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On the transition rates of the Fe X and Fe XIV coronal lines

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Abstract. Despite a considerable scatter of the theoretical predictions of the M1/E2 transition rate of the "red iron line" (Fe X) in the solar corona, there is disagreement of all the results with the single measurement that used an electrostatic ion trap. Employing a heavy-ion storage ring for measuring the same transition in isoelectronic ions of Co, Ni, and Cu, the situation has been clarified, and a new, accurate data point for Fe X can be determined by extrapolation. This result agrees with the basic atomic structure prediction for the line strength in combination with the experimental transition energy. For the "green iron line" (Fe XIV), a recent measurement with an electron beam ion trap has resolved similar discrepancies.

Key words. atomic data – Sun: corona – techniques: spectroscopic

1. Introduction

"Forbidden" lines, spectral lines that arise from transitions that are forbidden by the selection rules for electric-dipole ($E1$) transitions, are of great interest since Edlén (1942) identified various prominent coronal lines in the visible spectrum of the solar corona with just this type of transition between levels in the ground configurations of highly charged heavy ions. Among these lines the "red iron line" (Fe X, 637 nm) and the "green iron line" (Fe XIV, 532 nm) are standing out prominently. In fact, there have been publications in solar physics that refer to the ratio of the "red" and "green" corona lines in their title without even mentioning the element.

These two lines arise from magnetic dipole (M1) transitions (with a small electric quadrupole (E2) admixture) between the $J = 3/2, 1/2$ finestructure levels of the $3s^2 3p^5\ ^2P^o$ ground term of Fe X, and between the $J = 1/2, 3/2$ finestructure levels of the $3s^2 3p\ ^2P^o$ ground term of Fe XIV, respectively. Under typical coronal conditions, Fe X, the spectrum of the Cl-like ion (17 electrons) of Fe ($Z = 26$), with an IP of 262.1 eV, is one of the most prominent spectra. Fe XIV, the spectrum of the Al-like ion (13 electrons), has an IP of 392.2 eV. Such transitions in the ground configurations of various abundant ion species have been exploited in a wide variety of astrophysical studies, ranging from solar physics to planetary nebulae and AGNs (see the references given in our earlier papers (Träbert et al. 2002a; Beiersdorfer et al. 2003).

With the two iron lines so prominently observed, theory has long since been trying to determine the transition probability A_{ki} in order to enable quantitative modeling and the extraction of absorption data. In the nonrelativistic limit, this supposedly is simple. The transition rate, besides some conversion factors, depends only on the line strength S and on the (third power of) the transition energy (see Martin & Wiese 1996). The line strength follows from Racah algebra and turns out to be a simple fraction (4/3 for both, Fe X and Fe XIV). The calculational problems lie in the determination of the transition energy, which is the fine structure interval of the ground term. Because of these problems, it is customary to do whatever type of calculation first, and then scale the result by the ratio of calculated and observed transition energies (from the very wavelength observations of the aforementioned coronal lines). Of course, to an experimenter this roundabout solution seems a bit awkward. On the other hand, there is only a single, very recent, ab initio calculation (of Fe XIV) that has yielded a value of the ground term fine structure interval accurate enough so as not to require a significant adjustment (Vilkas & Ishikawa 2003). Apparently, no such accurate result has been published for Fe X yet.

Experimental tests of the calculated transition rate have not fared much better until recently either. The recent results of such measurements, however, now clarify matters and indicate that the simple recipe for the determination of the transition rates as given above is appropriate.

2. Experiment

The task of producing Fe ions of the desired charge states has been solved decades ago by suitable plasma discharges, by the technique of beam-foil spectroscopy, and by dedicated ion sources. The experimental problem with the observation of light emission from very long-lived ions is the clean storage of these ions for times longer than the radiative lifetime,

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which in the present cases is near 15 ms. Given the large electron capture cross sections of such highly charged ions, the vacuum has to be very good. In fact, particle densities as low as in the solar corona are desirable for the observation period, while higher densities would be beneficial for a higher ion production yield and thus signal rate. Three approaches have been tried, of which two have yielded reliable results.

2.1. Electrostatic ion trap

Measurements by a group from Texas A&M university (Moehs & Church 1999; Moehs et al. 2001) used Fe^{q+} ions produced in the Reno (Nevada) electron cyclotron resonance ion source (ECRIS). These ions were extracted from the source at energies of the order of 10 keV, selected for charge state, and directed to cross the volume of a cylindrical metal cage under ultrahigh vacuum (UHV) conditions. A wire along the axis of the cylinder was quickly put on a high negative potential, and thus a sizeable fraction of the ions on their trajectory across the cylinder was being trapped. A photomultiplier observing (through a suitably chosen interference filter) the center of the trap monitored the light emission of the stored ion cloud and, following the intensity as a function of time after closing the trap, yielded decay curves. These decay curves had to be corrected for the loss of ions from the trap. This was achieved in separate runs by switching off the trap voltage at various times after ion injection; some of the escaping ions would then hit a channeltron detector. From a sequence of such measurements the survival time of stored ions was determined.

These measurements yielded radiative lifetime data (the inverse of the radiative transition probabilities) for both Fe X and Fe XIV (Moehs & Church 1999; Moehs et al. 2001). The quoted uncertainties of a few percent were much smaller than the scatter of all the predictions available. However, the results did not overlap within the experimental errors with the straightforward predictions that used the basic-principle line strength and the experimental transition energy. For Fe X, the measured lifetime was clearly shorter than expected, while for Fe XIV the result was notably longer. An extensive discussion of the technique by the authors (Church et al. 1999) remained inconclusive in terms of the evident problems.

A number of measurements (on other atomic systems) at the Heidelberg heavy-ion storage ring TSR and at the Livermore electron beam ion trap (see below) was done in order to study systematic errors of any such lifetime experiments on multiply charged trapped ions. The results of both techniques, while compatible with each other (Träbert et al. 2002b), indicated that the experiments at the electrostatic ion trap might suffer from larger errors than assumed by their authors, among the problems noted being the poorer UHV conditions compared to the other two devices, possible systematic problems with the ion cloud survival measurements, and possible shortcomings of the data evaluation.

2.2. Electron beam ion trap

In the electron beam ion trap at the University of California Lawrence Livermore National Laboratory, an intense electron beam ionizes and confines ions that have been produced from a dilute gas jet at pressures below 10^{-10} mbar. The electron beam is guided by a strong (3 T) magnetic field that also helps to prevent radial diffusion; a set of drift tubes at different electric potentials confines the ions in their motion along the magnetic guide field. When the electron beam is switched off, the system remains acting (in "magnetic trapping" mode) as a Penning ion trap, with confinement times of the order of seconds (Beiersdorfer et al. 1996). The vacuum is at least an order of magnitude better than in the experiments with the electrostatic ion trap. Ion survival is measured in situ by monitoring X-rays from charge exchange; consequently there are no geometry problems with the ion monitoring process. However, the electron beam ion trap is a device designed for multi-keV electron beams, and running at the low energies needed in order not to burn out the Fe ion charge states of interest worked well only for Fe XIV. Problems of the technique lie in the fact that the ion cloud contains various ion species, so that narrowband filtering of the light emission is essential.

The lifetime result of $\tau = 16.74 \pm 0.12$ ms (Beiersdorfer et al. 2003) corroborates the predictions that were based on (theoretical) line strength and experimental transition energy (Fig. 1). A single ab initio calculation (Vilkas & Ishikawa 2003) has since been published that closely matches the experimental transition energy and thus also the measured transition rate.

2.3. Heavy-ion storage ring

The heavy-ion storage technique is an extension of the venerable beam-foil technique. At the heavy-ion storage ring TSR of the Max Planck Institute for Nuclear Physics, at Heidelberg, Germany, a fast (few percent of the speed of light) ion beam is excited by being passed through a thin foil. In traditional beam-foil spectroscopy the decays of levels with picosecond to nanosecond lifetimes are monitored within distances of a few centimeters from the exciter foil. For the many-millisecond lifetimes of interest here, however, the flight paths amount to many thousands of kilometers. Therefore the ions, after charge state separation, are being fed into a storage ring where they can pass in front of the detector over and over again. The injection into the ring is stopped after filling the phase space, and then the light from the circulating ion beam is monitored for its decay time. Continually the ion beam current is being monitored as a measure of ion loss. Fully separating ion production and observation regions (the latter in a vacuum of about 10^{-11} mbar), working with a single ion charge state, and providing on-line ion storage monitoring, this technique has the potential for the cleanest measurements. Last, but not least, at the multi-MeV energies employed at TSR, the ion loss rates are much lower than with the keV energies of the other experiments; usually the ion loss corrections are therefore minute. However, these experiments obviously hinge on the accelerator and the detector. The present tandem accelerator proved unable to deliver a sufficient supply of Fe^{13+} ions, but yielded plenty of Fe^{9+} ions. The low budget experiment, however, failed on obtaining a sufficiently effective detector for the "red" line.

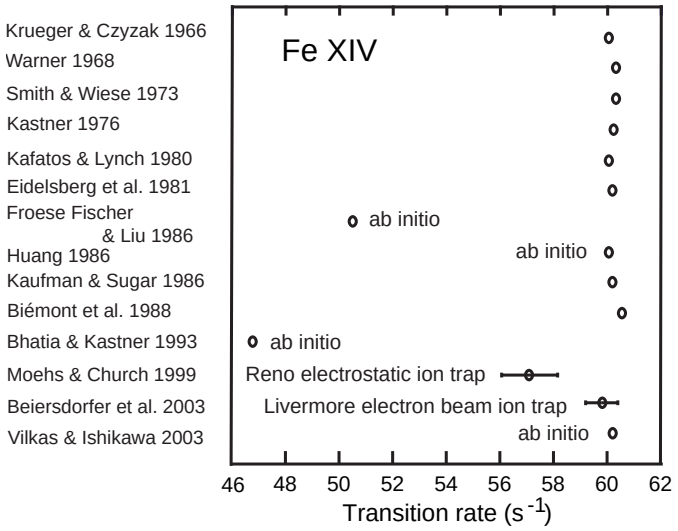

Fig. 1. Time line of the transition rates for the electric-dipole forbidden transition in the $3s^2 3p\ ^2P^o$ ground configuration of Fe XIV. Most calculations have been adjusted to the experimental transition energy (the ground term fine structure interval), which makes the results scatter very little. The ab initio calculations reflect theory without such adjustment. The first of the experimental data (with error bars), from an electrostatic ion trap (Moehs & Church 1999) does not match any of the predictions. The data from the electron beam ion trap at Livermore (Beiersdorfer et al. 2003) overcome this discrepancy in favour of semiempirically adjusted calculations. At long last, an ab initio calculation by Vilkas & Ishikawa (2003) has reached similar accuracy. At face value, the much earlier ab initio calculation by Huang (1986) may be seen as having similar quality. However, a calculation by Huang et al. (1983) that used the same algorithm and a similarly limited number of wave functions on Fe X (see Fig. 2) fared clearly less well, a comparison that indicates a lower predictive power than suggested by a single successful set of calculations.

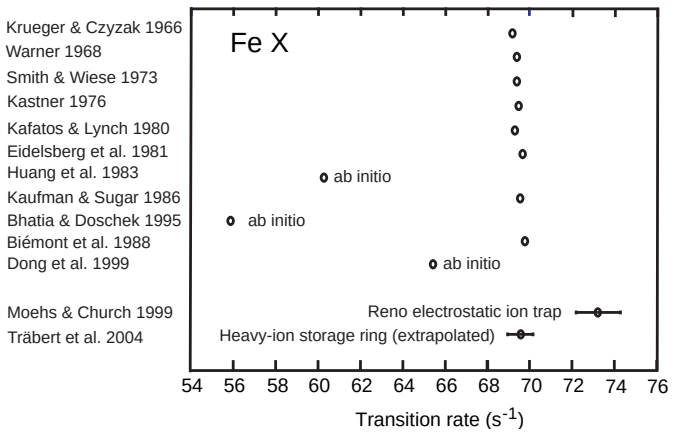

Fig. 2. Time line of the transition rates given for the electric-dipole forbidden transition in the $3s^2 3p^5\ ^2P^o$ ground configuration of Fe X. Most calculations have been adjusted to the experimental transition energy (the ground term fine structure interval), which makes the results scatter very little. The ab initio calculations reflect theory without such adjustment. The presently only available experimental data on Fe X are from an electrostatic ion trap experiment (Moehs & Church 1999) and do not match any of the predictions. An isoelectronic extrapolation of very recent measurements for Co, Ni, Cu (Träbert et al. 2004), which made use of a heavy-ion storage ring, fully corroborate the trend of the semiempirically adjusted calculations.

Table 1. Best experimental data on the transition probabilities in Fe X and Fe XIV.

Spectrum	Wavelength λ (nm)	Lifetime τ (ms)	Trans. prob. A_{ki} (s^{-1})
Fe X	637.451[a]	14.40 ± 0.14[b]	69.4 ± 0.7[b]
Fe XIV	530.286[a]	16.74 ± 0.12[b]	59.7 ± 0.4[b]

[a] Träbert et al. (2004).
[b] Beiersdorfer et al. (2003).

Instead, three other ions of the same isoelectronic sequence were studied, Co XI, Ni XII, and Cu XIII (Träbert et al. 2004). All three results corroborated the expected trend. The Ni XII results of 1.5% uncertainty, and the Cu XIII result with its precision of better than 1% test the aforementioned assumption of combining line strength S and transition energy. An extrapolation to Fe X indicates an experimental lifetime value of $\tau = 14.40 \pm 0.14$ ms, in full accord with the straightforward approach of combining theoretical line strength S (now tested experimentally) and experimental transition energy.

Figure 2 shows the state of affairs for Fe X after these measurements. Clearly, all of the available ab initio calculations fall short of delivering an accurate result, as does the first measurement that was done at an electrostatic ion trap.

3. Discussion and outlook

Pursuing two very different, complementary techniques, using a heavy-ion storage ring in one (Träbert et al. 2004) and an electron beam ion trap in the other (Beiersdorfer et al. 2003), experiments have produced accurate (reliable) and precise transition rate data on both of the prominent coronal Fe lines. These data (Table 1 evidently supersede the earlier experimental data from an electrostatic ion trap that must have suffered from unaccounted systematic error.

The new data validate the approach of combining theoretical line strength values with experimental transition energies in order to predict magnetic dipole transition rates in cases that are simple enough for such a procedure. As is evident from Figs. 1 and 2, most ab initio calculations have not reached this target. The general predictive power of calculations using a given algorithm may be overestimated from the success with a single atomic system. For example, Huang has done calculations on a variety of isoelectronic sequences employing the multi-configuration Dirack-Fock code developed by Desclaux. For Al-like Fe XIV (Huang 1986), the transition wavelength result is very close to the experimental value and consequently the predicted transition rate is close to what can now be termed the correct answer. This result is much better than the outcome of a similar calculation on Cl-like Fe X (Huang et al. 1983) that misses the true transition energy by a few percent and thus results in a significant error of the transition rate prediction. If – as done by Huang et al. – the ingredients to the final number are separately listed, a semiempirical correction can nevertheless

be applied. Such a correction, however, is futile in ions with a more complex level structure. Calculations that are reliable even at the fine structure level are called for.

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