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# MEASURED LEVEL LIFETIMES FOR THE CORONAL TRANSITIONS OF Fe X AND Fe XIV

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## ABSTRACT

In a laboratory study, the lifetimes of the $^2P$ levels producing the coronal transitions of Fe x and Fe XIV have been measured. The fluorescence from the metastable levels, which were populated when the ions were produced in a source of multiply charged ions, was studied after the selected ions were injected into an electrostatic ion trap. The results are $\tau$(Fe x, $3s^2 3p^5\ ^2P^o_{1/2}$) = 13.64 ± 0.25 ms and $\tau$(Fe XIV, $3s^2 3p\ ^2P^o_{3/2}$) = 17.52 ± 0.29 ms. The data significantly reduce the uncertainty of the lifetimes when compared with existing theory.

*Subject headings:* atomic data — Sun: corona — techniques: spectroscopic

## 1. INTRODUCTION

The red coronal line (Fe x, 637.4 nm) and the green coronal line (Fe XIV, 530.3 nm) are well known in astrophysics as forbidden transitions in the ground terms of highly charged metal ions that appear prominently in spectra of the solar corona, of highly ionized Seyfert I galaxies (Osterbrock 1981), in supernova remnants (Woodgate et al. 1974), and in other astrophysical plasmas characterized by energetic ionization leading to high charge states. The intensities of these transitions, by themselves, provide a local temperature calibration of the plasma if the radiative transition rates and collision strengths are known (Lynch & Kafatos 1991). The large-scale coronal temperature structure is derived from the Fe x/Fe XIV intensity ratio (Guhathakurta, Fisher, & Altrock 1993). In combination with allowed transitions, the relative intensities may also serve as a local density diagnostic. Although there have been several calculations of these rates, their accuracy is limited or uncertain, and measurements have only recently become possible (Yang & Church 1993; Moehs, Church, & Phaneuf 1998; Wargelin, Beiersdorfer, & Kahn 1993; Doerfert, Traebert, & Wolf 1996).

The ground term of Fe x has a $3s^2 3p^5$ configuration with two levels, the $^2P^o_{3/2}$ ground state and the $^2P^o_{1/2}$ excited state, associated with the hole in the *p*-shell. There are also the $3p^4(^3P)3d$ and $3p^4(^1D)3d$ excited metastable levels, but these levels eventually decay by magnetic quadrupole (M2) transitions (Fuhr, Martin, & Wiese 1988) only to the $3p^5\ ^2P^o_{3/2}$ ground state and, hence, are irrelevant to the present measurements. The ground term of Fe XIV has a $3s^2 3p$ configuration, with a $^2P^o_{1/2}$ ground state and a $^2P^o_{3/2}$ excited state. There are also $3s3p^2$ excited metastable doublet and quartet levels, but no identified branch to the $3s^2 3p$ configuration (Fuhr et al. 1988). The two ground term level schemes, with experimental wavelengths and theoretical transition rates for the magnetic dipole (M1) and electric quadrupole (E2) transitions between the levels, are shown in Figure 1. The magnetic dipole rates dominate by far. The relative uncertainties of the best transition rate calculations are estimated to be about 25% (M1) for Fe XIV and about 10% (M1) for Fe x, with 50% uncertainties for the much smaller E2 rates (Fuhr et al. 1988). The Fe XIV rates are the relativistic multiconfiguration Dirac-Fock (MCDF) calculations by Huang (1986), including a perturbative treatment of the Breit interaction and Lamb shift, with configuration mixing including all configurations within the $n = 3$ complex. The Fe x calculations were again the MCDF calculations by Huang et al. (1983), with mixing among odd-parity $3s^2 3p^5$, $3s3p^5 3d$, $3p^5 3d^2$, and $3s^2 3p^3 3d^2$ configurations included.

## 2. EXPERIMENTAL METHOD AND RESULTS

The present measurements were made possible by a low-energy source of highly charged Fe ions, the electron cyclotron resonance ion source (ECRIS) of the University of Nevada at Reno. An oven was used to evaporate Fe atoms into the plasma of the ECRIS, which was supported by a carrier gas. The operation of the source was optimized for the separate production, extraction, and charge-to-mass ratio separation of each charge state. The extracted ion beam was transported, using electrostatic optical elements, through an ultra–high vacuum beam line to a Kingdon ion trap.

The electrostatic Kingdon trap and measurement procedures for metal ions have been described recently (Moehs et al. 1998), so only a brief account is presented here. The outer cylinder of the trap was biased to a potential near the extraction voltage of the ECRIS, with the concentric central wire initially held near the same potential. Once decelerated ions entered the trap through an aperture in the cylinder, the potential of the central wire was rapidly (<100 ns) pulsed to a potential about 1300 V below the cylinder potential, suddenly producing a logarithmic radial potential that captured ions having sufficient angular momentum about the wire. Suitably biased end electrodes provided the axial confinement of the captured ions.

Fluorescence from the metastable fraction of the confined ions was collected by a lens, which was mounted behind another aperture in the cylinder, and transmitted to a photomultiplier. The count rate was measured as a function of time following ion capture by using a multichannel scalar to obtain information on the metastable level lifetime. The ion storage time constant was obtained separately by raising the wire potential after measured storage intervals, releasing some confined ions through another aperture, which were counted using a microchannel plate detector. Experimental ion-loss rates that were consistent with electron capture collision rates for multiply charged ions (Weinberg et al. 1998) were measured, with typical ion storage time constants exceeding 1.5 s during the present measurements. Small corrections for ion loss were made to the time constants from the fluorescence signal decay

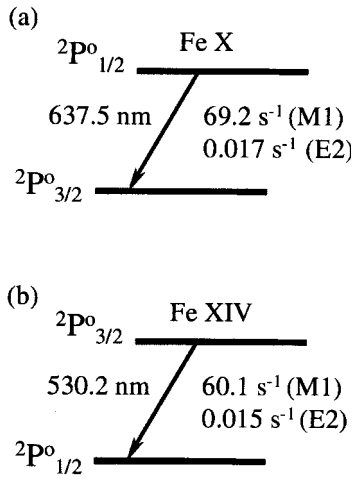


FIG. 1.—The ground term level diagrams for Fe x and Fe XIV, with experimental wavelengths and theoretical transition rates given for the M1 and E2 transitions between the levels (Fuhr et al. 1988).

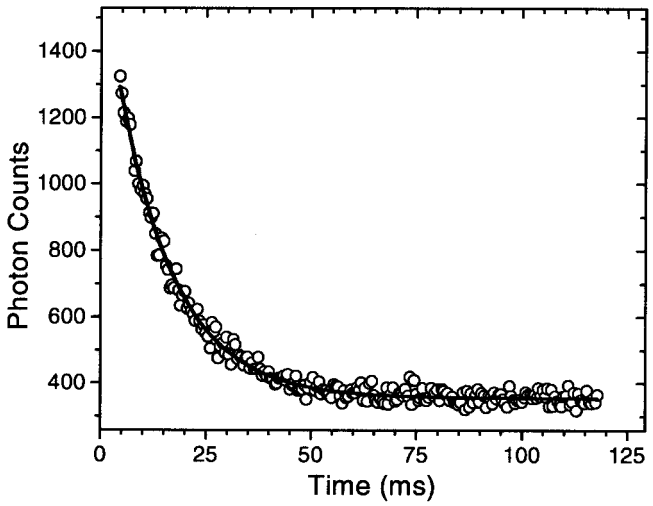


FIG. 2.—Measured photon signal associated with the decay of the $^2P^o_{1/2}$ level in Fe x, fitted by a single exponential and a constant background. Initial data points representing a rapid signal transient, which is thought to be associated with ion settling in the trap, were removed prior to the fit.

in order to obtain the metastable level lifetimes. It had previously been established that metastable quenching of highly charged ions under these experimental conditions is essentially due to charge-changing collisions (Church, Yang, & Tu 1994).

An interference filter with a center wavelength near 640 nm and a bandwidth of 10 nm was used to isolate the Fe x fluorescence. A beam current of 1.4 $\mu$A for $Fe^{9+}$ was obtained, resulting in about $10^6$ confined ions per cycle, with about 33% thought to be in the excited state, based on an assumed statistical population of the ground term levels. The fluorescence count data were accumulated for several hours and fitted to a single exponential plus a constant background (see Fig. 2). An initial fast decrease in the data with a time constant near 1.2 ms was observed in all measurements and is thought to be associated with ion settling in the trap; these initial data points were removed. The longer decay time constant of 13.53 $\pm$ 0.23 ms was associated with the metastable decay. This time constant was corrected for the finite ion storage time to yield the metastable lifetime $\tau$(Fe x, $3p^5\ ^2P^o_{1/2}$) = 13.64 $\pm$ 0.25 ms. The calculated MCDF transition rates are 69.2 s$^{-1}$ (M1) and 0.017 s$^{-1}$ (E2), leading to a theoretical lifetime of 14.44 ms, about 5%, or 2.6 standard deviations of the experimental uncertainty, longer than the measured result. This and other calculations are compared with the data in Table 1.

The Fe XIV transition was isolated with an interference filter centered near 530 nm. Only 0.5 $\mu$A of beam current could be obtained with this higher charge state, resulting in about 2.5 $\times$ $10^5$ stored ions per cycle. However, the higher statistical weight of the upper level benefited this measurement. Data including the initial transient are presented in Figure 3. The time constant of the decay was found to be 17.36 $\pm$ 0.26 ms. Correcting for the finite ion storage time results in the lifetime $\tau$(Fe XIV, $3p\ ^2P^o_{3/2}$) = 17.52 $\pm$ 0.29 ms. The MCDF transition rates are 60.1 s$^{-1}$ (M1) and 0.015 s$^{-1}$ (E2), resulting in a theoretical lifetime prediction of 16.63 ms, which, in this case, is about 3.2 standard deviations (5.5%) shorter than the experimental result. All the lifetimes are summarized in Table 1. In neither measurement was the E2 portion of the total transition rate testable within experimental precision. The nonrelativistic (NR) calculations (Eidelsberg, Crifo-Magnant, & Zeippen 1981) in Table 1 agree well with the relativistic calculations but are not thought to have higher accuracy. The experimental M1 transition rates are based strictly on the measured lifetimes, with no correction for the E2 branch, which is expected to contribute less than 1% to the total rate, much less than the experimental uncertainty.

## 3. CONCLUSION

M1 transition rates vary as $\lambda^{-3}$, while the matrix elements depend on the angular part of the wave functions. In both cases, there are experimental wavelengths, so the matrix elements are being tested. The M1 transition rates, calculated from the measured lifetimes, are 78.31 $\pm$ 1.34 s$^{-1}$ for the Fe x transition and 57.08 $\pm$ 1.34 s$^{-1}$ for the Fe XIV transition. The agreement of theory with experiment is well within the anticipated theoretical uncertainty and within 5%–6% of the experimental data. Consequently, all astrophysical models or calculations, which have used the existing theory, are more accurate than

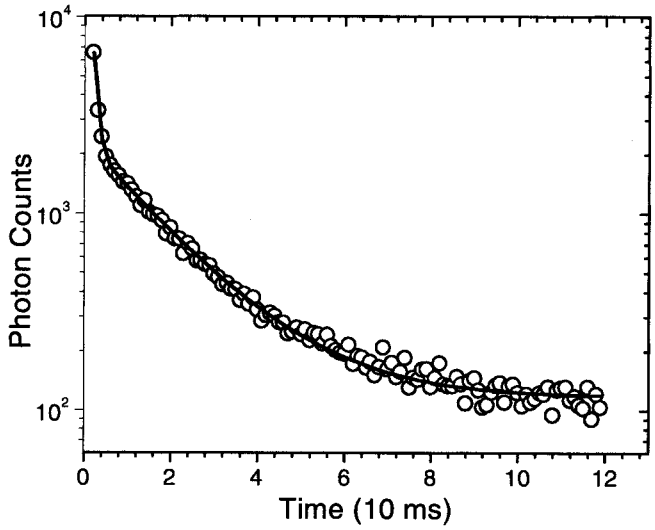


FIG. 3.—Data representing the lifetime of the $3p^2\ ^2P^o_{3/2}$ level in Fe XIV and an initial transient. A double exponential and a constant background were used to fit the data, with the longer decay being associated with the $^2P^o_{3/2}$ lifetime.

TABLE 1

A Comparison of Calculated and Experimental Lifetimes for the Fe x and Fe xiv Coronal Transitions

| Ion | Transition | Filter Bandwidth (nm) | Ion Storage Time (ms) | Measured Lifetime (ms) | Theoretical Lifetimes (ms) | | Experimental M1 Transition Rate ($s^{-1}$) |
|---|---|---|---|---|---|---|---|
| | | | | | MCDF | NR | |
| Fe x ..... | $^2P^o_{3/2}$–$^2P^o_{1/2}$ | 640 ± 2 | 1640 ± 228 | 13.64 ± 0.25 | 14.44 | 14.37 | 73.31 ± 1.34 |
| Fe xiv ..... | $^2P^o_{1/2}$–$^2P^o_{3/2}$ | 530 ± 2 | 1936 ± 312 | 17.52 ± 0.29 | 16.63 | 16.61 | 57.08 ± 0.94 |

expected and, in the case of these Fe ion transitions, can now be further enhanced in accuracy by use of the experimental data.

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