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Atomic Physics Studies of Highly Charged Ions on Tokamaks Using X-Ray Spectroscopy

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P. Beiersdorfer

*University of California, Lawrence Livermore National
Laboratory
Livermore, California 94550, USA*

S. von Goeler, M. Bitter, and K. W. Hill

*Princeton University, Plasma Physics Laboratory
Princeton, New Jersey 08543, USA*

Abstract

An overview is given of atomic physics issues which have been studied on tokamaks with the help of high-resolution x-ray spectroscopy. The issues include the testing of model calculations predicting the excitation of line radiation, the determination of rate coefficients, and accurate atomic structure measurements. Recent research has focussed primarily on highly charged heliumlike ($22 \leq Z \leq 28$) and neonlike ($34 \leq Z \leq 63$) ions, and results are presented from measurements on the PLT and TFTR tokamaks. Many of the measurements have been aided by improved instrumental design and new measuring techniques. Remarkable agreement has been found between measurements and theory in most cases. However, in this review those areas are stressed where agreement is worst and where further investigations are needed.

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1. Introduction

The spectroscopy of the x-ray line emission of highly charged ions plays a prominent role on present-day tokamaks.¹⁻⁴ High-resolution x-ray spectroscopy of highly charged ions provides crucial measurements of the ion temperature profile and the plasma rotation velocity.⁵⁻⁹ It is also used to measure the electron temperature profile, charge state distribution of impurity ions, transport phenomena, and the density profile of neutral hydrogen.¹⁰⁻¹⁵

The strong interest in the x-ray line emission of highly charged ions for plasma diagnostics has led to the development of precision spectroscopic instruments and is accompanied by the need to understand basic atomic physics issues. As a result, many important questions concerning the physics of highly charged ions have been investigated on tokamaks during the last decade following the development of high-resolution x-ray spectroscopy. Areas of investigation include precision atomic structure measurements, the testing of atomic physics models, and measurements of rate coefficients. Atomic physics investigations on tokamaks have been very fruitful because relevant parameters such as the electron temperature are accurately known from independent, nonspectroscopic measurements. Atomic physics models, therefore, can be tested under controlled conditions. The characteristics of tokamak plasmas are similar to those of solar flares. Hence analysis techniques developed for low-density, astrophysical plasmas^{16,17} can be applied to the study of highly charged ions in tokamaks. Atomic physics research on tokamaks is also aided by the capability to seed the plasma at precisely selected moments with any element of choice using fast gas valves or laser ablation.^{18,19} Moreover, the recent attainment of high electron temperatures has allowed the production and observation of very highly charged ions with net charges up to 53+.

In the following we discuss some of the aspects of the physics of highly charged ions which have been investigated with the help of high-resolution x-ray spectroscopy on tokamaks. We review new techniques and present recent measurements of highly charged heliumlike and neonlike ions from

the Princeton Large Torus (PLT) and the Tokamak Fusion Test Reactor (TFTR). We have given special attention to issues which are unresolved and which require further investigations before satisfactory agreement with theory is obtained.

The paper is organized as follows. In the next section a brief review of tokamaks, plasma parameters, and instrumentation used in x-ray spectroscopy is given. Recent investigations of the excitation mechanisms of heliumlike and neonlike ions are discussed in Section 3, and efforts are outlined which attempt to reconcile the measurements with atomic physics models. In Section 4 we focus on rate measurements. In Section 5 recent contributions to the atomic structure theory of highly charged ions are presented. In the concluding section we briefly outline areas of measurement which have not been considered but which are relevant for future studies.

2. Experimental Conditions

The plasmas in tokamak discharges are typically well diagnosed. A large assortment of plasma diagnostics measures such quantities as plasma current, magnetic oscillations, and density fluctuations.²⁰ Most important for atomic physics measurements are accurate determinations of the electron temperature and density. These measurements are reliably provided by laser scattering, microwave interferometry, x-ray pulse height spectrometry, and electron cyclotron emission.²⁰

Typical electron temperature and electron density profiles obtained with laser scattering on PLT are shown in Fig. 1. During ohmic heating the peak electron temperature in the center of PLT reaches 1—3 keV depending on plasma current, magnetic field, and electron density.²¹ The electron temperature can be increased considerably with auxiliary electron heating. In PLT peak temperatures in excess of 6 keV were attained with the addition of a modest amount of lower-hybrid wave heating.^{22,23} An electron temperature profile measured under such conditions is shown in Fig. 1. The line-averaged density is $1 \times 10^{13} \text{ cm}^{-3}$. The corresponding ion temperature ranges from 0.5

to 1.0 keV. Hence the broadening of a given x-ray line due to the Doppler effect ranges from $\lambda/\Delta\lambda \approx 3000-8000$ for elements below $Z=50$. Electron temperatures equal to or exceeding those on PLT have recently been achieved on TFTR. However, here high electron temperatures are attained as a by-product of ion heating. (Electron temperatures up to 8.5 keV and ion temperatures between 20 and 30 keV have been measured on TFTR in the so-called supersonic regime.^{7-9,24}) As a result, Doppler broadening of the x-ray lines increases significantly and can hamper the study of closely spaced lines because of overlap.

The attainment of high electron temperatures in tokamaks has allowed the production of very high ionization stages. In PLT we have been able to measure the x-ray transitions of neonlike europium (Eu^{53+}).²⁵ In Fig. 2 we have plotted the minimum central electron temperature which was necessary to detect $n = 3 \rightarrow 2$ x-ray line emission from an ion in the neonlike charge state on PLT with a bent-crystal spectrometer. The figure implies that it will be possible to observe neonlike ytterbium ($Z=70$) in plasmas with electron temperatures ≥ 10 keV. Such temperatures are presently within the range of TFTR and JET, and may be achieved in smaller tokamaks such as AS-DEX, DIII-D, T-10, or PLT by means of lower-hybrid or electron cyclotron-resonance heating.²⁶ At these temperatures we can also expect emission from heliumlike ions with $Z \approx 50$ or nickel-like ions with $Z \geq 92$.

Figure 1 shows that the electron temperature varies from several keV in the center to a few eV at the edge of the plasma. As a result, the plasma contains shells of ions whose charge states are decreasing from the inside out. This effect is illustrated in Fig. 3(a). The figure shows the charge state distribution of selenium calculated assuming coronal equilibrium for the temperature profile indicated. However, the radial ionization balance is not solely determined by ionization and recombination, as assumed in coronal equilibrium, but it is affected by ion transport, i.e., by radial ion motion and diffusion. The effect of including plasma transport in the ionization balance is shown in Fig. 3(b). Transport tends to broaden the spatial range (and thus the range in electron temperature) where a particular charge state is

located so that recombination can take place in colder plasma regions, and ionization in hotter regions, where the rates are higher in both cases, than without transport.²⁷

While the mechanisms leading to transport of electrons and ions in tokamak plasmas are still poorly understood, there is a large body of measurements of the transport parameters,²⁸⁻³³ so that the effect of transport on atomic processes can be adequately estimated from phenomenological transport models. Indeed, the profiles in Fig. 3(b) which have been calculated with a measured diffusion coefficient are in good accord with measured profiles of fluorinelike, neonlike, and sodiumlike selenium as shown in Ref. 15. Transport models could actually be improved, if atomic physics parameters, in particular ionization and recombination rate coefficients, were known with more certainty.

The instrumentation used to measure high-resolution x-ray spectra on tokamaks typically consists of bent-crystal spectrometers of the Johann^{10,34-39} or von Hámos^{13,40} type. Position-sensitive single- or multi-wire proportional counters are used for photon detection. The resolving power of these instruments typically equals or exceeds the x-ray line width due to Doppler broadening. Most crystal spectrometers operate in a low vacuum or helium atmosphere to avoid absorption by air and measure x rays below 5 Å. On PLT and TFTR we have used Johann-type bent-crystal spectrometers to measure high-resolution x-ray spectra of heliumlike ions in the range $18 \leq Z \leq 28$ and neonlike ions in the range $47 \leq Z \leq 63$. A new high-resolution ultra-soft x-ray (USX) spectrometer has been developed for use on PLT to study the wavelength region from 4–25 Å.¹⁵ The ultra-soft wavelength region was not accessible before with existing high-resolution spectrometers. The USX spectrometer uses a bent crystal in the Johann geometry, as other high-resolution spectrometers. However, the instrument uses a microchannel plate-intensified photodiode array for photon detection and operates in vacuo. The new instrument also has fast time resolution (4 msec per spectrum) and can scan the minor radius of the plasma. Examples of its use will be presented in Sections 3 and 4.

3. Study of the Excitation Processes

X-ray line emission can provide valuable information on the plasma which contains the emitting ions. For some plasmas such as laser-produced or astrophysical plasmas spectroscopy often is the only tool which gives access to the plasma properties. Hence a thorough understanding of the mechanisms which lead to x-ray line emission are paramount to the use of x-ray spectra for diagnostic purposes. Since the properties of tokamak plasmas are well known, x-ray line emission from tokamak plasmas can be used to perform careful tests of the atomic physics models used to interpret x-ray spectra.

In the next section we first discuss efforts to interpret x-ray spectra from heliumlike ions. Subsequently, we present new results on comparing tokamak spectra of neonlike ions with atomic models. In both cases considerable discrepancies between observations and model calculations are noted for specific transitions.

3.1. Heliumlike Ions

The x-ray spectra of highly charged heliumlike ions are the most studied on tokamaks. This is largely due to the stimulus provided by observations of similar spectra from the sun and by the concurrent development of a large theoretical database.^{16,17} X-ray spectra from heliumlike ions also have been exploited in fusion research for their great plasma diagnostics potential.¹ As a result of this interest, heliumlike spectra have now been observed in tokamaks from essentially all elements up to zinc ($Z=28$).⁴¹

Satellite spectra of heliumlike ions are understood the best. Extensive modelling efforts have shown that the satellite spectra can be explained by the two processes of dielectronic recombination and innershell excitation.⁴²⁻⁴⁶ In Fig. 4 the $n = 2 \rightarrow 1$ spectrum of heliumlike titanium ($Z=22$) measured on TFTR is shown together with a synthetic spectrum computed from recent theoretical predictions.^{44,47} As seen from the figure, data and the synthetic satellite spectrum are in excellent agreement.

The good agreement between data and theory for the satellite lines, however, does not carry over to the heliumlike lines, i.e., the resonance line w , the intercombination lines x and y , and the forbidden line z (using the notation of Gabriel¹⁶ to denote transitions from the levels 1P_1 , 3P_2 , 3P_1 , and 3S_1 , respectively). In Fig. 5 the observed line ratios x/w , y/w , and z/w are plotted as a function of electron temperature. The figure demonstrates that the theoretical calculations which include direct excitation, resonances, and radiative cascade contributions from levels $n \geq 2$ adequately describe the data only at high electron temperature $T_e \geq 1.2$ keV. At low temperature the discrepancies are as large as one order of magnitude. These results cannot be explained by recombination from hydrogenic titanium, which was left out in the calculations, because the line ratios are observed in the early phases of the discharge when the temperature is too low to ionize heliumlike ions in substantial amounts. On the other hand, the relative intensities of lines x , y , and z appear to be related to the abundance of lithiumlike ions.⁴⁴ This intimates that innershell ionization of lithiumlike ions may be the cause for the discrepancy with theory at low temperature. Innershell ionization, however, would only enhance line z . The enhancement of line ratio z/w is 0.1 at $T_e = 0.6$ keV and 0.03 at 2 keV for the measured abundance of lithiumlike ions. This enhancement is much too small to account for the observed discrepancies. Also, it cannot account for the anomalously large intensity of lines x and y . Other processes^{44,48,49} have been proposed which could, in principle, populate the triplet states, but so far none can explain the discrepancies given the conditions of the experiment.

While most observations of x-ray spectra of heliumlike ions have been made from Maxwellian plasmas, some observations have been made in plasmas which have a non-thermal component.⁵⁰⁻⁵³ In measurements of the x-ray spectrum of heliumlike titanium on the Doublet III tokamak during electron cyclotron heating an anomalously low intensity of line z was observed.^{52,53} The ratio $R = z/(x + y)$ was measured in the density range 2×10^{13} — 1.5×10^{14} cm⁻³ and found to decrease with increasing density. According to theoretical predictions R should not be density-sensitive for densities be-

low 10^{15} cm^{-3} . At the highest density R was an order of magnitude smaller than predicted. Similar to the large discrepancies with theory observed in Maxwellian plasmas, the anomalously low intensity of line z observed in non-Maxwellian plasmas challenges basic atomic physics to provide a satisfactory explanation.

Poor agreement between theoretical models which predict the relative line intensities of the heliumlike lines and measurements has also been noted for cases where radiative recombination of hydrogenic ions is a significant mechanism for the population of excited levels in heliumlike ions.^{8,54,55} In Fig. 6 we show two spectra of heliumlike iron which we have measured recently on TFTR.⁸ The spectrum in (a) has been recorded from the plasma center where recombination from Fe^{25+} is negligible; the spectrum in (b) was measured from a non-central region where recombination plays an important role because of rapid transport of hydrogenic iron from the center to cooler plasma regions. The spectra have been fitted to synthetic spectra using least squares. Good accord between data and calculations is found. However, the fit in Fig. 6(b) requires a substantially higher recombination rate coefficient than provided by theory. Further investigations are in progress.

The effect of recombination on the $n = 2 \rightarrow 1$ spectrum of heliumlike argon has also been studied in the Alcator C tokamak,^{54,55} and a rate coefficient five times larger than predicted was necessary to obtain quantitative agreement with the data. Although there were uncertainties in the models used due to approximations in the treatment of cascades from upper levels in heliumlike argon,⁵⁵ the results provide further evidence that the excitation mechanisms of the heliumlike lines are not yet fully understood and that some atomic physics parameters may need to be revised.

3.2. Neonlike Ions

X-ray spectra from neonlike ions are more complex and cover a much wider spectral region than heliumlike spectra. Nevertheless, the spectra are simple enough that reasonable progress can be made in their interpretation.

Interest in neonlike spectra originated from astrophysical observations, and the early detailed atomic models were developed to interpret the x-ray spectrum of neonlike iron in the sun.^{56,57} New studies have recently shown the usefulness of neonlike x-ray emission for diagnostic purposes in laser-produced plasmas and tokamaks.^{15,58,59} Interest in neonlike ions has also greatly intensified after the successful demonstration of x-ray amplification in neonlike selenium.^{60,61} These x-ray lasing experiments have clearly shown the need for a thorough understanding of the excitation mechanisms of neonlike ions.

High-resolution x-ray spectra of highly charged neonlike ions have been observed in tokamaks from titanium ($Z=22$) through europium ($Z=63$).^{11,25,62-65} A spectrum of neonlike selenium obtained on the PLT tokamak with the USX spectrometer mentioned in Section 2 is shown in Fig. 7. A Grotrian diagram of the neonlike lines observed in selenium is given in Fig. 8. Electric dipole transitions are labelled $3A$ — $3G$ according to the notation of Ref. 56. $M2$ represents the magnetic quadrupole transition $(2p_{3/2}^5 3s_{1/2})_{J=2}$ to the $2p^6 {}^1S_0$ ground state; $E2L$, $E2M$, and $E2U$ denote $3p \rightarrow 2p$ electric quadrupole transitions. These transitions are of importance in x-ray lasing experiments because their upper levels correspond to the levels which have exhibited the strongest lasing gain.^{60,61} The lines labelled $N47$, $F55$, and $F56$ represent $3d \rightarrow 2p$ electric dipole transitions in sodiumlike and fluorinelike selenium, respectively. These lines have been used in Ref. 15 together with the neonlike electric dipole transition $3d \rightarrow 2p$, labelled $3C$, to measure ion transport coefficients.

In order to study the temperature dependence of the line intensities of neonlike selenium, a new technique was employed in Ref. 65 which related Abel-inverted radial profiles of the spectral emission to the electron temperature profile. The temperature variation of the line ratio $3A/3C$ obtained with this technique is shown in Fig. 9. Here $3A$ represents the strongest $3p \rightarrow 2s$ electric dipole transition in neonlike selenium. Both lines are excited predominantly by electron collisions. The data appear to be in reasonable agreement with predictions from model calculations.^{64,66} The calculations take into ac-

count electron-impact excitation and radiative decay among the ground state and the 36 excited levels which have an excited electron in the $n = 3$ shell and a vacancy in the $n = 2$ shell. The temperature variation of the ratios of other neonlike lines is in similar agreement with the model calculations as that of the ratio $3A/3C$.⁶⁷

While the observed temperature variation is in reasonable agreement with theory, this is not true for the observed magnitude of some ratios. For example, the ratio of lines $M2$ and $3G$ in neonlike selenium (cf. Fig. 7) is measured to be twice as large as predicted by the model calculations. In contrast to lines $3A$ and $3C$, lines $M2$ and $3G$ are strongly fed by cascades from higher levels (direct excitation contributes less than 10 % to the total excitation of these lines in neonlike silver⁶⁴), and they can be excited by innershell ionization of sodiumlike ions and recombination from fluorinelike ions. Hence, it is presumed that excitation processes involving neighboring charge states play a significant role. We have found similar discrepancies between data and predictions for the line ratio $M2/3G$ also in neonlike germanium⁶⁸ and neonlike silver.⁶⁴ The results are summarized in Table I. As is the case for the heliumlike spectra, a satisfactory model which can account for the observed line intensities, given the plasma conditions in the experiment, has not yet been constructed.

4. Measurements of Rate Coefficients

Accurate (relative) rate coefficients can be inferred from the relative intensities of a given set of spectral lines provided the excitation mechanisms are well known. An example of this procedure is provided by a measurement of the dielectronic recombination rate for heliumlike iron in Ref. 47. Because the satellite spectrum of a heliumlike ion is well described by dielectronic recombination and innershell excitation, the dielectronic recombination rate can be inferred relative to the rate for direct excitation of line w from the intensity of the satellite structure.⁴⁷ However, as the discussion in Section 3 has shown, the excitation mechanisms of heliumlike or neonlike ions are

generally not well known. Therefore, accurate rates cannot be inferred from the x-ray spectra of these ions, unless the experimental conditions are chosen such that one particular excitation mechanism can be investigated at a time.

Recent developments in instrumentation have made it possible to identify and isolate individual excitation processes and thus have greatly enhanced the capabilities for measuring rate coefficients in tokamak plasmas. High-resolution x-ray spectrometers have typically viewed the center of the plasma along a fixed line of sight. However, recently spectrometers have been developed capable of viewing the plasma along different sightlines. For example, compact spectrometers which radially scan the plasma on a shot-to-shot basis have been installed on the Alcator C and PLT tokamaks.^{13,15} In a different approach, multiple sightlines are used for the vertical spectrometer on TFTR in order to view different regions of the plasma simultaneously.^{8,38} The profile information provided by these spectrometers has been used to isolate certain excitation mechanisms which have been obscured in sightline-integrated spectra. The development of a spectrometer with fast time resolution¹⁵ has made it possible to study transient phenomena in a single discharge and to identify individual population mechanisms which are blended in time-integrated spectra.

Using the radial scanning capabilities of a compact von Hámos spectrometer,¹³ Rice *et al.* have made measurements of the radial profiles of the transitions $1snp \rightarrow 1s^2$ with $3 \leq n \leq \infty$ on the Alcator C tokamak.^{14,55} The data have shown charge-exchange between intrinsic neutral hydrogen to populate high- n states of hydrogenic argon. In particular, charge exchange with neutral hydrogen populates the levels $n = 9, 10$, while charge exchange with excited hydrogen populates mainly levels $15 \leq n \leq 40$.¹⁴ Because this process is the dominant population mechanism for these high- n levels, uncertainties due to other population mechanisms are small. Thus, it was possible to use the measurements to provide the first estimate of the charge-exchange cross section involving excited hydrogen, i.e. for the process $\text{Ar}^{17+}(1s^2S) + \text{H}^*(n = 2, 3) \rightarrow \text{Ar}^{16+}(1snp^1P) + \text{H}^+$.

Time- and space-resolved measurements of the spectrum of neonlike se-

lenium on PLT (Fig. 7) have enabled us to estimate the effective innershell ionization rate of sodiumlike selenium.⁶⁵ Innershell ionization leaves the resulting neonlike ion in an excited state according to the process: $2p^63s + e \rightarrow 2p^53s + 2e$. This process, therefore, enhances the intensities of the neonlike transitions $3s \rightarrow 2p$, i.e., lines $3F$, $3G$, and $M2$ (cf. Fig. 8). Because these lines are also excited by a variety of other mechanisms, the contribution due to innershell ionization usually cannot be determined unequivocally. The problem was avoided by making measurements of the intensity profiles with 4 msec time resolution immediately following the injection of selenium into the plasma.⁶⁵ This procedure enabled us to relate the intensity variations of lines $3F$, $3G$, and $M2$ directly to the relative abundance of sodiumlike selenium under identical plasma conditions. The results are illustrated in Fig. 10. The figure shows that the relative intensities of lines $3F$, $3G$, and $M2$ are larger when a higher concentration of sodiumlike selenium is in the plasma. From these data we have been able to infer a value of 8.3×10^{-11} cm³/sec at $T_e = 2$ keV for the innershell ionization rate.⁶⁵ This value is 2.5 times larger than the value calculated by Sampson and Zhang in Ref. 69.

5. Precise Wavelength Measurements

A major concern of present-day atomic physics research is the development and testing of atomic structure theories which accurately describe relativistic and quantum electrodynamical (QED) effects in highly charged ions.^{70,71} These effects are particularly important for high- Z multi-electron ions where the treatment of electron correlations and the screening of radiative corrections introduces uncertainties into the calculations.⁷²

Tokamak plasmas provide good conditions for absolute measurements of the transition energies of highly charged ions. The electron density is low so that line shapes are unaffected by density effects; and Doppler shifts which affect spectra from vacuum spark plasmas or beam-foil interactions are virtually absent. Despite these advantages tokamak x-ray spectroscopy has mainly been employed to make precise measurements of transitions within

the same spectrum relative to each other. These measurements include measurements of the relative wavelengths of the x-ray transitions in helium-like argon,^{64,73} potassium,⁶⁴ scandium,^{65,73} titanium,^{6,8,44,65,74} vanadium,^{65,73} chromium,^{8,73,75} manganese,^{64,73} iron,^{8,42,64,76} and nickel.^{8,45,46} Similarly, x-ray spectroscopy has been used to measure the fine structure splitting of the hydrogenic lines $\text{Ly-}\alpha_1$ and $\text{Ly-}\alpha_2$ of argon,^{64,76} scandium,⁶⁵ titanium,^{65,77} chromium,⁶⁵ iron,⁶⁴ and nickel.⁴⁵ X-ray measurements thus complement measurements of the fine structure from observations of $\Delta n = 0$, $n = 2$ transitions in the ultraviolet region.⁷⁸⁻⁸⁰ Wavelength measurements have been made relative to reference lines from x-ray tubes only of the $n = 2 \rightarrow 1$ transitions in hydrogenic chlorine⁸¹ and argon⁸² on the Alcator C tokamak.

Recently we have utilized the capability of making precision relative wavelength measurements to measure wavelengths of heliumlike and neonlike x-ray transitions to within 0.1 mÅ or 30–50 ppm with respect to sets of hydrogenic reference lines which were recorded concurrently.^{25,64} This technique is illustrated in Fig. 11. The figure shows the location of observed x-ray transitions from heliumlike and neonlike ions in the wavelength region between 2.3 and 3.0 Å together with the location of the hydrogenic reference lines. The large number of hydrogenlike reference lines minimizes errors which arise from uncertainties in the dispersion of the spectrometer. The $\text{Ly-}\alpha$ lines of hydrogenic ions are suitable calibration lines, because their wavelengths can be calculated with high precision from first principles.^{83,84} Because we use hydrogenic lines as references, our measurements do not test the accuracy of theoretical predictions of the single-electron, hydrogenic lines, but they check the atomic structure calculations for multi-electron ions, which are less certain than those for hydrogenic ions.⁷²

A comparison of transition energies of the neonlike lines $M2$ and $3G$ measured on PLT for elements between $Z=47$ and 63 with multiconfigurational Dirac-Fock calculations which include QED corrections is shown in Fig. 12. The experimental energies are found consistently to be about 1.5 eV higher than predicted. This discrepancy has been attributed to ground state electron correlations which were estimated to increase the theoretical transition

energies by 1.7 eV.²⁵ For other transitions such as $3F$ or $3D$ (cf. Fig. 8) the estimated value of the ground state correlation correction, however, did not account for observed discrepancies.²⁵ Detailed, relativistic calculations of the electron correlations are needed to address this discrepancy.

The self-energy contribution to the energy of transitions in multi-electron ions has not yet been calculated from first principles.⁷² Thus its value remains uncertain, and measurements of the self-energy in multi-electron ions are needed to determine the size of the effect. In neonlike ions transitions of the type $3p \rightarrow 2s$ (lines $3A$ and $3B$, cf. Figs. 7 and 8) are the most affected by contributions from radiative effects.²⁵ Assuming that the Dirac energy, Breit interaction, vacuum polarization, and residual electron correlation energies can be calculated accurately, we can determine the self-energy contribution for these transitions from the experimental transition energies.⁶⁵ The results are listed in Table II. Here we have also listed self-energies calculated using an effective-charge approach.⁸⁵ This approach is an *ad hoc* method to account for screening of the nuclear potential. Also listed are the self-energies calculated from unscreened, bare hydrogenic wavefunctions.

Table II shows that the experimental values are closest to the hydrogenic self-energies. The error in the experimental value for the self-energy is dominated by the uncertainties in the calculated values of the residual electron correlation energies and may be as large as 0.7 eV.⁶⁵ However, even if the value of the residual correlation energy were reduced by 0.7 eV, the experimental values for the self-energy would on average exceed the screened values significantly. The result implies that present methods for estimating the self-energy in multi-electron ions are inadequate and that calculations from first principles are needed.

Systematic differences have also been observed between calculated transition energies for lines w of heliumlike ions and values measured on PLT. The measurements are described in Ref. 86. The transition energy of lines w in heliumlike potassium, scandium, titanium, vanadium, chromium, and iron were found to be consistently larger than predicted by several different types of calculations. The differences are plotted in Fig. 13 and are consistent with

differences noted by Deslattes⁸⁷ in an examination of data from accelerator facilities. The nature of the differences is not yet understood. The wavelengths of a large number of heliumlike resonance lines have recently also been measured in a vacuum spark source.⁸⁸

6. Conclusion

We have presented an overview of various physics aspects of highly charged ions which have been addressed recently on tokamaks: testing of atomic physics models, measurements of rate coefficients, and precise wavelength determinations. Our discussion has focussed on recent developments brought about by the achievement of high-electron-temperature plasmas, progress in instrumentation, and new measurement schemes.

Remarkable agreement between measurements and theoretical predictions can be noted in many areas of investigation. However, in this review we have placed special emphasis on atomic physics issues which are unresolved in the hope that this will stimulate new research. These issues concern the population mechanisms of excited levels in heliumlike and neonlike ions, the magnitude of the recombination rates, and multi-electron effects on the transition energies of highly charged ions.

There are a variety of issues which we have not addressed in this review. For instance, charge transfer between energetic neutral hydrogen and highly charged ions is a major process in neutral-beam-heated plasmas, and the polarization of x rays needs to be understood in tokamak discharges which have a non-Maxwellian component in the electron distribution function.

As the goal of ignition and burning is approached in controlled thermonuclear fusion research, diagnostics will be needed which provide information on the density, temperature, transport, slowing down, and confinement time of the 3.5-MeV alpha particles produced in the fusion reactions. Interactions of fast alphas with highly charged ions may provide the key for the development of such diagnostics. Such processes, however, still need to be identified.

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TABLE I. Comparison of theoretical and experimental intensity ratios of lines $M2$ and $3G$ for Ge^{22+} (Ref. 68), Se^{24+} (Ref. 67), and Ag^{37+} (Ref. 64). The theoretical values are from Ref. 66, and are calculated using a 37-level collisional-radiative model. The electron temperature assumed in the calculations is given in the last column and corresponds to the temperature of the measurements.

<i>Element</i>	<i>M2/3G</i>	<i>M2/3G</i>	<i>T_e</i> (keV)
	<i>Experiment</i>	<i>Theory</i>	
<i>Ge</i>	0.83	0.45	1.5
<i>Se</i>	0.80	0.41	2.0
<i>Ag</i>	0.74	0.38	3.0

TABLE II. Comparison of theoretical and experimental values for the self-energies of the $3p \rightarrow 2s$ transitions $3A$ and $3B$ in Ag^{37+} , Xe^{44+} , and La^{47+} . E_{measured} is the transition energy reported in Ref. 64 for silver and in Ref. 25 for xenon and lanthanum. The theoretical energies have been obtained from multiconfigurational Dirac-Fock calculations and are the same as in Ref. 25. E_{Coulomb} is the relativistic Coulomb energy, E_{Breit} is the transverse Breit correction, E_{VP} is the vacuum polarization energy, and E_C is the residual correlation energy. The experimental self-energy SE_{exp} is obtained by subtracting the theoretical energies from the measured transition energy. $\text{SE}_{\text{screen}}$ is the self-energy computed using the effective-charge approach, and SE_{bare} is the self-energy computed assuming bare, unscreened hydrogenic wavefunctions.

<i>Transition</i>	<i>Element</i>	E_{measured} (eV)	E_{Coulomb} (eV)	E_{Breit} (eV)	E_{VP} (eV)	E_C (eV)	SE_{exp} (eV)	$\text{SE}_{\text{screen}}$ (eV)	SE_{bare} (eV)
$3A$	<i>Silver</i>	3646.54	3654.93	-3.73	+0.45	-0.90	-4.2	-3.5	-4.6
	<i>Xenon</i>	5039.93	5053.18	-6.09	+0.86	-0.91	-7.1	-5.9	-7.6
	<i>Lanthanum</i>	5721.21	5737.04	-7.37	+1.11	-0.92	-8.7	-7.3	-9.5
$3B$	<i>Silver</i>	3598.47	3605.64	-2.98	+0.44	-0.90	-3.7	-3.5	-4.6
	<i>Xenon</i>	4949.20	4961.57	-4.84	+0.84	-0.91	-7.5	-6.0	-7.7

Figures

FIG. 1. Electron temperature profiles measured with Thomson scattering on the PLT tokamak. The discharge parameters are (a) open circles: ohmic heating only, hydrogen plasma, $I_P = 450$ kA, $B_T = 31.3$ kG; (b) solid circles: Lower-hybrid heating with $P_{LH} = 650$ kW, hydrogen plasma with some neon component, $I_P = 530$ kA, $B_T = 31.4$ kG. The line-averaged density for each case is 1×10^{13} cm $^{-3}$. The electron density profile is shown in the inset.

FIG. 2. Minimum central electron temperature necessary to detect x-ray line emission from neonlike ions of atomic number Z with the PLT high-resolution Bragg-crystal spectrometer. The line-averaged electron density in each case is 1×10^{13} cm $^{-3}$. The solid line is drawn as a visual aid only.

FIG. 3. Radial distribution of selenium ions in PLT for the measured electron temperature profile shown. (a) profiles calculated assuming coronal equilibrium; (b) profiles calculated assuming a diffusion coefficient $D = 5 \times 10^3$ cm 2 /sec.

FIG. 4. Satellite spectrum of Ti XXI, Ti XX, and Ti XIX. The notation used is that of Gabriel.¹⁶ The data have been recorded with a high-resolution Bragg-crystal spectrometer on TFTR. The plasma parameters are $T_e(0) = 1.8$ keV, $n_e(0) = 2.7 \times 10^{13}$ cm $^{-3}$, $I_P = 1$ MA. The solid curve in (a) represents a theoretically predicted spectrum. The contributions from various processes are shown in (b)-(d). The theoretical intensities for lines x , y , and z in (b) only include direct excitation from the ground state.

FIG. 5. Comparison of the measured relative intensities of the triplet lines x , y , and z in heliumlike titanium (points) with calculations which include direct excitation, cascade feeding, and contributions from resonances. The data were obtained from TFTR plasmas at the major and minor radii indicated.

FIG. 6. Satellite spectra of Fe XXV, Fe XXIV, and Fe XXIII observed on TFTR with $n_e(0) = 1.5 \times 10^{13} \text{ cm}^{-3}$ and $I_P = 0.7 \text{ MA}$. The notation is that of Gabriel.¹⁶ Unlike the spectrum in (a) the spectrum in (b) is recorded during a time interval when significant amounts of Fe XXVI are in the plasma.

FIG. 7. Spectrum of neonlike selenium covering the wavelength region 7.20--9.00 Å. The spectrum was recorded on PLT with a vacuum crystal spectrometer in the Johann geometry. All neonlike transitions as well as the sodiumlike transition *N*47 and the fluorinelike transitions *F*55 and *F*54 have been labelled. The unmarked features are due to transitions in sodiumlike, fluorinelike, and oxygenlike selenium. The spectrum is a composite of four individual spectra joined at the wavelengths indicated by the solid triangles.

FIG. 8. Grotrian diagram of selected energy levels in Se XXV. Levels have been designated using jj coupling, i.e., $(j_1, j_2)_J$, where j_1 , j_2 , and J are the angular momentum of the core state and of the excited electron, and the total angular momentum, respectively. Transitions to the ground state are labelled using the same notation as in Fig. 7.

FIG. 9. Relative intensity of line 3A in neonlike selenium versus electron temperature. The theoretical intensity has been calculated by a 37-level collisional-radiative model.⁶⁶ The intensity of line 3A is normalized to the intensity of line 3C.

FIG. 10. Variation of the relative intensities of the $3s \rightarrow 2p$ transitions *3F*, *3G*, and *M*2 in Se XXV with the relative abundance of Se XXIV.

FIG. 11. Overview of x-ray transitions observed in the wavelength region 2.30--3.00 Å showing the location of spectra from hydrogenlike, heliumlike, and neonlike ions. The hydrogenlike lines are used as wavelength references.

FIG. 12. Comparison of measured and calculated energies for transitions $(2p_{3/2}^5 3s)_{J=1,2} \rightarrow 2p^6$ in various neonlike ions. The transitions are labelled $3G$ and $M2$, respectively.

FIG. 13. Differences in transition energies between data obtained on PLT and calculations for the transition $1s2p\ ^1P_1 \rightarrow 1s^2\ ^1S_0$ in various heliumlike ions. The calculations are by: (a) Indelicato, Ref. 89; (b) Drake, Ref. 90; and (c) Vainshtein and Safronova, Ref. 91.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

#87X1229

Fig. 7

Fig. 8

Fig. 9

Fig. 10

Fig. 11

Fig. 12

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