5g	² G		[1647511]	4	16
1s ² 6s	² S	1/2	[1727579]	15	21
1s ² 6p	² P ^o	1/2	[1731708]	8	21
1s ² 6p	² P ^o	3/2	[1731768]	8	23
1s ² 6d	² D	3/2	[1733224]	5	20
1s ² 6d	² D	5/2	[1733242]	5	21
1s ² 6f	² F ^o		[1733339]	5	16
1s ² 6g	² G		[1733351.4]	2.0	15
1s ² 6h	² H ^o		[1733357.0]	1.7	15
1s ² 7s	² S	1/2	[1781495]	15	21
1s ² 7p	² P ^o	1/2	[1784078]	7	21
1s ² 7p	² P ^o	3/2	[1784116]	7	23
1s ² 7d	² D	3/2	[1785029]	3	17
1s ² 7d	² D	5/2	[1785041]	3	18
1s ² 7f	² F ^o		[1785103]	3	15
1s ² 7g	² G		[1785111.4]	2.0	15
1s ² 7h	² H ^o		[1785115.0]	1.0	15
1s ² 7i	² I		[1785117.1]	1.0	15
1s ² 8s	² S	1/2	[1816292]	15	20
1s ² 8p	² P ^o	1/2	[1818014.9] ^d	3.2	20
1s ² 8p	² P ^o	3/2	[1818040.8] ^d	3.2	20
1s ² 8d	² D		[1818655]	10	17
1s ² 8f	² F ^o		[1818691.1] ^d	3.2	15
1s ² 8g	² G		[1818704.9] ^d	3.2	15
1s ² 8h	² H ^o		[1818709] ^d	5	15
1s ² 8i	² I		[1818710] ^d	5	15
1s ² 8k	² K ^o		[1818711] ^d	5	15
1s ² 9s	² S	1/2	[1840047.0]	3.2	20
1s ² 9p	² P ^o		[1841265]	7	16
1s ² 9d	² D		[1841702]	10	17
1s ² 9f	² F ^o		[1841734]	3	15
1s ² 9g	² G		[1841738.2]	2.0	15
1s ² 9h	² H ^o		[1841739.9]	1.0	15
1s ² 9i	² I		[1841740.9]	1.0	15

Table 2. *Continued.*

Configuration	Term	J	Energy ^a (cm ⁻¹)	Unc. rel. ^b (cm ⁻¹)	Unc. ^c (cm ⁻¹)
1s ² 9k	² K ^o		[1841741.7]	1.0	15
1s ² 9l	² L		[1841742.2]	1.0	15
1s ² 10s	² S	1/2	[1856983]	20	20
1s ² 10p	² P ^o		[1857869]	15	21
1s ² 10d	² D		[1858187]	5	16
1s ² 10f	² F ^o		[1858210.3]	1.0	15
1s ² 10g	² G		[1858213.1]	1.0	15
1s ² 10h	² H ^o		[1858214.3]	1.0	15
1s ² 10i	² I		[1858215.1]	1.0	15
1s ² 10klm			[1858216.0]	0.5	15
1s ² 11s	² S	1/2	[1869480]	13	19
1s ² 11p	² P ^o		[1870144]	15	21
1s ² 11d	² D		[1870383]	5	16
1s ² 11f	² F ^o		[1870400.5]	1.0	15
1s ² 11g	² G		[1870402.6]	1.0	15
1s ² 11h	² H ^o		[1870403.5]	1.0	15
1s ² 11i	² I		[1870404.1]	1.0	15
1s ² 11klmn			[1870404.9]	0.5	15
1s ² 12d	² D		[1879658]	5	16
1s ² 12f	² F ^o		[1879672.1]	1.0	15
1s ² 12g	² G		[1879673.7]	1.0	15
1s ² 12h	² H ^o		[1879674.5]	1.0	15
1s ² 12i	² I		[1879674.9]	1.0	15
1s ² 12klmno			[1879675.5] ^e	0.5	15
1s ² 13ghiklmnoq			[1886890] ^e	5	15
1s ² 14fghiklmnoqr			[1892615] ^e	5	15
1s ² 15ghiklmnoqrt			[1897233] ^e	5	15
1s ² 16hiklmnoqrtu			[1901013] ^e	5	15

^a The energies of the 1s²2p ²P^o_{1/2,3/2} levels are quoted from Bockasten et al. [2]. All energies given in square brackets are calculated in this work using semiempirical formulas from Edlén [37,48], unless otherwise stated.

^b Minimum uncertainty relative to other levels. Generally, this value determines the number of significant figures in the energy value. However, in some cases extra digits were required in order to reproduce precisely known separations between the levels.

^c Uncertainty relative to the ground level.

^d The values calculated using semiempirical formulas from Edlén [37,48] were adjusted in order to account for experimentally observed level separations.

^e Calculated in this work by using the polarization formula.

respectively [6]) are more accurate than the calculated ones, so a small correction (about 5 cm⁻¹) was applied in Table 2 to the calculated 1s²3s and 1s²3p energies in order to account for the observed intervals. Similarly, the 8p – 9d, 8f – 9d, 8g – 9h, 8h – 9i, 8i – 9k, and 8k – 9l separations are better known from experiment [20,40]. Therefore, we determined the 8p, 8f, 8g, 8h, 8i, and 8k levels based on these separations from the n = 9 levels. All other energies in Table 2 were obtained from Edlén’s semiempirical formulas using the procedure described above. Their estimated uncertainties relative to the ground state are between 15 cm⁻¹ and 30 cm⁻¹. The uncertainties of the fine-structure splittings of the np (n = 3 to 7), nd (n = 3

to 5), and 4*f* states are smaller than 10 cm⁻¹, decreasing to less than 5 cm⁻¹ for 8*p*, *nd* ($n \geq 6$) and 5*f*. Energy intervals between all *nl* ($l \geq 3$) states with the same *n* are accurate to less than 5 cm⁻¹. Their uncertainties are the worst for the 5*f* – 5*g* interval and rapidly decrease for higher *n* and *l* values.

5 Spectral lines of core-excited Ne VIII

The list of observed lines of the core-excited Ne VIII spectrum is given in Table II (see the *Supplementary Online Materials*). All experimental data on the states involving excitation of the inner-shell electron published before 1997 were compiled and critically analyzed by Kramida and Ivanov [25]. The subsequent observations [21–24, 26, 27] confirmed and significantly extended this analysis. The identification of the lines is discussed below.

5.1 X-ray satellite spectrum

Kramida and Ivanov [25] listed 13 lines in the region 11.6 Å to 14.2 Å observed in the spectra of a plasma focus discharge [5], theta pinch [64], recoil ions produced by collisions with energetic ion beams [65–67], and solar flares [68, 69] (see also references in [25]). Several identifications were given as questionable either because of insufficient measurement accuracy or because of lack of information about other transitions involving the same energy levels. Since new observations have become available, some of the questions can now be resolved.

Assignment of the line at 11.905 ± 0.005 Å to the $1s^2 2s^2 S - 1s 2s 3p^4 P^\circ$ transition [5, 25] is confirmed by the observation of the $1s 2p^2^4 P - 1s 2s 3p^4 P^\circ$ line at 97.03 ± 0.15 Å [21, 26]. The other two assignments of the 11.905 Å line remain questionable.

The $1s^2 2p^2 P^\circ - 1s 2p^2^2 S$ and $1s^2 2s^2 S - 1s(2s 2p^1 P^\circ)^2 P^\circ$ transitions previously reported at 13.525 ± 0.010 Å and 13.564 ± 0.010 Å, respectively [25, 64], are now measured with high precision by Wargelin et al. [27] who observed them in the dielectronic recombination spectrum obtained with an electron-beam ion trap. Their wavelengths are 13.533 ± 0.004 Å and 13.561 ± 0.003 Å, respectively.

The strongest dielectronic satellite line in Ne VIII is due to the $1s^2 2p^2 P^\circ - 1s 2p^2^2 D$ transition. Its wavelength is now precisely measured as 13.7083 ± 0.0012 Å [27].

5.2 Extreme ultraviolet spectrum

All measurements above 15 Å were done using high-energy ion beams colliding with foils or gases. Kramida and Ivanov [25] tabulated three EUV lines at 63.1 Å, 86.6 Å, and 92.4 Å quoted from Buchet et al. [14], Buchet [15], and To et al. [16]. The works of Denis et al. [21, 23], and Lapierre and Knystautas [26] extended the EUV line list by twenty more lines and improved the accuracy of the previous measurements. However, because of the moder-

ate spectral resolution, most of the lines in this region are multiply classified, and their fine structure remains unresolved.

The unresolved $1s 2s 2p^4 P^\circ - 1s 2s 4d^4 D$ multiplet, previously reported at 63.1 Å [16, 25], is now firmly established at 64.42 ± 0.03 Å [21, 26]. The $1s 2p^2^4 P - 1s 2p 3d^4 D^\circ$ multiplet is unambiguously identified and re-measured at 86.85 ± 0.03 Å [21, 22]. The $1s 2p^2^4 P - 1s 2p 3s^4 P^\circ$ multiplet was observed by Lapierre and Knystautas [26] as a broad asymmetric line at 92.20 Å. By decomposing its profile presented in Figure 3 of reference [26], we extracted the three wavelengths 92.11 ± 0.03 Å, 92.19 ± 0.02 Å, and 92.27 ± 0.03 Å, which we assigned to the $^4 P_{1/2} - ^4 P^\circ$, $^4 P_{3/2} - ^4 P^\circ$, and $^4 P_{5/2} - ^4 P^\circ$ transitions, respectively. The upper term has a much smaller splitting than the lower and remains unresolved.

The $1s 2p^2^4 P - 1s 2p 3d^4 D^\circ$ multiplet was reported in reference [26] at 86.22 ± 0.02 Å. In the spectrogram presented in Figure B11 of Lapierre's thesis [42] this line is distinctly resolved from the neighboring Ne VII line at 86.29 Å. We assigned this line to the $1s 2p^2^4 P_{3/2} - 1s 2p 3d^4 P^\circ$ transition, while the other two lines seen at 86.09 ± 0.03 Å and 86.40 ± 0.02 Å in the same figure are associated with the $1s 2p^2^4 P_{1/2} - 1s 2p 3d^4 P^\circ$ and $1s 2p^2^4 P_{5/2} - 1s 2p 3d^4 P^\circ$ transitions, respectively. As in the case with the $1s 2p^2^4 P - 1s 2p 3s^4 P^\circ$ multiplet, the splitting of the upper term is much smaller than that of the lower and remains unresolved.

The lines at 61.48 ± 0.03 Å and 65.44 ± 0.02 Å were tentatively identified by Lapierre and Knystautas [26] as the unresolved $1s 2s 2p^4 P^\circ - 1s 2p 4p^4 P$ and $1s 2s 2p^4 P^\circ - 1s 2s 4s^4 S$ multiplets, respectively. The upper terms of these two multiplets are defined solely by each of these two lines. Our calculations with Cowan's codes [31] support these identifications. However, since no other transitions involving their upper terms were observed, we noted these lines as questionable.

The line at 92.65 ± 0.02 Å was tentatively assigned to the $1s 2p^2^2 D - 1s 2p(^3 P^\circ) 3d^2 D^\circ$ transition by Lapierre and Knystautas [26] in agreement with the wavelength 92.5 Å predicted for this transition by Kramida and Ivanov [25]. This identification is confirmed by our parametric calculations with Cowan's codes [31], as well as by the observation of the $1s 2p(^3 P^\circ) 3d^2 D^\circ - 1s 2p(^3 P^\circ) 4f^2 F$ transition at 276.06 ± 0.05 Å [24]. The latter identification was supported by an isoelectronic comparison.

The $1s 2p^2^2 P - 1s 2p(^3 P^\circ) 3d^2 D^\circ$ transition is predicted to occur at 93.8 ± 0.5 Å. According to our calculations with Cowan's codes [31], its rate is approximately half that of the $1s 2p^2^2 D - 1s 2p(^3 P^\circ) 3d^2 D^\circ$ transition. In the beam-foil spectrum observed by Lapierre and Knystautas [26] it was probably masked by the $1s(^2 S) 2s 2p^2(^4 P) ^5 P - 1s 2s 2p 3d^5 D^\circ$ multiplet of Ne VII [41].

The electric quadrupole transition $1s 2s 2p^4 P_{5/2}^\circ - 1s 2p 3d^4 F_{9/2}^\circ$ was identified at 78.71 ± 0.05 Å by Denis et al. [21, 23] in recoil spectra of gaseous targets. Lapierre and Knystautas [26] noted that this transition cannot be observed in beam-foil experiments.

For the centers of gravity of the $1s2s2p\ ^4P^\circ - 1s2p3p\ ^4P$, $1s2s2p\ ^4P^\circ - 1s2p3p\ ^4S$, and $1s2p^2\ ^4P - 1s2p3d\ ^4D^\circ$ multiplets, we adopted the smoothed wavelengths $79.04 \pm 0.01\ \text{\AA}$, $79.33 \pm 0.01\ \text{\AA}$, and $86.85 \pm 0.03\ \text{\AA}$, respectively. They were determined by Lapierre and Knystautas [26] by isoelectronic interpolation.

5.3 Vacuum ultraviolet spectrum

Kramida and Ivanov [25] listed five lines around $725\ \text{\AA}$ quoted from Livingston et al. [18]. These observations were extended to shorter wavelengths by Denis et al. [21] and Buchet-Poulizac et al. [24].

The lines at $163.46 \pm 0.15\ \text{\AA}$ and $190.07 \pm 0.15\ \text{\AA}$ were identified as the $1s2s3d\ ^4D - 1s2s6f\ ^4F^\circ$ and $1s2s3d\ ^4D - 1s2s5f\ ^4F^\circ$ transitions, respectively [21].

On the basis of an isoelectronic comparison, the lines at $277.11 \pm 0.05\ \text{\AA}$, $272.31 \pm 0.05\ \text{\AA}$, $286.61 \pm 0.05\ \text{\AA}$, and $289.09 \pm 0.05\ \text{\AA}$ were identified in reference [24] as the $1s2p3d\ ^4F^\circ - 1s2p4f\ ^4G$, $1s2s3d\ ^4D - 1s2s4f\ ^4F^\circ$, $1s2p3d\ ^4D^\circ - 1s2p4f\ ^4F$, and $1s2p3d\ ^4P^\circ - 1s2p4f\ ^4D$ transitions, respectively. The line at $276.06 \pm 0.05\ \text{\AA}$ was identified as the transition between the core-excited doublet levels $1s2p(^3P^\circ)3d\ ^2D^\circ$ and $1s2p(^3P^\circ)4f\ ^2F$. Our calculations confirmed all these assignments from the points of view of energy intervals and transition rates (either for radiative and autoionizing decays).

In the spectrograms obtained in the course of the work of Buchet-Poulizac et al. [24] we found three more lines belonging to the quartet spectrum of Ne VIII. These are the lines at $251.81 \pm 0.15\ \text{\AA}$, $394.25 \pm 0.15\ \text{\AA}$, and $406.78 \pm 0.15\ \text{\AA}$ identified as the $1s2p3s\ ^4P^\circ - 1s2p4p\ ^4D$, $1s2s4d\ ^4D - 1s2s6f\ ^4F$, and $1s2s4f\ ^4F^\circ - 1s2s6g\ ^4G$ transitions. The line at $251.81\ \text{\AA}$ fits well with the line at $61.73\ \text{\AA}$ ($1s2s2p\ ^4P^\circ - 1s2p4p\ ^4P$ [26]). The line at $394.25\ \text{\AA}$ fits well with the line at $163.46\ \text{\AA}$ ($1s2s3d\ ^4D - 1s2s6f\ ^4F$ [21]), which supports both identifications. The line at $406.78\ \text{\AA}$ fits well with the line at $1942\ \text{\AA}$ ($1s2s6g\ ^4G - 1s2s7h\ ^4H^\circ$ [22]) and is further supported by our analysis of the $1s2snl\ ^4L$ doubly-excited Rydberg levels (see Sect. 6).

The lines at $283.74 \pm 0.05\ \text{\AA}$ and $285.16 \pm 0.05\ \text{\AA}$ were assigned by Buchet-Poulizac et al. [24] to the $1s2p(^1P^\circ)3d\ ^2D^\circ - 1s2p(^1P^\circ)4f\ ^2F$ and $1s2s(^3S)3d\ ^2D - 1s2s(^3S)4f\ ^2F^\circ$ transitions, respectively. It had been argued by Denis et al. [21] that a more probable origin of the $283.74\ \text{\AA}$ line is the $1s2s(^3S)3d\ ^2D - 1s2s(^3S)4f\ ^2F^\circ$ transition. Our calculations showed that all doublet states with the $1s2p\ ^1P^\circ$ core have very strong radiative decay channels to the $1s^2nl\ ^2L$ states. These channels should manifest themselves as soft X-ray lines. Such lines with $n = 3$ were indeed observed (see top of Tab. II). The branching ratios of the VUV transitions originating from the $1s2p(^1P^\circ)nl$ doublet states are too small compared to those of the states with the triplet core. Therefore, these doublet terms are not likely to be observed in the VUV region. Our parametric calculations support the original assignment of the $283.74\ \text{\AA}$ line to the $1s2s(^3S)3d\ ^2D - 1s2s(^3S)4f\ ^2F^\circ$

transition [21], while the $285.16\ \text{\AA}$ line is probably due to the $1s2p3d\ ^4D^\circ - 1s2p4f\ ^4G$ transition. The latter assignment is in good agreement with our calculations of transition rates and fits well with the $271.11\ \text{\AA}$ line ($1s2p3d\ ^4F^\circ - 1s2p4f\ ^4G$).

The revisions made above imply that the identifications of the $1s2p(^1P^\circ)3d\ ^2D^\circ - 1s2p(^1P^\circ)4f\ ^2F$ and $1s2s(^3S)3d\ ^2D - 1s2s(^3S)4f\ ^2F^\circ$ transitions in isoelectronic spectra C IV, N V, O VI, F VII, Al XI, and Si XII, proposed by Buchet-Poulizac et al. [24], should also be revised.

We identified a line seen at $626.63 \pm 0.10\ \text{\AA}$ in the second order of diffraction on the spectrogram given by Berry and Hardis [17] as the $1s2s4f\ ^4F^\circ - 1s2s5g\ ^4G$ transition in Ne VIII. It should be noted that, although this line appears very weak in Figure 1 of reference [17], the heights of the peaks in this region of the spectrum should be multiplied by approximately a factor of 7 in order to match the longer integration times for the $1s^24f - 1s^25g$ and $1s^24d - 1s^25f$ lines of Ne VIII near $632\ \text{\AA}$. Our identification of the $626.63\ \text{\AA}$ line follows from the analysis of the high- l Rydberg states by means of the polarization formula (see Sect. 6).

5.4 Ultraviolet and visible spectra

Lapierre and Knystautas [22] identified 25 lines in the region between $1820\ \text{\AA}$ and $4500\ \text{\AA}$ as transitions between highly excited quartet states $1s2snl\ ^4L$ ($n = 6 - 9$, $l = 0 - 8$) with $\Delta n = 1$. Identification of two of these lines (those at $2988\ \text{\AA}$ and $3013\ \text{\AA}$, assigned to the $1s2s7p\ ^4P^\circ - 1s2s8s\ ^4S$ and $1s2s7d\ ^4D - 1s2s8p\ ^4P^\circ$ transitions, respectively) is questionable since, as noted in reference [22], transitions corresponding to radiative decays of lower- l states to higher- l ones should have very small rates compared to transitions from higher- l to lower- l states.

On the basis of their Hartree-Fock calculations that include configuration interactions, Lapierre and Knystautas [22] suggested that the three unidentified lines observed by Gauntt and Danzmann [40] near $4380\ \text{\AA}$ are due to the $1s2s8h\ ^4H^\circ - 1s2s9i\ ^4I$ and $1s2s8i\ ^4I - 1s2s9k\ ^4K^\circ$ transitions. According to their calculations, the $J = 15/2 - J = 17/2$ component of the latter multiplet should be separated from the other lines of this multiplet, which are located close to each other, by approximately $5\ \text{\AA}$. Our calculations gave similar results. The wavelengths of the lines measured by Gauntt and Danzmann given in Table II have been adjusted relative to the observed wavelength of the $1s^28k - 1s^29l$ line ($4340.9 \pm 0.6\ \text{\AA}$ [19]) in the same way as was done for the other lines reported by these authors (see Sect. 2). They may possess a systematic shift of $\pm 0.6\ \text{\AA}$, although their separations from the $1s^28k - 1s^29l$ line were measured with uncertainties as small as $\pm 0.07\ \text{\AA}$. According to our calculations, the strongest contributions to the $1s2s8i\ ^4I - 1s2s9k\ ^4K^\circ$ line at $4380.09\ \text{\AA}$ are from the $J = 13/2 - J = 15/2$, $J = 11/2 - J = 13/2$, and $J = 9/2 - J = 11/2$ transitions. The separation of the $J = 15/2 - J = 17/2$ component from the rest of the multiplet is due to the interaction of the $1s2s8i\ ^4I_{15/2}$ level with

Table 3. Auger electron lines of Ne VIII.

E_{obs} (eV)	Unc. (eV)	Obs. Int.	$E_{\text{Ritz}}^{\text{a}}$ (eV)	Unc. (eV)	$E_{\text{obs}} - E_{\text{Ritz}}$	Configuration	Term	J	Ref.	Other Refs.
652.47	0.10	7.1	652.43	0.10	0.04	$1s2s^2$	2S	1/2	70	44,71
656.59	0.10	1.4	656.77	0.04	-0.18	$1s2s2p$	$^4P^{\circ}$	1/2	70	44,71
			656.82	0.04	-0.23	$1s2s2p$	$^4P^{\circ}$	3/2	70	44,71
			656.96	0.04	-0.37	$1s2s2p$	$^4P^{\circ}$	5/2	70	44,71
			668.75	0.11	8.4	668.81	0.09	$1s(2s2p\ ^3P^{\circ})$	$^2P^{\circ}$	
674.05	0.13	26.2	674.02	0.04	0.03	$1s2p^2$	4P	5/2	70	44,71
674.65	0.14	17.3	674.82	0.12	-0.17	$1s(2s2p\ ^1P^{\circ})$	$^2P^{\circ}$		70	44
681.16	0.10	32.7	681.29	0.06	-0.13	$1s2p^2$	2D		70	44
693	1	6.5	693.1	0.3	0	$1s2p^2$	2S	1/2	44	
796	1	2.0	796.23	0.04	0	$1s2s(^3S)3s$	4S	3/2	? 44	
800	1	2.2				$1s2s(^3S)3s$	2S	1/2	44	
803	1	6.3	801.76	0.20	1	$1s2s(^3S)3p$	$^4P^{\circ}$		44	
			802.5	0.6	0	$1s2s(^3S)3p$	$^2P^{\circ}$		44	
806	1	7.7				$1s2s(^1S)3s$	2S	1/2	? 44	
808	1	12.7	806.91	0.07	1	$1s2s(^3S)3d$	2D		44	
811	1	6.3				$1s2s(^1S)3p$	$^2P^{\circ}$? 44	
813	1	18.8				$1s2p(^3P^{\circ})3s$	$^2P^{\circ}$		44	
815	1	25.5	814.46	0.06	1	$1s2p(^3P^{\circ})3d$	$^4F^{\circ}$		44	
						$1s2s(^1S)3d$	2D		44	
						$1s2p(^3P^{\circ})3p$	2D		44	
						$1s2p(^1P^{\circ})3s$	$^2P^{\circ}$? 44	
818	1	9.6	818.3	0.7	0	$1s2p(^3P^{\circ})3p$	2S	1/2	? 44	
						$1s2p(^1P^{\circ})3p$	2D		44	
822	1	8.9	821.0	0.4	1	$1s2p(^3P^{\circ})3p$	2S	1/2	? 44	
						$1s2p(^1P^{\circ})3p$	2D		44	
850	1	2	823.6	0.4	-2	$1s2p(^1P^{\circ})3d$	$^2F^{\circ}$		44	
						$1s2s(^3S)4d$	2D		44	
852	1	5	850.61	0.06	1	$1s2s(^3S)4f$	$^2F^{\circ}$		44	

^a The Ritz energies and their uncertainties were calculated using the computer code LOPT [50]. They are supposed to be close to 1σ values. If the Ritz energy is not given, it means that one of the levels is determined from this line alone.

$1s2p(^3P^{\circ})6h\ ^4I_{15/2}$, the mixing between these two states being approximately 2%. The upper $1s2s9k\ ^4K^{\circ}$ term is not perturbed by configuration interaction and has very small fine-structure intervals ($<2\text{ cm}^{-1}$).

5.5 Auger electron spectrum

The list of observed Auger electron lines of Ne VIII is given in Table 3. These lines are due to autoionization of core-excited levels of Ne VIII into the ground state of Ne IX.

In the previous compilation [25] the analysis of the Ne VIII Auger electron spectrum was based mainly on the low-resolution observations of Schumann et al. [44]. The high-resolution experiments of Kádár et al. [70] and Bruch et al. [71] were left out of the scope of that work because of an apparent contradiction between some of their measurements. For example, the line originating from the $1s2s^2\ ^2S_{1/2}$ level was measured by Bruch et al. [71] at 652.7 eV with the total uncertainty of ± 0.1 eV, while Kádár et al. [70] reported the energy of 652.47 eV with the statistical uncertainty of ± 0.02 eV. However, considering that the measurements of Kádár et al. [70] had an additional calibration uncertainty of ± 0.1 eV and comparing their measurements for other ionization stages of

neon with the measurements of Bruch et al. [71], we find that this and all other discrepancies between their results can well be explained by statistical deviations. We gave preference to the results of Kádár et al. because in their work the width of the lines was smaller by a factor of three compared to Bruch et al.

6 Core-excited energy levels of Ne VIII

The list of core-excited energy levels of Ne VIII is given in Table 4. The energies of the levels were derived from the observed optical and Auger lines given in Tables 4 and 5 using the least-squares level optimization code LOPT [50]. In the process of level optimization, the separations between highly-excited terms $1s2s8g\ ^4G - 1s2s8i\ ^4I$, $1s2s7g\ ^4G - 1s2s7i\ ^4I$, $1s2s7i\ ^4I - 1s2s7h\ ^4H^{\circ}$, $1s2s(^3S)4f\ ^4F^{\circ} - 1s2s(^3S)4f\ ^2F^{\circ}$, and $1s2p(^3P^{\circ})4f\ ^4G - 1s2p(^3P^{\circ})4f\ ^2G$ were fixed at their values resulting from our parametric calculations ($140 \pm 100\text{ cm}^{-1}$, $80 \pm 100\text{ cm}^{-1}$, $60 \pm 100\text{ cm}^{-1}$, $1500 \pm 500\text{ cm}^{-1}$, and $1500 \pm 500\text{ cm}^{-1}$, respectively). The indicated uncertainties are rough estimates of the accuracy of the parametric calculations.

The $1s2s(^3S)nl$ quartet levels are not connected with the ground state by any observed spectral line except for

Table 4. Core-excited energy levels of Ne VIII.

Configuration ^a	Term	J	Energy ^b (cm ⁻¹)	Unc. rel. ^c	Unc. ^d	Leading percentages ^e				
1s2s ²	² S	1/2	7190600		900	800	91	9	1s2p ²	² S
1s2s2p	⁴ P ^o	1/2	7225645		19	300	100			
1s2s2p	⁴ P ^o	3/2	7226091		11	300	100			
1s2s2p	⁴ P ^o	5/2	7227183		19	300	100			
1s(2s2p ³ P ^o)	² P ^o		7322700		800	700	95			
1s2p ²	⁴ P	1/2	7363159		19	300	100			
1s2p ²	⁴ P	3/2	7363903		11	300	100			
1s2p ²	⁴ P	5/2	7364768		20	300	100			
1s(2s2p ¹ P ^o)	² P ^o		7371200		1600	900	95			
1s2p ²	² D		7423400		800	500	100			
1s2p ²	² P		7437000		5000	5000	100			
1s2p ²	² S	1/2	7518600		2200	2100	91	9	1s2s ²	² S
1s2s(³ S)3s	⁴ S	3/2	8350440		110	300	95	5	1s2p(³ P ^o)3p	⁴ S
1s2s(³ S)3s	² S	1/2	8381000		8000	8000	94	6	1s2p(³ P ^o)3p	² S
1s2s(³ S)3p	⁴ P ^o		8395000		1600	1600	97			
1s2s(³ S)3p	² P ^o		8401000	?	5000	5000	81	14	1s2p(³ P ^o)3s	² P ^o
1s2s(³ S)3d	⁴ D		8420320		70	140	93	7	1s2p(³ P ^o)3p	⁴ D
1s2s(¹ S)3s	² S	1/2	8429000		8000	8000	93	7	1s2p(¹ P ^o)3p	² S
1s2s(³ S)3d	² D		8436600		60	500	94	3	1s2p(³ P ^o)3p	² D
1s2p(³ P ^o)3s	⁴ P ^o		8448680		140	300	98			
1s2s(¹ S)3p	² P ^o		8470000	?	8000	8000	43	40	1s2p(³ P ^o)3s	² P ^o
1s2p(³ P ^o)3p	⁴ D		8474800		500	400	90	7	1s2s(³ S)3d	⁴ D
1s2p(³ P ^o)3s	² P ^o		8486000		8000	8000	44	41	1s2s(¹ S)3p	² P ^o
1s2p(³ P ^o)3p	⁴ S	3/2	8487000		500	400	92	5	1s2s(³ S)3s	⁴ S
1s2p(³ P ^o)3p	⁴ P		8491800		500	400	99			
1s2p(³ P ^o)3d	⁴ F ^o		8497530		70	500	100			
1s2s(¹ S)3d	² D		8502000	?	17000	17000	68–78	15–13	1s2p(¹ P ^o)3p	² D
1s2p(³ P ^o)3d	² D ^o		8502720		230	600	98			
1s2p(³ P ^o)3p	² D		8508000		6000	6000	77–86	21–10	1s2s(¹ S)3d	² D
1s2p(³ P ^o)3d	⁴ D ^o		8515700		60	400	83–100	13–0	1s2p(¹ P ^o)3s	² P ^o
1s2p(³ P ^o)3d	⁴ P ^o		8523300		600	300	95			
1s2p(¹ P ^o)3s	² P ^o		8526000	?	11000	11000	65–76	17–0	1s2p(³ P ^o)3d	⁴ D ^o
1s2p(³ P ^o)3p	² S	1/2	8528000	?	6000	6000	77	16	1s2p(¹ P ^o)3p	² S
1s2p(¹ P ^o)3p	² D		8550000		3000	3000	84	9	1s2s(¹ S)3d	² D
1s2p(¹ P ^o)3d	² F ^o		8571000		3000	3000	84	16	1s2p(³ P ^o)3d	² F ^o
1s2s(³ S)4s	⁴ S	3/2	8754700	?	600	500	98			
1s2s(³ S)4d	⁴ D		8778880		100	120	99			
1s2s(³ S)4d	² D		8784000	?	8000	8000	99			
1s2s(³ S)4f	⁴ F ^o		8787560		60	130	100			
1s2s(³ S)4f	² F ^o		8789040		60	500	99			
1s2p(³ P ^o)4s	⁴ P ^o		8839200		500	500	98			
1s2p(³ P ^o)4p	⁴ D		8845860		240	400	98			
1s2p(³ P ^o)4p	⁴ P		8853300	?	900	800	59–99	39–0	1s2p(³ P ^o)4p	⁴ S
1s2p(³ P ^o)4d	⁴ D ^o		8862700		600	500	82–98	15–0	1s2p(³ P ^o)4d	⁴ P ^o
1s2p(³ P ^o)4d	⁴ P ^o		8864600		500	500	81–96	16–2	1s2p(³ P ^o)4d	⁴ D ^o
1s2p(³ P ^o)4f	⁴ F		8864610		60	500	53–98	33–0	1s2p(³ P ^o)4f	² F
1s2p(³ P ^o)4f	² F		8864960		70	600	58–72	27–11	1s2p(³ P ^o)4f	⁴ F
1s2p(³ P ^o)4f	⁴ G		8866380		50	400	68–99	16–0	1s2p(³ P ^o)4f	⁴ F
1s2p(³ P ^o)4f	² G		8867600		500	700	79–94	12–5	1s2p(³ P ^o)4f	⁴ G
1s2p(³ P ^o)4f	⁴ D		8869180		60	300	82–100	14–0	1s2p(³ P ^o)4f	² D
1s2s(³ S)5f	⁴ F ^o		8946290		50	80	100			
1s2s(³ S)5g	⁴ G		8947150		30	140	99			
1s2s(³ S)6p	⁴ P ^o		9028350		30	80	43–50	44–55	1s2p(³ P ^o)5d	⁴ P ^o
1s2s(³ S)6d	⁴ D		9030120		30	100	98			
1s2s(³ S)6f	⁴ F ^o		9032530		40	80	99			
1s2s(³ S)6g	⁴ G		9033420		60	110	94	5	1s2p(³ P ^o)5f	⁴ G
1s2s(³ S)6h	⁴ H ^o		9034330		80	100	48–87	9–20	1s2p(³ P ^o)5g	⁴ H ^o

Table 4. *Continued.*

Configuration ^a	Term	J	Energy ^b (cm ⁻¹)	Unc. rel. ^c	Unc. ^d	Leading percentages ^e				
1s2s(³ S)7s	⁴ S	3/2	9079020	21	80	99				
1s2s(³ S)7p	⁴ P ^o		9081480	40	110	99				
1s2s(³ S)7d	⁴ D		9083294	18	80	100				
1s2s(³ S)7f	⁴ F ^o		9084495	15	100	100				
1s2s(³ S)7g	⁴ G		9084791	17	80	100				
1s2s(³ S)7i	⁴ I		9084870	30	70	61–100	39–0	1s2s(³ S)7i	² I	
1s2s(³ S)7h	⁴ H ^o		9084924	17	80	53–100	46–0	1s2s(³ S)7h	² H ^o	
1s2s(³ S)8s	⁴ S	3/2	9114940	30	120	96				
1s2s(³ S)8p	⁴ P ^o		9116487	9	80	95	5	1s2p(³ P ^o)6d	⁴ P ^o	
1s2s(³ S)8d	⁴ D		9117478	8	100	100				
1s2s(³ S)8f	⁴ F ^o		9118338	6	70	100				
1s2s(³ S)8k	⁴ K ^o		9118529	19	60	62–100	38–0	1s2s(³ S)8k	² K ^o	
1s2s(³ S)8g	⁴ G		9118602	14	100	98				
		9/2,								
1s2s(³ S)8i	⁴ I	11/2,	9118707.6	3.2	80	60–99	38–0	1s2s(³ S)8i	² I	
		13/2								
1s2s(³ S)8i	⁴ I	15/2	9118737.7	3.2	80	98	2	1s2p(³ P ^o)6h	⁴ I	
1s2s(³ S)8h	⁴ H ^o		9118780.5	3.2	80	54–98	43–0	1s2s(³ S)8h	² H ^o	
1s2s(³ S)9s	⁴ S	3/2	9138725	7	80	99				
1s2s(³ S)9p	⁴ P ^o		9139964	8	100	100				
1s2s(³ S)9d	⁴ D		9140918	6	80	100				
1s2s(³ S)9f	⁴ F ^o		9141384	9	100	100				
1s2s(³ S)9g	⁴ G		9141513	8	70	100				
1s2s(³ S)9k	⁴ K ^o		9141531.8	0.3	80	62–100	38–0	1s2s(³ S)9k	² K ^o	
1s2s(³ S)9l	⁴ L		[9141567]	16	60	62–100	37–0	1s2s(³ S)9l	² L	
1s2s(³ S)9i	⁴ I		9141623.2	0.4	80	61–100	39–0	1s2s(³ S)9i	² I	
1s2s(³ S)9h	⁴ H ^o		9141637	22	100	55–100	45–0	1s2s(³ S)9h	² H ^o	
1s3p ²	² P	3/2	9760000	?	60000	60000	92	8	1s3p ²	² D
2s ² 2p	² P ^o	3/2	15220000	?	30000	30000	92	8	2p ³	² P ^o

^a Configuration and term labels assigned to highly mixed levels such as 1s2s6p ⁴P^o do not fully reflect the physical nature of these levels. In the designations of the 1s2s2p quartet terms, the ³P^o intermediate term of the 2s2p sub-configuration is omitted for brevity. Similarly, the intermediate terms of the 2p² and 3p² sub-configurations are omitted. These omissions do not lead to ambiguities in the term designations.

^b Energy levels and their uncertainties were determined by means of the least-squares level optimization code LOPT [50]. They were derived from the list of observed optical and Auger lines given in Tables II (see the *Supplementary Online Materials*) and 3. Details of the optimization procedure are explained in the text. The uncertainties are supposed to be close to 1 σ values. A question mark after the energy value means that the identification of this level is uncertain.

^c Minimum uncertainty relative to other levels. Generally, this value determines the number of significant figures in the energy value. However, in some cases extra digits were required in order to reproduce precisely known separations between the levels.

^d Uncertainty relative to the ground level.

^e Percentage compositions were determined by a parametric fit using Cowan's codes [31]. For unresolved terms, ranges of percentages are given when the percentages strongly differ for the fine structure levels. The percentage composition of the fine structure levels of these terms is given in Table 5.

the blended X-ray lines at 11.905 Å and 13.844 Å. Therefore, they form a quasi-isolated level subsystem with the lowest level 1s2s4p ⁴P^o_{1/2}. The position of this subsystem relative to the ground level can be determined from the observed Auger transition 1s2s2p ⁴P^o → 1s² ¹S₀ + e at 656.59 ± 0.10 eV (see Tab. 3). However, the uncertainty of this determination is too large compared with the uncertainties of the level separations within the quartet system. To determine the position of the quartet levels more accurately, we used an iterative procedure. As a first step, we found the energies of all quartet levels based on the experimental energy of the above-mentioned Auger transition.

Then, using the polarization formula, we derived the least-squares fitted value of the 1s2s ³S ionization limit from the experimental energies of the 1s2s(³S)nl ⁴L terms (nl = 4f, 6f, 7f, 7g, 7h, 7i, 8f, 8g, 8h, 8i, 8k, 9f, 9g, 9h, 9k, and 9l). The strongly perturbed 6g ⁴G and 6h ⁴H^o terms were excluded from the fit, and the slightly perturbed 8g ⁴G, 8h ⁴H^o, and 8i ⁴I terms were given a reduced weight of 0.2, while the weights of the other terms were inversely proportional to their experimental uncertainties and varied between 0.8 and 5. The resulting value of the limit turned out to be 9226148 cm⁻¹, the standard deviation being 15 cm⁻¹. This value, which represents the actual

Table 5. Percentage compositions for highly mixed Ne VIII terms with unresolved fine structure.

Configuration	Term	J	Energy (cm ⁻¹)	1st %	2nd %	Configuration	Term	3rd %	Configuration	Term
$1s2s(^1S)3d$	2D	3/2	8502000	68	15	$1s2p(^1P^\circ)3p$	2D	13	$1s2p(^3P^\circ)3p$	2D
		5/2		78	13	$1s2p(^1P^\circ)3p$	2D	5	$1s2p(^3P^\circ)3p$	2D
$1s2p(^3P^\circ)3p$	2D	3/2	8508000	77	21	$1s2s(^1S)3d$	2D			
		5/2		86	10	$1s2s(^1S)3d$	2D			
$1s2p(^3P^\circ)4p$	4P	1/2	8853300	99						
		3/2		59	39	$1s2p(^3P^\circ)4p$	4S			
		5/2		99						
$1s2p(^3P^\circ)4f$	4F	3/2	8864610	98						
		5/2		75	19	$1s2p(^3P^\circ)4f$	2F			
		7/2		53	33	$1s2p(^3P^\circ)4f$	2F	6	$1s2p(^3P^\circ)4f$	2G
		9/2		85	13	$1s2p(^3P^\circ)4f$	4G			
$1s2p(^3P^\circ)4f$	2F	5/2	8864960	72	15	$1s2p(^3P^\circ)4f$	4G	11	$1s2p(^3P^\circ)4f$	4F
		7/2		58	27	$1s2p(^3P^\circ)4f$	4F	13	$1s2p(^3P^\circ)4f$	4G
$1s2p(^3P^\circ)4f$	4G	5/2	8866380	80	11	$1s2p(^3P^\circ)4f$	4F	7	$1s2p(^3P^\circ)4f$	2F
		7/2		68	16	$1s2p(^3P^\circ)4f$	4F	13	$1s2p(^3P^\circ)4f$	2G
		9/2		82	15	$1s2p(^3P^\circ)4f$	4F			
		11/2		99						
$1s2p(^3P^\circ)4f$	2G	7/2	8867600	79	12	$1s2p(^3P^\circ)4f$	4G	8	$1s2p(^3P^\circ)4f$	2F
		9/2		94	5	$1s2p(^3P^\circ)4f$	4G			
$1s2p(^3P^\circ)4f$	4D	1/2	8869180	100						
		3/2		94						
		5/2		82	14	$1s2p(^3P^\circ)4f$	2D			
		7/2		95						
$1s2s(^3S)7i$	4I	9/2	9084870	100						
		11/2		61	39	$1s2s(^3S)7i$	2I			
		13/2		71	28	$1s2s(^3S)7i$	2I			
		15/2		100						
$1s2s(^3S)8i$	4I	9/2	9118707.6	99						
		11/2		60	38	$1s2s(^3S)8i$	2I			
		13/2		70	28	$1s2s(^3S)8i$	2I			
		15/2		98						
$1s2s(^3S)9l$	4L	13/2	9141564	100						
		15/2		62	37	$1s2s(^3S)9l$	2L			
		17/2		70	30	$1s2s(^3S)9l$	2L			
		19/2		100						
$1s2s(^3S)9i$	4I	9/2	9141623.2	100						
		11/2		61	39	$1s2s(^3S)9i$	2I			
		13/2		71	29	$1s2s(^3S)9i$	2I			
		15/2		100						
$1s2p(^3P^\circ)3d$	$^4D^\circ$	1/2	8515700	83	13	$1s2p(^1P^\circ)3s$	$^2P^\circ$			
		3/2		97						
		5/2		98						
		7/2		100						
$1s2p(^1P^\circ)3s$	$^2P^\circ$	1/2	8526000	65	17	$1s2p(^3P^\circ)3d$	$^4D^\circ$	8	$1s2s(^1S)3p$	$^2P^\circ$
		3/2		76	9	$1s2s(^1S)3p$	$^2P^\circ$			

Table 5. *Continued.*

Configuration	Term	J	Energy (cm^{-1})	1st %	2nd %	Configuration	Term	3rd %	Configuration	Term
$1s2p(^3P^\circ)4d$	$^4D^\circ$	1/2	8862700	98						
		3/2		91	7	$1s2p(^3P^\circ)4d$	$^4P^\circ$			
		5/2		82	15	$1s2p(^3P^\circ)4d$	$^4P^\circ$			
		7/2		98						
$1s2p(^3P^\circ)4d$	$^4P^\circ$	1/2	8864600	96						
		3/2		90	8	$1s2p(^3P^\circ)4d$	$^4D^\circ$			
		5/2		81	16	$1s2p(^3P^\circ)4d$	$^4D^\circ$			
$1s2s(^3S)6p$	$^4P^\circ$	1/2	9028350	43	55	$1s2p(^3P^\circ)5d$	$^4P^\circ$			
		3/2		45	51	$1s2p(^3P^\circ)5d$	$^4P^\circ$			
		5/2		50	44	$1s2p(^3P^\circ)5d$	$^4P^\circ$			
$1s2s(^3S)6h$	$^4H^\circ$	7/2	9034330	87	13	$1s2p(^3P^\circ)5g$	$^4H^\circ$			
		9/2		48	36	$1s2s(^3S)6h$	$^2H^\circ$	9	$1s2p(^3P^\circ)5g$	$^4H^\circ$
		11/2		62	21	$1s2s(^3S)6h$	$^2H^\circ$	12	$1s2p(^3P^\circ)5g$	$^4H^\circ$
		13/2		80	20	$1s2p(^3P^\circ)5g$	$^4H^\circ$			
$1s2s(^3S)7h$	$^4H^\circ$	7/2	9084924	99						
		9/2		53	46	$1s2s(^3S)7h$	$^2H^\circ$			
		11/2		76	24	$1s2s(^3S)7h$	$^2H^\circ$			
		13/2		100						
$1s2s(^3S)8k$	$^4K^\circ$	11/2	9118529	100						
		13/2		62	38	$1s2s(^3S)8k$	$^2K^\circ$			
		15/2		71	29	$1s2s(^3S)8k$	$^2K^\circ$			
		17/2		100						
$1s2s(^3S)8h$	$^4H^\circ$	7/2	9118780.5	98	2	$1s2p(^3P^\circ)6g$	$^4H^\circ$			
		9/2		54	43	$1s2s(^3S)8h$	$^2H^\circ$			
		11/2		73	24	$1s2s(^3S)8h$	$^2H^\circ$			
		13/2		96	4	$1s2p(^3P^\circ)6g$	$^4H^\circ$			
$1s2s(^3S)9k$	$^4K^\circ$	11/2	9141531.8	100						
		13/2		62	38	$1s2s(^3S)9k$	$^2K^\circ$			
		15/2		71	29	$1s2s(^3S)9k$	$^2K^\circ$			
		17/2		100						
$1s2s(^3S)9h$	$^4H^\circ$	7/2	9141637	100						
		9/2		55	45	$1s2s(^3S)9h$	$^2H^\circ$			
		11/2		80	19	$1s2s(^3S)9h$	$^2H^\circ$			
		13/2		100						

$1s2s\ ^3S$ limit plus the error in the position of the quartet level subsystem, should be compared to the more accurate theoretical result discussed below.

The $n = 2$ energy levels of helium-like ions were calculated by Plante et al. [72] using relativistic all-order many-body perturbation theory with QED corrections. Their value for the excitation energy of the $1s2s\ ^3S_1$ level of Ne IX is $7299823\ \text{cm}^{-1}$. Cheng et al. [73] used a relativistic configuration-interaction method with QED corrections to calculate the energies of the $n = 1$ and $n = 2$ singlet levels of helium-like ions. Although Cheng et al. [73] did not calculate the triplet levels, the differences between their results and those of Plante et al. [72] for the singlet levels can be used as an estimate of the uncertainties of the calculations. These differences are $60\ \text{cm}^{-1}$ on average. Combining the calculated excitation energy of the $1s2s\ ^3S_1$ level with the ionization energy of Ne VIII derived above

in Section 3.2, we obtain $9228270 \pm 60\ \text{cm}^{-1}$ for the $1s2s\ ^3S$ ionization limit of Ne VIII.

The second step of our iterative procedure consisted of fixing the energy of the $1s2s9l\ ^4L$ level at a value increased by $2122\ \text{cm}^{-1}$ from the experimental value used in the first iteration in order to compensate for the difference between the precisely calculated value of the $1s2s\ ^3S$ ionization limit and the one derived from the polarization formula. The $1s2s9l\ ^4L$ level was chosen because it has the largest number of observed transitions measured sufficiently accurately. Then the level optimization procedure was repeated, resulting in increased (and more accurate) energies of all quartet terms. The level optimization, rather than simple adding of the same correction to all levels, was necessary because the observed Auger transitions, despite their high uncertainties, make a noticeable contribution to the level energies.

At the third iteration, using the improved energy levels obtained at the second iteration, we easily identified the $1s2s4d\ ^4D - 1s2s6f\ ^4F^\circ$, $1s2s4f\ ^4F^\circ - 1s2s6g\ ^4G$, and $1s2s4f\ ^4F^\circ - 1s2s5g\ ^4G$ lines at 394.25 Å, 406.78 Å, and 626.63 cm⁻¹, respectively. Then the level-optimization procedure was repeated, taking into account the new identifications. The least-squares fitting of the $1s2s\ ^3S$ limit was repeated with the improved level energies. The resulting value of the limit was only 9 cm⁻¹ lower than the theoretical one.

At the fourth and final iteration we raised the $1s2s9l\ ^4L$ level by the above-mentioned 9 cm⁻¹, so that it was fixed at 9141564 cm⁻¹, repeated the level-optimization procedure, and made the final fitting of the $1s2s\ ^3S$ limit with the polarization formula. At this step we arrived at the same value of the limit as the theoretical one.

The uncertainty of the $1s2s9l\ ^4L$ level is dominated by the uncertainty of the adopted theoretical value of the $1s2s\ ^3S$ limit, which is ± 60 cm⁻¹. The highly-excited quartet levels are interconnected by a large number of long-wavelength lines. Therefore, their uncertainties are the smallest for the most highly excited levels and progressively increase as the energies decrease. For all quartet terms above (and including) $1s2s5f\ ^4F^\circ$, the uncertainties are between ± 60 cm⁻¹ and ± 140 cm⁻¹. Among the lower quartets, only $1s2s4f\ ^4F^\circ$, $1s2s4d\ ^4D$, and $1s2s3d\ ^4D$ have uncertainties this small. The other low-lying quartets, connected to the lowest term of the subsystem $1s2s2p\ ^4P^\circ$ by EUV lines, have uncertainties between ± 300 cm⁻¹ and ± 500 cm⁻¹.

The $1s2pnl$ quartet levels are connected to the $1s2snl$ quartets by observed VUV and EUV transitions to the $1s2s2p\ ^4P^\circ$ levels. Therefore, their uncertainties are dominated by the uncertainty of the latter and vary between ± 300 cm⁻¹ and ± 500 cm⁻¹.

The fine structure was resolved only for the lowest quartet terms $1s2s2p\ ^4P^\circ$ and $1s2p^2\ ^4P$. For the $1s2s8i\ ^4I$ term it was partially resolved due to the fact that an interaction with the $1s2p(^3P^\circ)6h$ configuration repelled the $J = 15/2$ level by 30 cm⁻¹ from the tight group of the other fine-structure levels of this term.

The energies of the doublet terms are based on the observed X-ray and Auger electron lines. Therefore, only a few of them have uncertainties smaller than 1000 cm⁻¹. The $1s3p^2\ ^2P$ and $2s^22p\ ^2P^\circ$ terms are determined from weak and broad X-ray lines and hence have very large uncertainties of 60000 cm⁻¹ and 30000 cm⁻¹, respectively.

The fine structure was not resolved for any of the doublet terms.

We calculated the percentage compositions of the core-excited levels by a parametric fitting of all known energy levels. The levels having uncertainties larger than 8000 cm⁻¹ were excluded from the fitting. For even-parity configurations, 47 distinct level values (not counting the repeated values for unresolved terms) were fit with 19 parameters with an average deviation of 520 cm⁻¹. For odd-parity configurations, 39 distinct level values were fit with 28 parameters with an average deviation of 800 cm⁻¹.

Although Cowan's codes were found by Kramida and Ivanov [25] to give worse results for the wavefunction compositions than the MZ code [73], the MZ-code calculations could not be extended to include the highly excited Rydberg states. Therefore, we give our present results for all levels in Table 4.

A number of terms having unresolved fine structure were found to have strong variations in the percentage compositions of their fine-structure levels. The percentage compositions of these levels are given in Table 5.

7 Conclusion

All available experimental data on the optical and Auger electron spectra of Li-like neon have been critically evaluated and compiled. Supplementing these data with selected theoretical and semi-empirical results, we have derived sets of recommended energy levels for valence-shell-excited and core-excited configurations of Ne VIII. For most of the EUV and VUV spectral lines and some of the Auger electron lines, the Ritz wavelengths and energy intervals derived from these recommended energy levels have much smaller uncertainties than the observed ones. Seventeen new lines have been identified in the VUV range. An accurate value of the ionization potential has been derived from existing theoretical data.

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