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Abstract. Recent measurements of the K-shell and L-shell x-ray spectra of highly charged heliumlike and neonlike ions are presented that were performed on the Livermore electron beam ion traps and the Princeton tokamaks. These measurements provide new insights into collisional and indirect line formation processes, identifications of forbidden lines, and a new plasma line diagnostic of magnetic field strength.

INTRODUCTION

The x-ray spectra of heliumlike and neonlike ions provide excellent diagnostic opportunities of high-temperature plasmas, including those found in magnetic and inertial confinement fusion research, the Sun, stellar coronae, supernova remnants, galaxy clusters, and cometery comae. These spectra are now commonly used to measure such parameters as the plasma density, temperature, bulk motion, opacity, and ionization balance. Despite this widespread use and the ensuing familiarity with the spectral emission, continued investigation of the spectra and the underlying atomic physics still offers surprises.

In the following we present several examples of new insights gained in recent studies of the x-ray spectra of heliumlike and neonlike ions. The studies were carried out at the EBIT-I and EBIT-II electron beam ion traps at the Lawrence Livermore National Laboratory and at the National Spherical Tokamak Experiment (NSTX) facility at the Princeton Plasma Physics Laboratory. Our studies of heliumlike ions include the identification of the lithiumlike $1s2s2p\ {}^4P_{5/2} \rightarrow 1s^22s\ {}^2S_{1/2}$ magnetic quadrupole line in the K-shell satellite spectrum of heliumlike Ar^{16+}, which has generally been overlooked in past analyses of tokamak spectra. We also present high-resolution measurements of the K-shell x-ray emission produced by charge exchange between plasma ions and cold neutrals. These measurements were carried out with the Goddard Space Flight Center high-resolution x-ray microcalorimeter. The measurements show that a description of the resulting x-ray emission requires capture cross sections into individual atomic levels and that statistical assumptions for populating angular momentum states used in cometary x-ray models are insufficent for proper description.

Our measurements of the L-shell spectra of neonlike ions have revealed what we believe are the first x-ray lines that are sensitive to the magnetic field. These lines can be used as magnetic field diagnostic of low-density high-temperature plasmas. Moreover, our measurements resolved many questions surrounding the relative intensities of $3d \rightarrow 2p$ and $3s \rightarrow 2p$ transitions in neonlike ions. The puzzles surrounding these lines ratios had resulted in wide speculation on possible physical processes left out in the modeling calculations. For example, the discrepancy between solar observations and models had been attributed to opacity effects. This, however, could be ruled out when our measurements on the opacity-free Princeton tokamaks found the same ratios as in the Sun and other stellar coronae. Combined with measurements on EBIT-I and EBIT-II, our measurements demonstrated instead that most of the discrepancy was due to a systematic overestimate or underestimate of the relative excitation rates in the available calculations. Our electron beam ion trap measurements showed that the remainder was due to blending with lines whose existence had been missed in many recent calculations.

The present measurements should encourage continued investigations on tokamaks and electron beam ion traps to resolve further puzzles in the x-ray spectra of highly charged ions in high-temperature plasmas.

K-SHELL SPECTRA OF HELIUMLIKE IONS

Beginning with early measurements on tokamaks and the Sun [1, 2, 3, 4, 5, 6], the K-shell spectra of heliumlike ions are probably by now the most studied high-resolution x-ray spectra from high-temperature collisional plasmas. The following examples highlight two recent advances in our understanding these spectra.

Identification of the $1s2s2p\ ^4P_{5/2} \rightarrow 1s^22s\ ^2S_{1/2}$ magnetic quadrupole line among the heliumlike K-shell satellite lines

Gabriel, in his fundamental work on the K-shell satellite lines to the x-ray emission lines of heliumlike ions, reserved 22 letters of the alphabet (*a*–*v*) for labeling all electric-dipole allowed lithiumlike transitions [7]. He used the remaining four letters (*w*–*z*) to label the heliumlike lines. One possible transition in lithiumlike ions was not labeled. This was the dipole-forbidden magnetic quadrupole transitions $1s2s2p\ ^4P_{5/2} \rightarrow 1s^22s\ ^2S_{1/2}$.

Many, though not all, lithiumlike satellite lines have been identified in the K-shell spectra of heliumlike ions from tokamaks or the Sun. Others have been observed in high-density laser-produced plasmas. The $1s2s2p\ ^4P_{5/2} \rightarrow 1s^22s\ ^2S_{1/2}$ magnetic quadrupole (M2) line has eluded identification, however. Although it was observed in time-delayed beam-foil spectroscopy [8, 9], resulting in the measurements of the lifetime of its upper level, it was thought to be too weak to be seen in collisional plasmas.

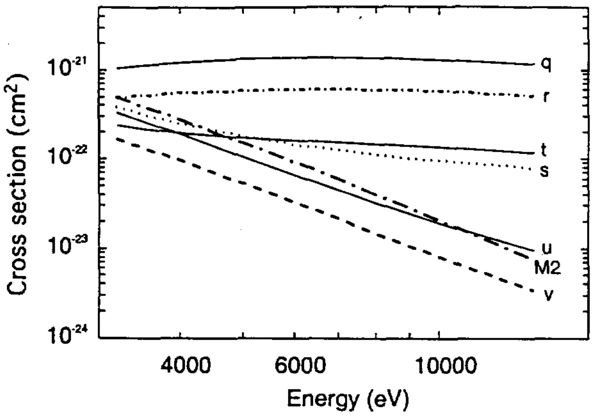

FIGURE 1. Electron-impact excitation cross sections for populating the upper levels of the lithiumlike innershell satellite lines *q*, *r*, *s*, *t*, *u*, *v*, and the $1s2s2p\ ^4P_{5/2} \rightarrow 1s^22s\ ^2S_{1/2}$ quadrupole line, labeled *M*2. (From [11].)

Excitation by dielectronic recombination is essentially non-existent because of the small radiative and Auger rates associated with the forbidden decay of the $1s2s2p\ ^4P_{5/2}$ level. Morever, the level decays predominantly by Auger decay. However, it turns out that electron-impact excitation is very effective in populating the $1s2s2p\ ^4P_{5/2}$ level close to threshold [10]. In fact, in lithiumlike Ar^{15+} it is second only to the excitation of the resonance line *q*, intimating that the line may be seen in low-temperature, low-density plasmas where electron collisions near threshold dominate the excitation process, as illustrated by a distorted wave calculation of the electron-impact excitation cross sections shown in Fig. 1.

By analyzing relatively cold spectral data from the Princeton NSTX tokamak in comparison with measurements on the Livermore EBIT-II electron beam ion trap where electron-impact excitation near threshold was the only excitation mechanism, we were able to identify the line in the K-shell spectrum of Ar^{16+} [11], as shown in Fig. 2.

Heliumlike x-ray spectra excited by charge exchange

The heliumlike K-shell spectra from non-collisional plasmas have received much less attention in the laboratory, including charge-exchange produced spectra which have now found an important application in understanding cometary x-ray emission [12]. Crossed-beam experiments generated extensive charge-exchange cross sections using particle counting techniques, but they did not record the x-ray emission. By contrast, some x-ray measurements were reported from tokamaks where charge exchange contributed to various extent to the excitation of K-shell spectra [13, 14, 15, 16]. K-shell x-ray spectra produced purely by charge-exchange, however, have not been reported until recently, when we started using the Livermore electron beam ion traps to measure charge-exchange produced spectra [17, 18, 19].

High-resolution measurements of charge-exchange produced x-ray emission were

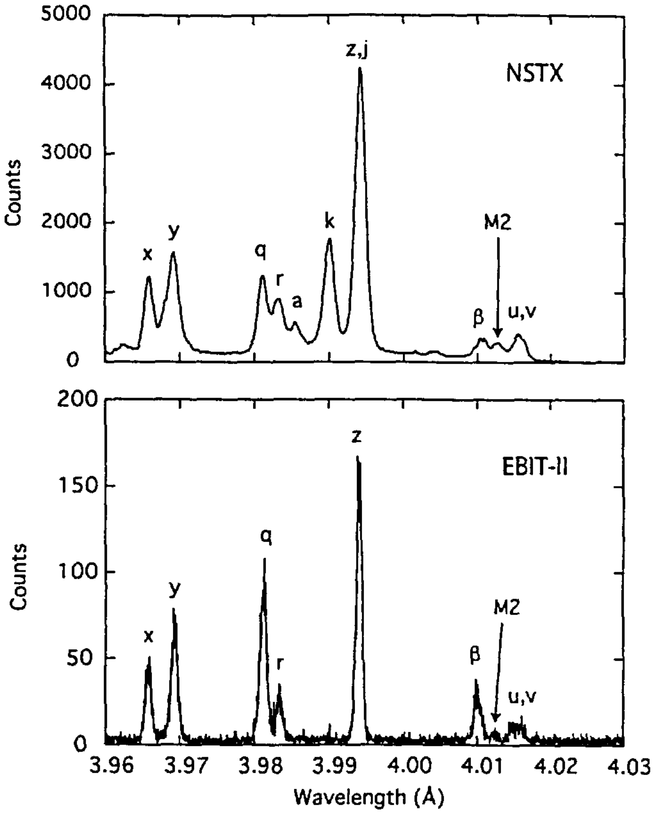

FIGURE 2. K-shell emission spectrum of argon. Top: obtained with the von Johann crystal spectrometer on NSTX. This spectrum shows the Ar^{16+} lines x, y, and z, the Ar^{15+} lines a, j, k, q, r, u, v, and the $M2$ line, and the Ar^{14+} line β. The spectrum was obtained at a plasma temperature of about 700 eV. Bottom: obtained with the von Hámos crystal spectrometer on EBIT-II. Only collisionally excited lines are seen; the dielectronic satellite lines (a, j, and k) are absent. The spectrum was obtained at a constant electron beam energy 200 eV above threshold for electron-impact excitation where dielectronic resonances cannot be excited. (From [11].)

enabled on the Livermore EBIT-I and EBIT-II electron beam ion traps through the use of the Goddard Space Flight Center high-resolution x-ray microcalorimeter [20]. The x-ray emission from Ne^{8+} following charge exchange between Ne^{9+} and neutral neon is shown in Fig. 3.

The $np \rightarrow 1s$ emission from levels with principal quantum number $n \geq 3$ is not very bright. It is, however, stronger than predicted by early models developed for describing cometary x rays [21]. In fact, the early x-ray models predicted the $1s2p\ ^1P_1 \rightarrow 1s^2\ ^1S_0$ resonance transition, labeled w by Gabriel [7], to be the only emission. Our measurements show that this is not correct. This line is neither the only line, nor is it the strongest. Instead, the $1s2s\ ^3S_1 \rightarrow 1s^2\ ^1S_0$ forbidden transition (line z) is the strongest line produced. A subsequent model based on equipartition of the x-ray emission [22] is just as poor in predicting the correct x-ray emission.

Recently, we were also able to record charge-exchange produced spectra on the NSTX tokamak. This was possible because the line of sight of the NSTX high-resolution crystal

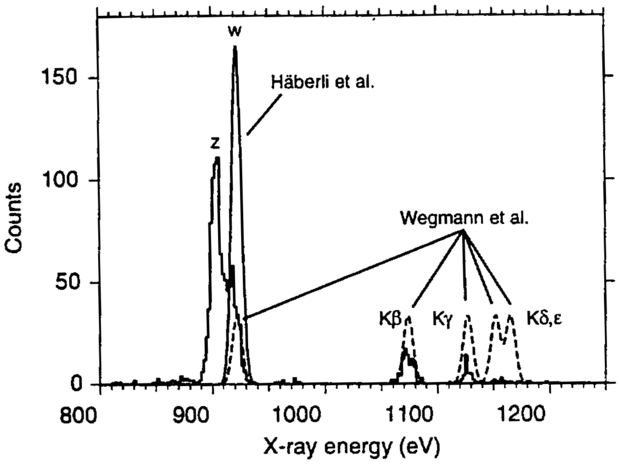

FIGURE 3. K-shell emission spectrum of Ne^{8+} produced by charge exchange between neutral neon and Ne^{9+} ions. The measurements were made with the Goddard microcalorimeter on EBIT-II. Also shown are the predictions from [21] and [22]. The ion-neutral interaction energy was about 150 ± 100 eV.

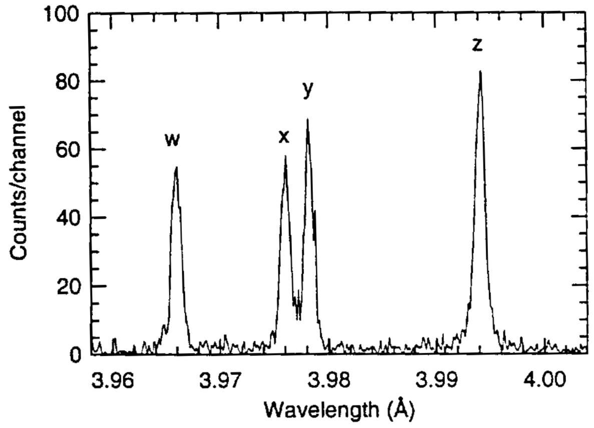

FIGURE 4. K-shell emission spectrum of Ar^{16+} produced by charge exchange between atomic hydrogen and Ar^{17+} ions. The measurements were made with the Johann crystal spectrometer on NSTX. The ion-neutral interaction energy is 80 keV for the dominant hydrogen component in the neutral beam.

spectrometer crosses the path of the diagnostic neutral beam injector [23]. The spectrum in Fig. 4 shows the emission of Ar^{16+} produced by the reaction of Ar^{17+} with H. The interaction energy was 80 keV (full energy). This contrasts with a (thermal) interaction energy of about 150 ± 100 eV in the EBIT-I experiments above involving neon.

L-SHELL SPECTRA OF NEONLIKE IONS

L-shell x-ray spectra are much more complex than the K-shell spectra of heliumlike ions and therefore offer the possibility of greater diagnostic utility. However, these spectra have not been as intensely studied, and therefore their diagnostic utility is still rather

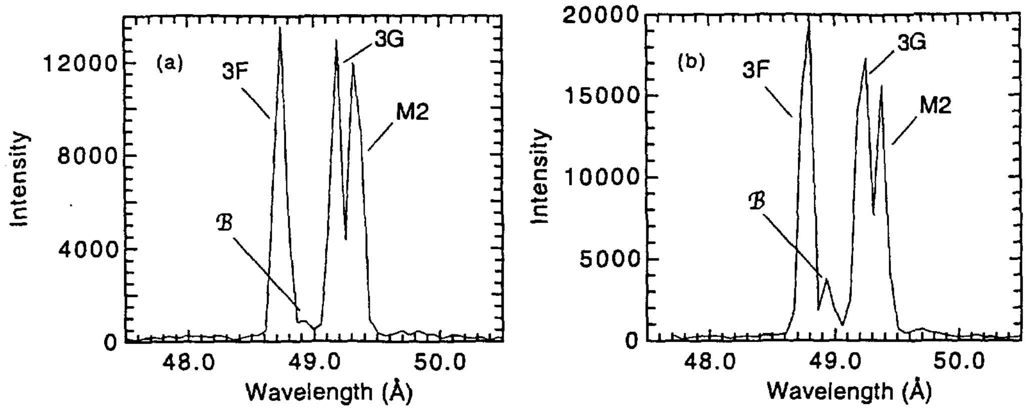

FIGURE 5. Spectra of the Ar^{8+} $3s \rightarrow 2p$ emission for different magnetic field values: (a) $B = 1$ T, (b) $B = 3$ T. The spectra were obtained on EBIT-II. (From [24].)

limited. New discoveries are readily made, as we illustrate by showing that neonlike lines can be used as a magnetic field diagnostic. Moreover, our measurements illustrate that theory has not been able to give a reliable model of the observed spectra.

Magnetic field x-ray diagnostic for high-temperature plasmas

Measurements of magnetic fields embedded in astrophysical plasmas have relied on measuring the line splitting in the optical caused by the Zeeman effect. X-ray lines typically split much less than optical lines, and this technique cannot be used. To our knowledge there are currently no x-ray line diagnostics of magnetic field strength.

Using the Livermore electron beam ion trap we showed that the $(2p^5_{1/2}3s)_{J=0}$ level can decay to the $2p^6_{J=0}$ neonlike ground state provided there is a sufficiently strong magnetic field. In the absence of a magnetic field this decay channel is strictly forbidden. In the presence of a field, the $(2p^5_{1/2}3s)_{J=0}$ level mixes with the neighboring $(2p^5_{1/2}3s)_{J=1}$ level, making decay to the ground state possible [24]. A comparison of the L-shell emission of neonlike Ar^{8+} recorded in a high (3 T) and low (1 T) field is shown in Fig. 5. The magnetic field induced line, labeled $\mathcal{B}$ is clearly seen in the high field case. The ratio of this line to that of the $(2p^5_{1/2}3s)_{J=1} \rightarrow 2p^6_{J=0}$ resonance line (labeled $3F$ in Fig. 5) is sensitive to the magnetic field. This ratio is shown for Ar^{8+} in Fig. 6. The principle behind this line diagnostic applies to all neonlike ions, and thus higher magnetic fields can be measured with higher-Z neonlike ions.

Resolving puzzles in L-shell diagnostic line ratios

The L-shell x-ray spectra of neonlike ions have posed several puzzles over the years that have not been resolved by theory. One such puzzle concerned the ratio of the $(2p^5_{1/2}3d_{3/2})_{J=1} \rightarrow 2p^6_{J=0}$ resonance line, labeled $3C$, to that of the $(2p^5_{3/2}3d_{5/2})_{J=1} \rightarrow$

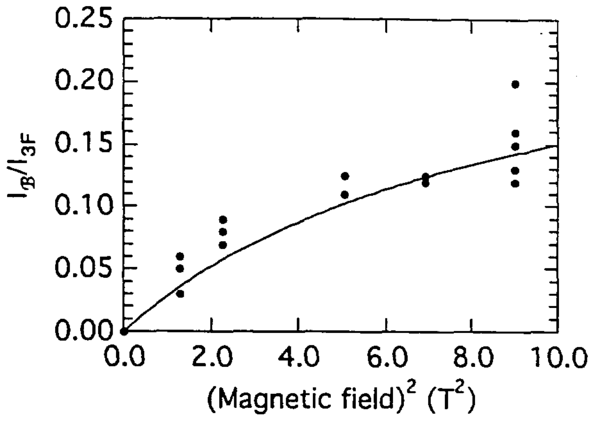

FIGURE 6. Intensity of the magnetic field induced line $\mathcal{B}$ relative to that of the *3F* line as a function of the square of the applied magnetic field in EBIT-II. The line is drawn to guide the eye. The scatter in the data represents the statistical uncertainty of each measurement. (From [24].)

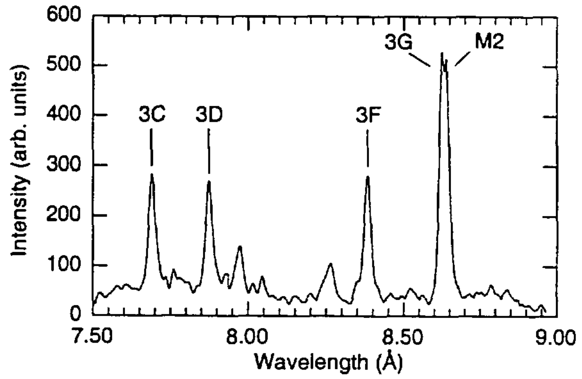

FIGURE 7. L-shell emission spectrum of Se XXV recorded with the vacuum flat-crystal spectrometer on the PLT tokamak. The spectrum represents the sum of 17 similar discharges. (From [26].)

$2p^6_{J=0}$ intercombination line, labeled *3D*. This ratio was observed to be consistently smaller than predicted when studying astrophysical plasmas and the Sun. This led to the hypothesis that resonant scattering of the *3C* line causes a reduction in its intensity. In other words, it was assumed that this line was optically thick compared to the *3D* line.

Systematic studies of this line ratio along the isoelectronic sequence both with our electron beam ion traps and with the Princeton Large Torus tokamak have shown that opacity does not need to be invoked to explain the solar and astrophysical observations [25, 26]. A typical spectrum of neonlike Se^{24+} recorded on the Princeton Large Torus is shown in Fig. 7.

Opacity effects play neither a role in an ion trap nor in a tokamak. Yet the observed ratios reproduced those of astrophysical and solar plasmas. The reason is that collisonal excitation calculations clearly overestimated this ratio. This is demonstrated in Fig. 8,

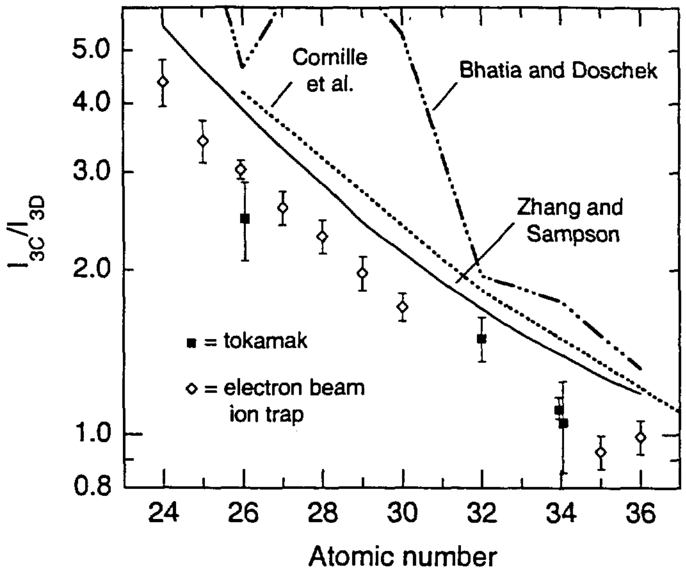

FIGURE 8. Comparison of the ratios measured on the EBIT-II electron beam ion trap (open diamonds) [25] and the PLT tokamak (closed squares) [26] with theory values from Zhang *et al.* (solid line) [29], Cornille *et al.* (dotted line) [30], and Bhatia *et al.* (dot-dashed line) [31]. (From [26].)

which compares the ratios measured in the laboratory to various calculations. In cases where the solar or astrophysical line ratio is even smaller than the laboratory ratio, the differences could be attributed to line blending with a sodiumlike transition that perfectly coincides with line 3*D* [27, 28].

The ratio of the intensity of the $3s \rightarrow 2p$ transitions to those of the $3d \rightarrow 2p$ transitions in neonlike Fe^{16+} ions was found to be much larger in astrophysical plasmas than predicted by model calculations. The difference was roughly a factor of two. A measurement of this ratio in the laboratory using the NIST electron beam ion trap claimed to demonstrate that the modeling calculations were correct [32]. The authors, therefore, invoked yet-to-be-determined mechanisms that would bring the calculations to the level observed in the astrophysical sources. Needless to say, finding such mechanisms should be paramount to any spectral studies of the Sun and deep-space plasmas.

Using the Livermore electron beam ion trap, we have made careful studies that disprove the NIST claims. Our laboratory measurements of this ratio utilized not only crystal spectrometers, but also the Goddard microcalorimeter and a grating spectrometer. All three instruments provided measurements that agreed very well with the ratios observed in the Sun and other astrophysical objects, such as the stars Capella and HR 1099 as well as the galaxy NGC 4636 [28, 33, 34, 35, 36, 37, 38]. The comparison is shown in Fig. 9. Following our laboratory measurements, no additional mechanisms are needed to explain the extraterrestrial observations.

As Fig. 9 shows, there is no substitute for careful laboratory measurements. Measurements of this ratio in Fe^{16+} are now planned on the NSTX tokamak with a new high-resolution crystal spectrometer.

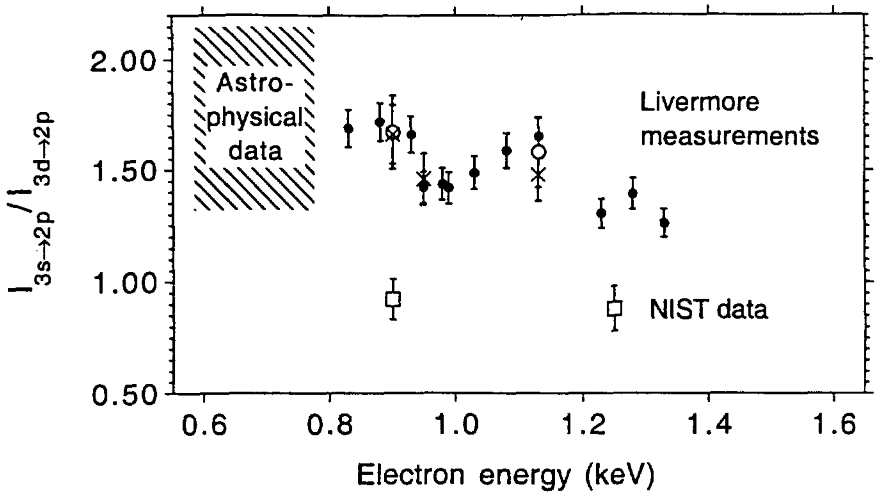

FIGURE 9. Measured $3s \to 2p$ to $3d \to 2p$ line intensities versus electron energy. Livermore data [39]: solid circles – Goddard X-ray calorimeter; crosses – crystal spectrometer; open circles – grating spectrometer. NIST results [32]: open squares – Harvard-Smithsonian calorimeter. Also shown are observational values. The energy scale on the x-axis should be disregarded for these. In collisional ionization equilibrium, the Fe XVII emission is dominated by collisions with electrons near excitation threshold, i.e., the region shown. (From [39].)

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