

# EUV Line Identifications and Lifetime Measurements in Highly Charged Iron Ions

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## Abstract

When beam-foil experiments on ions of the iron group were done at the Bochum Dynamitron tandem accelerator, line identifications of intercombination lines in Mg- and Al-like Fe matched previously unclassified lines that appear in the EUV spectrum of the solar corona. Beam-foil work continued on Si- to Cl-like Fe ions, identifying in particular decays of high- $J$  levels with nanosecond lifetimes. Millisecond lifetimes in the same ions were then measured at a heavy-ion storage ring and at an electron beam ion trap. Remaining problems and prospects for solutions are discussed.

## 1. Introduction

Some sixty years ago, Bengt Edlén by a laboratory experiment [1] confirmed Grotrian's suggestion to the nature of some of the visible corona lines, by showing the coincidence of some of the transition energies with fine structure intervals in the ground configurations of highly charged ions of iron group elements. This recognition implied a corona that is much hotter than the underlying solar surface layers and revolutionized our models of the sun. In such a hot environment, most atomic species are highly ionized, and most radiation of such ions is in the X-ray and EUV ranges that are not observable through Earth's atmosphere. Even as highly charged ions were produced in various spark and early fusion test plasma sources, collision rates usually were too high to observe the low-rate radiative transitions (magnetic dipole, M1, and electric quadrupole, E2, the so-called electric-dipole *forbidden*) transitions in these terrestrial light sources. The situation changed with the appearance of sounding rockets and satellites that were to observe Sun from outside Earth's atmosphere (for observations of the corona and of solar flares in the EUV to VUV wavelength ranges, see, for example, [2–8]). Around the same time on Earth, the dilute, hot plasmas of tokamaks then also permitted the study of intercombination and forbidden lines [9, 10].

Concurrently, computer codes were developed to help with systematic spectroscopic studies; such computer algorithms converge more easily for an atomic potential dominated by a central charge, that is for highly charged ions. However, multi-electron ions have complex spectra, and neither are observations complete nor are calculations sufficiently precise. In observations, the relative line intensities may depend on the environmental conditions in the light source, a fact which is being used as a diagnostic tool wherever possible. However, that environmental influence implies that certain (otherwise long-lived) levels may be collisionally quenched and therefore their radiative decay may become invisible. Another serious problem is the fact that in most terrestrial light sources there are contaminations (sometimes wanted), while the solar corona anyway contains many elements

with their natural abundances. Consequently, it is often not obvious which element (and in which charge state) gives rise to a particular solar spectral line. A considerable number of line identifications in the coronal EUV spectra are based on chance wavelength coincidences with laboratory data, not on a consistent physical model. These line identifications need to be reviewed eventually. (For low charge states of iron, hollow-cathode spectra at Lund at least indicate that many solar UV lines belong to this element [11].)

Parameter variations in the running of terrestrial light sources go only part of the way towards helping line identification, although a combination of the various light sources, solar corona, tokamak and the more recent laser-produced plasma can achieve a very wide coverage of densities and excitation conditions. Two particular light sources with very different properties have notably complemented the traditional spectroscopic tool box of arcs, sparks and plasma discharges, and these are the foil-excited fast ion beam (and its derivative techniques of beam-foil, beam-gas, beam-laser spectroscopy, and, lately, heavy-ion storage ring techniques), and more recently the electron beam ion trap (EBIT).

Fourty years after its inception [12–14], beam-foil spectroscopy is still a valuable and unique tool for purposes quite similar to those outlined in one of the earliest publications from the field [14]. That light source offers isotopic purity (a spectral line seen is from a given element), clues to the ionic charge state via a beam-energy variation, and intrinsic time resolution, which is used for time-differential spectra and for lifetime measurements [15–17]. The drawback of this light source is the usually poorer spectral resolution and wavelength accuracy in survey measurements (due to the low light level and to Doppler broadening and shifts), compared to stationary light sources like the tokamak or the solar corona. A particular extension of the fast ion beam technique is the observation of stored ion beams in a heavy-ion storage ring, enabling the measurement of decay rates of some of those very long-lived levels that decay only via electric-dipole forbidden transitions [18–20]. These measurements complement experiments using other types of ion traps [21], for example, using an electrostatic ion trap [22–25] or an electron-beam ion trap [26], which I will discuss in section III.

In the solar corona, the spectra of the iron group elements figure prominently, of ions that are missing about half of their electrons. Given the relatively high abundance of Fe, the spectra Fe X (Cl-like) to Fe XVI (Na-like) are expected to be rather bright in the EUV corona. The simpler ones of these spectra are rather well known by now, from combinations of data obtained at the various light sources mentioned above [27–29]. The knowledge

of the level structure (lowest shells only) and of the spectra is much less complete for the ions with more electrons, that is for the spectra Fe XIII (Si-like), Fe XII (P-like), Fe XI (S-like) and Fe X. With the open 3d electron shell, calculations need to take into account enormous numbers of configurations (see the studies by the Kassel group [30–34] and references therein). Even for the decay of the lowest excited level in Fe X, the results of the available calculations scatter by a factor of two, and very few come close to the experimental results [35, 36]. On the positive side, the combination of data from all available light sources has been demonstrated for the above Fe spectra a few years ago [37], and a few more lines of Fe XI through Fe XIII that appear in solar spectra have been identified on the basis of further beam-foil studies thereafter [38–41].

The present paper summarizes what has been achieved in the work on highly charged Fe ions by various ion-beam techniques and by ion trapping techniques. The work recalled here was done largely in a long-standing Bochum-Lund collaboration with I. Martinson, C. Jupén, R. Hutton, N. Reistad, L. Engström; this fruitful collaboration based on common beam-foil spectroscopy interests comes to an end, because in both places new faculty orientations resulted in phasing out the use of the local accelerators for the long-time good purpose [42]. This recollection of work done leads to a discussion of some open problems.

## 2. Beam-foil experiments

The 4 MV Dynamitron tandem accelerator at Bochum is capable of delivering much higher ion beam currents than most other machines of its class because it boasts of a fully electronic, no-moving-parts high voltage system (related to the Cockroft-Walton design). Consequently, high-current ion sources can be used to their full potential. Ion currents of several  $\mu\text{A}$  on target were achieved for 20 MeV  $\text{Ti}^{4+}$ , and this encouraged the Bochum experimenters in the mid-1980s to ask the accelerator crew for a beam of Fe ions, even though Fe was considered a “difficult” ion beam to produce from a sputter ion source. The tests were most successful; several  $\mu\text{A}$  of  $\text{FeO}^-$  ions were extracted from the source and converted into particle currents of hundreds of nA for each of the charge states of interest, permitting a multitude of beam-foil investigations that were to cover charge states from Na-like to Ar-like Fe, at energies from about 8 MeV to 36 MeV.

The high ion beam current permitted the study of not only the prompt emission of bright resonance transitions, for example of Na-like and Mg-like ions [43, 44], but also afforded the luxury of observations away from the foil, at times (nanoseconds) after excitation when most of the fast decays (lifetimes in the range of a few dozen picoseconds) have already died out. Only with such a high ion beam current (and an efficient diffraction grating in the spectrometer) was the signal from the decays of long-lived levels sufficient to be observed well above the background. This observation of delayed spectra opened up the field of investigating the decays of, for example, intercombination transitions [15, 16, 45, 46]. In due course, Fe was tackled for these ‘slow’ decays, too. When the lines were seen and roughly calibrated, the search for comparison data began, none of which were to be found in the usual spectral tables. Indrek Martinson (Lund) fortunately was present at the experiment, and he had the right idea: he looked up EUV observations of the solar corona [2, 5]. Indeed, they had nothing labeled as the intercombination

lines in Mg- or Al-like Fe ions, but they had precise wavelength data on unidentified lines that coincided with our less precise, but uniquely determinative beam-foil observations. Thus our work in the basement told about something that could be seen only from outside Earth’s atmosphere. We had no means for an accurate wavelength calibration of the delayed spectra, since all well known laboratory lines originate from short-lived levels, but this linkage to precise astrophysical data immediately yielded wavelengths more precise than our own observations by an order of magnitude. Roger Hutton later on went to Japan and pursued lifetime studies of intercombination lines in the  $n = 2$  shell of Fe ions [47]. Of course, beam-foil spectra of Fe have been studied in other places as well, for example at Brookhaven [48, 49] and by the group from Lyon [50–52].

Subsequently, Christer Jupén (Lund) communicated his interest in delayed beam-foil spectra of Fe ions with more than two, three, or four electrons in the  $n = 3$  valence shell. Bochum beam-foil work then contributed to his intercomparison of observations from tokamaks and laser-produced plasmas [37]. Systematic beam-foil work at Bochum identified rather prominent lines from the decays of long lived levels in Si-like ions (Fe XIII  $3s^2 3p 3d^3 F_3^o$ ) or the ground state intercombination multiplet Fe XI  $3s^2 3p^4 \ ^3P_J - 3s^2 3p^3 3d \ ^5D_J^o$ , [35, 36, 38–41]. In the latter case then also an M2 decay of the  $^5D_4^o$  level to the  $^3P_2$  level of the ground term was identified in solar spectra, on the basis of the calculated multiplet structure and after identifying the decays of the shorter-lived members of the transition array first in beam-foil and then in solar spectra [34]. The perhaps amusing aspect of this case was no longer an identification with previously unidentified solar lines but the unequivocal identification with (among others) a prominent line in the solar EUV spectrum that had been identified previously with a transition in a different ion (an identification that in hindsight made less sense). In fact, the strongest line of the multiplet had been identified earlier on with a variety of other lines, none of which (in combination with nearby lines) fitted the expected multiplet structure.

The obvious misidentifications in so-called up-to-date representations of solar spectra (for example [53]) must be plenty, since at the time (decades ago) when many of these identifications were made – on the basis of coincidences with laboratory wavelengths of whatever element in whatever charge state – spectral data of the right ion species were often just not available, and possibly insufficient consideration may sometimes have been given to elemental and ion species abundances. Many of the EUV line assignments are therefore to be doubted. On the other hand, typically half of all observed solar lines throughout the UV, VUV and EUV are presently unidentified [7, 8].

On the beam-foil side, we have already mentioned the recent study [41] that identified triplet-quintet intercombination transitions in Fe XI and decays from  $J = 7/2$  levels in Fe XII. Here the problem lies in the fact that these high- $J$  levels have only a single decay channel. Obviously, it is daring to assign a level on the basis of a single line observation. In these cases, the assignment was corroborated by the longevity of the particular decay curves, in combination with theoretical guidance and experimental charge state identification.

Although the spectral resolution of the coronal spectra is high, some intense lines from abundant ion species mask lines of other ions. Furthermore, there also are incidental line coincidences among the many Fe ion species. For example, “missing” lines held up the analysis of the spectra Fe X and Fe XI, until it was realized that some lines that were expected to be prominent, but were not

all recognized individually, do most probably coincide with each other. An example is the Fe X 257.26-Å line that blends with the strong  $J = 2-3$  component of the Fe XI  $3s^2 3p^4 \ ^3P - 3s^2 3p^3 3d \ ^5D^o$  multiplet [41].

### 3. Ion traps

Astrophysics often interprets the properties of remote plasmas by line ratios of intercombination to resonance lines, or among electric-dipole forbidden lines [54–56]. It would be good to be able to measure such line ratios of forbidden lines in the laboratory, under controlled conditions. Unfortunately, this process runs into the problem of requiring a very low particle density (extremely high vacuum) and then not having anything “in there” that produces enough detectable signal. In order to test the calculations that are involved in the interpretation of the astrophysical observations, one can take the observed wavelengths and compare them with predictions, and one can measure some decay rates that are needed to make line ratios work and compare those with the results of the calculations. This is not the same as testing the full calculations that often involve thousands of levels and tens of thousands of transitions, but one can thus test at least the validity of some of the key elements of radiative-collisional models.

Level lifetimes of highly charged Fe ions that can be obtained by the beam-foil technique range from, say, 10 ps to 30 ns. Longer lifetimes are difficult to measure by traditional beam-foil spectroscopy, because the decays stretch out so long that a travelling detector (usually mimicked by a moving foil) faces a signal per unit length of ion beam that is too low in comparison with the background or the noise. One then either has to confine the ions in front of the detection system (in an ion trap) or, which is easier to do at the multi-MeV ion energies needed to produce those charge states with an ion accelerator, make them run in a closed loop so that they pass in front of the detector many times – the very concept of a storage ring. Both, a small trap for low-energy highly charged ions, and a large trap for fast ion beams, have been used to obtain the lifetimes of very long lived levels in highly charged Fe ions. Such levels typically are the fine structure levels in the ground term that cannot decay by electric dipole (E1) transitions, as well as some high- $J$  levels in excited configurations that are also barred by selection rules from undergoing E1 decays [57]. The lifetimes of interest are in the millisecond range, some six orders of magnitude up from the nanosecond range that is routinely dealt with by standard beam-foil techniques [21].

The first such millisecond-range lifetime data on highly charged Fe ions have been reported from experiments with an ECR ion source feeding keV-range ions to an electrostatic (Kingdon) ion trap at Reno (NV, USA) [22–24]. When comparing their results on  $n = 3$  levels of Fe ions to predictions, the authors did not find a clear pattern. This might be seen as a fault of theory that anyway provided predictions with quite some scatter (some 30% for the Fe ions of primary interest). However, the Reno results for  $n = 2$  levels in few-electron Ar ions, for which the scatter of the predicted values is less than 1%, deviated from prediction by much more than the stated experimental uncertainty. Experiments using a different type of ion trap seemed to be called for.

#### 3.1. Heavy-ion storage ring

Lifetimes of levels in singly charged Fe ions have been studied at the CRYRING storage ring in Stockholm [18]. Work on multiply

charged Fe ions took advantage of the tandem accelerator that serves as an injector for the TSR heavy-ion storage ring at Heidelberg [19, 20]. Ions of many charge states can be produced in the (gas or foil) stripper section of the accelerator, and then only ions of a single charge state are transported to and injected into the storage ring. After filling the ring over about 30 revolutions, injection stops and observation begins on the coasting ions. The observation uses photomultiplier tubes (PMT) for (suitably filtered) visible light, a solar blind PMT for near UV light, and the built-in beam profile monitor for EUV light and rest gas ionization. With all the excitation being achieved in the injector, this is indeed a derivative of the beam-foil technique, but involving decay paths of hundreds of kilometers instead of the traditional few centimeters. However, without any mechanical movements, or foils subject to change, or beam divergence problems, the overall uncertainty of lifetime measurements can be very small, indeed.

The electric-dipole forbidden transitions in Fe XIV and Fe X ranked highest on the agenda. Unfortunately, the injector accelerator did not produce enough Fe<sup>13+</sup> ions to reach a sufficient signal level. In contrast, Fe<sup>9+</sup> beams were easily generated, but of several PMTs that were tried to capture 637 nm light from Fe<sup>9+</sup> none proved sufficiently red-sensitive. What did work were measurements on other ions from Fe<sup>12+</sup> to Fe<sup>6+</sup>, both on  $3s^2 3p^k$  levels and some 3d levels (see Table I). Our data do not compare well with those from the aforementioned electrostatic ion trap [22–24]. The differences often are much larger than the combined error bars. However, having tested our systematic errors in some

Table I. *Experimental lifetime coverage of levels with dominant M1/E2/M2 decays in multiply charged ions of Fe. Wavelength data are approximate from various sources.*

Isoelectronic sequence	Ion	Level	Lifetime $\tau$	Trap type Reference		
Al	Fe <sup>13+</sup>	$3s^2 3p^2 \ ^2P^o_{3/2}$	$(17.52 \pm 0.29)$ ms	EKT [22, 24]		
			$(16.74 \pm 0.12)$ ms	EBIT [26]		
Si	Fe <sup>12+</sup>	$3s^2 3p^2 \ ^1D_2$	$(6.93 \pm 0.18)$ ms	EKT [24]		
			$(8.0 \pm 0.1)$ ms	HSR [19]		
P	Fe <sup>12+</sup>	$3s^2 3p 3d \ ^3F^o_4$	$(9.9 \pm 0.4)$ ms	HSR [20]		
			Fe <sup>11+</sup>	$3s^2 3p^3 \ ^2P^o_{3/2}$	$(1.85 \pm 0.24)$ ms	EKT [24]
	$(1.70 \pm 0.02)$ ms	HSR [19]				
	$(4.38 \pm 0.42)$ ms	EKT [24]				
	$(4.1 \pm 0.12)$ ms	HSR [19]				
	Fe <sup>11+</sup>	$3s^2 3p^3 \ ^2D^o_{3/2}$	$(20.35 \pm 1.24)$ ms	EKT [24]		
$(18.0 \pm 0.1)$ ms			HSR [19]			
S	Fe <sup>10+</sup>	$3s^2 3p^3 \ ^2D^o_{5/2}$	$(306 \pm 10)$ ms	HSR [19]		
			Fe <sup>10+</sup>	$3s^2 3p^4 \ ^1D_2$	$(9.86 \pm 0.22)$ ms	EKT [24]
		$(11.05 \pm 0.1)$ ms			HSR [19]	
Cl	Fe <sup>10+</sup>	$3s^2 3p^3 \ (^2D^o) 3d \ ^3G^o_4$	$(68 \pm 4)$ ms	HSR [19]		
			Fe <sup>9+</sup>	$3s^2 3p^5 \ ^2P^o_{1/2}$	$(13.64 \pm 0.25)$ ms	EKT [22, 24]
	Fe <sup>9+</sup>	$3s^2 3p^4 \ (^3P) 3d \ ^2F_{7/2}$			$(17.0 \pm 1.7)$ ms	HSR [19]
					Fe <sup>9+</sup>	$3s^2 3p^4 \ (^1D) 3d \ ^2F_{7/2}$
	Fe <sup>9+</sup>	$3s^2 3p^4 3d \ ^4F_{9/2}$	$(85.7 \pm 9.2)$ ms	EKT [23]		
				$(110 \pm 5)$ ms	HSR [20]	
Ar	Fe <sup>9+</sup>	$3s^2 3p^4 3d \ ^4F_{7/2}$	$(93 \pm 30)$ ms	EKT [23]		
				$(70 \pm 25)$ ms	HSR [19]	
	Fe <sup>9+</sup>	$3s^2 3p^4 3d \ ^2G^o_{9/2}$	$(17.8 \pm 3.1)$ ms	EKT [23]		
			Fe <sup>8+</sup>	$3s^2 3p^5 \ 3d \ ^3D^o_3$	$(29 \pm 3)$ ms	HSR [20]
Fe <sup>8+</sup>	$3s^2 3p^5 \ 3d \ ^3D^o_2$	$(10.5 \pm 1)$ ms			HSR [20]	
		Ca	Fe <sup>8+</sup>	$3s^2 3p^5 \ 3d \ ^1F^o_3$	$(6.9 \pm 0.3)$ ms	HSR [20]
Fe <sup>6+</sup>	$3s^2 3p^6 \ 3d^2 \ ^1S_0$				$(29.6 \pm 1.8)$ ms	HSR [20]

EBIT Electron-beam ion trap, EKT ECR ion source plus Kingdon ion trap, HSR Heavy-ion storage ring.

detail (for example, the very important ion loss from the sample was measured on-line in our experiment, but only inferred from auxiliary experiments in the other work), and having found very good agreement of our results with theory for lighter ions (fewer electrons,  $n = 2$  levels), where theory seems to do well, we feel to be on firm ground with our data. The comparison with theory reveals agreement with some calculation (among several) in most cases; however, there is no consistent set of calculations that would treat all the  $n = 3$  levels of our sample. In some cases, calculations were tried for a first time only after our measurements, and second opinions would be welcome.

### 3.2. Electron beam ion trap

The Livermore electron beam ion trap was used in cross checks with our heavy-ion storage ring lifetime measurement technique [58]. It was also used to obtain lifetime data on Fe XIV, the green solar corona line at 530 nm that had eluded us at the storage ring. The lifetime result of about 16.6 ms with an uncertainty of less than 1% [26] clearly confounds the result from the electrostatic ion trap (for this discussion, consult figure 1). A measurement at Caltech, employing an older version of the electrostatic ion trap, had a result somewhere in between [25], but that has not been formally released yet. An interesting point now is the comparison with the outcomes of quite a number of calculations of the transition rate. With two exceptions, all agree with each other and are compatible with our experimental result. Are the calculations so good, and why then do two of them differ from the rest by up to 30%?

As Werner Eissner kindly pointed out to me, the line strength of this transition is a matter of Racah algebra. In the nonrelativistic limit, without Breit-Pauli contributions, it is equal to  $4/3$  (he finds 1.331 with Breit-Pauli). The only other ingredient needed for a determination of the transition rate is the transition energy.

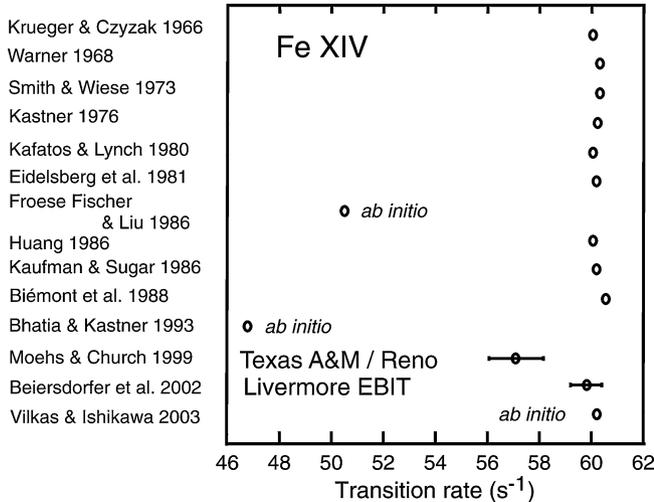


Fig. 1. Transition rate data for the  $3s^2 3p^2 P_{3/2}$  level in the ground state of the Al-like ion  $Fe^{13+}$ . Note how most calculational results (without error bars) agree within a close interval with each other. The two deviating theoretical results apparently have not been adjusted for the experimental fine structure intervals, clearly underlining the computational problems with that entity. The first (Texas A&M/Reno) electrostatic ion trap measurement (by Moehs and Church) [22], however, did not resolve the evident discrepancy. The electron beam ion trap measurement at Livermore (by Beiersdorfer *et al.*) [26] clearly agrees with the (semiempirically adjusted) majority of the predictions and settles the case. The last figure entry is from the first *ab initio* calculation (by Vilkas and Ishikawa) [59] that closely matches the experimental fine structure interval and thus does not need semiempirical adjustment.

Whatever complex methods were applied in all those calculations, they usually did not yield a value for the  $3s^2 3p J = 1/2 - 3/2$  fine structure interval that was close to the experimentally known value. Therefore in the end experimental transition energies were used which, combined with the given line strength from basic principles, would result in always the same number for the transition rate. The slight differences among the predictions then simply reflect “improved” line strength values. The two theoretical transition rate results that are so very different from the rest did not do this adjustment to experimental energies. They thus reveal the true state of affairs on the side of those calculational approaches. However, there is hope: in a very recent study, Vilkas and Ishikawa [59] have obtained *ab initio* level splittings and transition rates that closely match the experimental ones for Fe XIV.

Now that in this case all results can be traced back to basic principles and experimental transition energies, it does not take much to speculate that the electrostatic ion trap lifetime result for Fe X [22] that deviates from the bulk of the semiempirically scaled predictions won’t hold, and that for the time being, semiempirically corrected predictions provide a more accurate value, until a reliable experiment can be done.

Overall, using the Heidelberg heavy-ion storage ring and the Livermore electron beam ion trap, electric-dipole forbidden transition rates with uncertainties of as little as a few percent have been determined in ions from  $Fe^{6+}$  to  $Fe^{13+}$ . This precision exceeds the accuracy of the available predictions, and it seems quite adequate for the needs of the astrophysics community. One might ask for more such Fe lifetime data from the Livermore electron beam ion trap. However, the Fe ions with more electrons than those in  $Fe^{13+}$  have lower ionization potentials. It is very tedious to operate an electron beam ion trap with an electron beam of an energy of only a few hundred eV; the electron beam current is low under such conditions, and several ion charge states are equally prominently present. This reduces the signal for a given line. Moreover, excited configurations are not effectively excited in the electron beam ion trap.

## 4. Discussion and outlook

Forbidden lines and their line ratios play a significant role in the diagnostics of astrophysical plasmas, ranging from the solar corona to planetary nebulae, active galaxies and so on [26, 54–56]. Transitions within the ground configurations of  $n = 2$  and  $n = 3$  shell Fe ions are well established. Inspection of level compilations [27, 28, 61] or of published Grotrian diagrams [29], however, shows that much of the level structure of low-lying excited configurations remains to be measured. Calculations like the aforementioned Kassel papers (and a number of studies by the astrophysics community) provide transition probabilities for M1 and E2 transitions between excited levels in Fe X which help with the modeling of spectra and enable estimates of which forbidden lines to look for in solar spectra. Theory can guide, but so far it is not capable of predicting most of the spectra with anywhere near spectroscopic accuracy. However, good calculations can point out inconsistencies in experimental analyses (for very recent examples, see [59, 60]). On the experimental side there are problems, too. For example, most spectroscopic work has not been done under ultrahigh vacuum conditions, including ion confinement, so that long-lived levels are being collisionally quenched, or their emitters may be leaving the field of view, rather than their radiative decays be observed in full. This is important,

since the vacuum of the solar corona is of much lower density than that of most laboratory light sources. One of the most promising low-density laboratory light sources, the electron beam ion trap, features typical electron densities of the order of  $10^{10}$  to  $10^{11}$   $\text{cm}^{-3}$  for low energy electron beams, which is higher than that of many astrophysically important plasmas by several orders of magnitude. At this density, a search for counterparts to solar forbidden UV lines that are expected to arise from transitions between excited 3d levels has been attempted at the Livermore electron beam ion trap, but has failed so far [62]. It seems straightforward to reduce the electron density by an order of magnitude, or more, but only at the cost of a signal rate that might then be forbiddingly low. However, this procedure has to be tried eventually to find out whether observations under such conditions are feasible nevertheless.

A combination of the above beam-foil work on high-J levels and of theory (analyses and calculations by C. Jupén, private communication) points to several candidate forbidden lines near the upper end of the wavelength range of the SUMER spectra (near 160 nm). It is tantalizing to realize that some of these lines might be just nanometers away (in wavelength) from the end of such a good set of observations. The eventual identification of forbidden lines from excited configurations may help to clarify the identities of a few still unassigned electric-dipole forbidden solar coronal lines [8, 63–65], as well as provide candidate lines for the improved diagnostics of fusion plasmas. In this way, studies employing different types of light sources would benefit from each other.

Moreover, the interpretation of astrophysical data like the soft-X-ray spectra from the *Chandra* and *XMM-Newton* spacecrafts calls for dedicated laboratory work, also on Fe. The Livermore electron beam ion trap laboratory is performing the overwhelming amount of work on this [66–72]. There is much interesting work out there, even after the heavy-ion accelerators that for several decades provided most valuable data on the spectra of Fe ions seem to fade away.

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