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Extreme ultraviolet emission lines of Ni XII in laboratory and solar spectra

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ABSTRACT

Wavelengths for emission lines arising from $3s^23p^5$–$3s3p^6$ and $3s^23p^5$–$3s^23p^43d$ transitions in Ni XII have been measured in extreme ultraviolet spectra of the Joint European Torus (JET) tokamak. The $3s^23p^5\ ^2P_{1/2}$–$3s^23p^4(^3P)3d\ ^2D_{3/2}$ line is found to lie at 152.90 ± 0.02 Å, a significant improvement over the previous experimental determination of 152.95 ± 0.5 Å. This new wavelength is in good agreement with a solar identification at 152.84 ± 0.06 Å, confirming the presence of this line in the solar spectrum. The Ni XII feature at 152.15 Å may be a result only of the $3s^23p^5\ ^2P_{3/2}$–$3s^23p^4(^3P)3d\ ^2D_{5/2}$ transition, rather than a blend of this line with $3s^23p^5\ ^2P_{3/2}$–$3s^23p^4(^3P)3d\ ^2P_{1/2}$, as previously suggested. Unidentified emission lines at 295.32 and 317.61 Å in solar flare spectra from the *Skylab* mission are tentatively identified as the $3s^23p^5\ ^2P_{3/2}$–$3s3p^6\ ^2S_{1/2}$ and $3s^23p^5\ ^2P_{1/2}$–$3s3p^6\ ^2S_{1/2}$ transitions in Ni XII, which have laboratory wavelengths of 295.33 and 317.50 Å, respectively. Additional support for these identifications is provided by the line intensity ratio for the solar features, which shows good agreement between theory and observation.

Key words: methods: laboratory – Sun: flares – ultraviolet: general.

1 INTRODUCTION

For a number of years the identification of transitions in intermediate and high ionization stages of iron and neighbouring elements has been a major topic of research (see, for example, Jordan 1968; Träbert 1998). Such lines may be prominent in solar extreme ultraviolet (EUV) spectra, and indeed the classification of 3p–3d transitions was first undertaken to provide identifications for some of the strongest lines observed from the Sun (Alexander, Feldman & Fraenkel 1965; Fawcett & Gabriel 1965; Gabriel, Fawcett & Jordan 1966). More recently, reliable identifications for weak emission lines has become increasingly important, given the availability of high-quality solar EUV spectra from the *Solar and Heliospheric Observatory* (*SOHO*) mission (Harrison et al. 1997). There is also the possibility of detecting such features in stellar observations from, for example, the *Chandra* and *Extreme Ultraviolet Explorer* (*EUVE*) satellites (Jordan 1996).

In this paper we present measurements of wavelengths for $3s^23p^5$–$3s3p^6$ and $3s^23p^5$–$3s^23p^43d$ transitions in Ni XII, identified in EUV spectra of the Joint European Torus (JET) tokamak. We compare these measurements with previous experimental and theoretical values, and also identify the lines where possible in solar observations.

2 WAVELENGTH MEASUREMENTS

The wavelengths of Ni XII lines were measured from spectra of the Joint European Torus (JET) tokamak. JET is currently the largest tokamak experiment in the world. The project was designed with the objectives of obtaining and studying plasmas in conditions and dimensions approaching those needed in a fusion reactor (Rebut et al. 1987). JET has overall dimensions of about 15 m in diameter and 12 m in height, and the D-shaped vacuum vessel is of major radius $R_0 = 2.96$ m, with minor radii of $a = 1.25$ m (horizontal) and $b = 2.10$ m (vertical). The toroidal component of the magnetic field is generated by 32 D-shaped coils equally spaced around the torus and enclosing the vacuum vessel, and at the plasma centre the maximum field strength is 3.45 T. A plasma current of up to 7 MA is produced by transformer action using an eight-limbed magnetic circuit. Around the centre limb of the magnetic circuit is a set of coils, which acts as the primary winding, the plasma itself acting as the secondary. Poloidal coils situated around the outside of the vacuum vessel are used to shape and position the plasma. Normally the duration of a plasma pulse in JET is 20–30 s, with the plasma current sustainable at peak values for several seconds. However, the plasma duration can be extended to 60 s by the use of a non-inductive current drive system (LHCD).

Spectra of JET pulses were recorded using a 2-m extreme grazing-incidence (Schwob–Fraenkel) spectrometer (Schwob et al. 1987), equipped with a 600 g mm^{-1} grating and two microchannel-plate image intensifier-convertor detector systems, fibre-optically

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coupled to 1024-element photodiode arrays. The two detectors are moveable along the Rowland circle, and cover 20–60-Å sections of spectra, depending on the wavelength. Two wavelength regions were observed, namely 142–163 Å and 288–323 Å, at a spectral resolution of 0.2 Å (FWHM).

We note that nickel is an intrinsic impurity in the JET plasma, arising from sputtering from the walls of the tokamak. However, the electron temperature of maximum Ni xii fractional abundance in ionization equilibrium within a plasma is $T_e \simeq 2 \times 10^6$ K (Mazzotta et al. 1998). In JET, the central electron temperatures are greater than 10^7 K (see, for example, Coffey et al. 1994), and hence Ni xii will only be observed in the cooler, outer layers of the plasma. We therefore ensured that the data recorded by the spectrometer were for lines-of-sight through the outer edge of JET, and not through the bulk region.

Spectra of the JET pulses were wavelength calibrated using, as standards, the emission lines of other species which are also intrinsic to the plasma, including C iv 312.45 Å and Ni xviii 292.00 Å (see Denne et al. 1989 for more details). In Figs 1 and 2 we show spectra for two pulses, to illustrate the quality of the observational data.

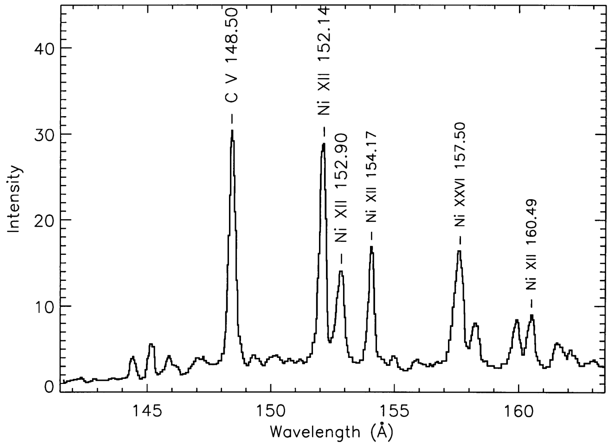

Figure 1. Plot of JET pulse 31273 in the wavelength range 142–163 Å. Several Ni xii lines are identified in the spectrum, as well as transitions of C v and Ni xxvi.

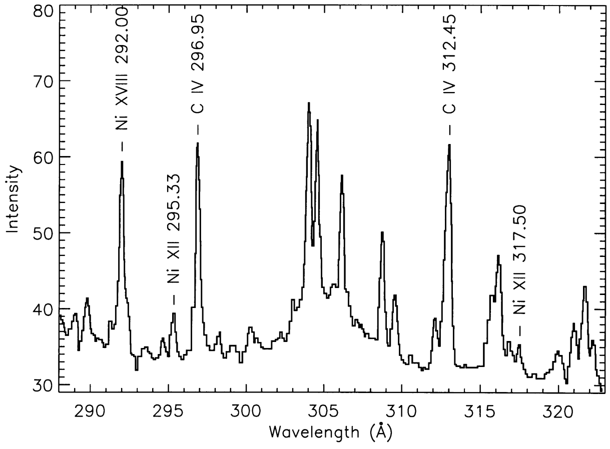

Figure 2. Plot of JET pulse 34938 in the wavelength interval 288–323 Å. Several Ni xii lines are identified in the spectrum, as well as transitions of C iv and Ni xviii.

3 RESULTS AND DISCUSSION

The Ni xii line identifications and wavelengths, which should be accurate to ±0.02 Å, are summarized in Table 1. Also listed in the table are previous wavelength measurements for these transitions. These should be accurate to ±0.01–0.03 Å, apart from the Gabriel et al. (1966) estimates, which have uncertainties of ±0.5 Å. The theoretical wavelengths provided in Table 1 are from Fawcett (1987).

An inspection of Table 1 reveals generally very good agreement between the present results and previous measurements. For the $3s^23p^5\ ^2P_{1/2}$–$3s^23p^4(^3P)3d\ ^2D_{3/2}$ transition, we note that our derived wavelength of 152.90 ± 0.02 Å represents a significant improvement over the 152.95 ± 0.5 Å determination by Gabriel et al. (1966), the only previous wavelength measurement (to our knowledge) for this line.

In the case of the $3s^23p^5\ ^2P_{3/2}$–$3s^23p^4(^3P)3d\ ^2P_{1/2}$ and $3s^23p^5\ ^2P_{3/2}$–$3s^23p^4(^3P)3d\ ^2D_{5/2}$ transitions, Goldsmith & Fraenkel (1970) measured wavelengths of 152.152 and 152.153 Å, respectively. We therefore assumed that our feature at 152.14 Å must be a blend of these lines. However, the accuracy of the Goldsmith & Fraenkel wavelength determinations is at best ~0.005 Å, so it is difficult to see how they could measure two lines with a separation of only 0.001 Å. Fawcett (1987) calculated wavelengths of 152.08 and 151.95 Åfor the $3s^23p^5\ ^2P_{3/2}$–$3s^23p^4(^3P)3d\ ^2P_{1/2}$ and $3s^23p^5\ ^2P_{3/2}$–$3s^23p^4(^3P)3d\ ^2D_{5/2}$ lines, respectively. His theoretical result for the $3s^23p^5\ ^2P_{1/2}$–$3s^23p^4(^3P)3d\ ^2D_{3/2}$ transition differs by 0.18 Å from the experimental value. As this transition arises from the same multiplet as $3s^23p^5\ ^2P_{3/2}$–$3s^23p^4(^3P)3d\ ^2D_{5/2}$, it is therefore possible that the calculated wavelength for the latter may be in error by a similar amount, in which case its theoretical value of 151.95 Å is compatible with an experimental determination of 152.15 Å. However, the calculated wavelength for $3s^23p^5\ ^2P_{3/2}$–$3s^23p^4(^3P)3d\ ^2P_{3/2}$ is within 0.01 Å of the measured result. This makes it less likely (but not impossible) that the theoretical value of 152.08 Å for $3s^23p^5\ ^2P_{3/2}$–$3s^23p^4(^3P)3d\ ^2P_{1/2}$ in the same multiplet is in error by the 0.07 Å required for this feature to have the experimental wavelength of 152.15 Å indicated by Goldsmith & Fraenkel. It therefore appears possible that the 152.15 Å feature is a result of the $3s^23p^5\ ^2P_{3/2}$–$3s^23p^4(^3P)3d\ ^2D_{5/2}$ transition alone, while the $3s^23p^5\ ^2P_{3/2}$–$3s^23p^4(^3P)3d\ ^2P_{1/2}$ line lies at a shorter, unidentified wavelength. We note that Ryabtsev (1979) and Gabriel et al. (1966) both assign the 152.15-Å line to the $3s^23p^5\ ^2P_{3/2}$–$3s^23p^4(^3P)3d\ ^2D_{5/2}$ transition, with no mention of $3s^23p^5\ ^2P_{3/2}$–$3s^23p^4(^3P)3d\ ^2P_{1/2}$. However, clearly more experimental and theoretical work on these lines is required.

Several of the Ni xii lines in Table 1 should be detectable in solar spectra, and in Table 2 we provide a summary of possible solar identifications. Our improved wavelength determination for the $3s^23p^5\ ^2P_{1/2}$–$3s^23p^4(^3P)3d\ ^2D_{3/2}$ feature at 152.90 Å is in good agreement with an identification at 152.84 ± 0.06 Å by Malinovsky & Heroux (1973), and confirms the presence of this feature in the solar spectrum. There is an unidentified line at 295.32 Å in the solar flare list of Dere (1978) based on *Skylab* observations, which the present work suggests may be the $3s^23p^5\ ^2P_{3/2}$–$3s3p^6\ ^2S_{1/2}$ transition. Although there is no line listed by Dere at the laboratory wavelength for the $3s^23p^5\ ^2P_{1/2}$–$3s3p^6\ ^2S_{1/2}$ transition (317.50 Å), there is a feature at 317.61 Å. Dere suggested that this was the $3s3p\ ^3P_1$–$3p^2\ ^3P_0$ transition of Fe xv, with a laboratory wavelength of 317.60 Å (Churilov et al. 1985). However, Bhatia & Kastner (1980) pointed out that the 317.60-Å line intensity should be more than 10 000 times weaker than that of the Fe xv 284.15-Å

Table 1. Ni XII line wavelengths (in Å).

Transition	Present result	Previous measurement	Theoretical value[a]
$3s^23p^5\ ^2P_{3/2}$–$3s^23p^4(^3P)3d\ ^2P_{1/2}$	152.14	152.15[b]	152.08
$3s^23p^5\ ^2P_{3/2}$–$3s^23p^4(^3P)3d\ ^2D_{5/2}$	152.14	152.15[b] 152.15[c] 152.14[d]	151.95
$3s^23p^5\ ^2P_{1/2}$–$3s^23p^4(^3P)3d\ ^2D_{3/2}$	152.90	152.95[d]	152.72
$3s^23p^5\ ^2P_{3/2}$–$3s^23p^4(^3P)3d\ ^2P_{3/2}$	154.17	154.18[b] 154.17[c] 154.15[d]	154.17
$3s^23p^5\ ^2P_{3/2}$–$3s^23p^4(^1D)3d\ ^2S_{1/2}$	160.49	160.55[b] 160.56[e]	160.56
$3s^23p^5\ ^2P_{3/2}$–$3s3p^6\ ^2S_{1/2}$	295.33	295.32[f]	295.32
$3s^23p^5\ ^2P_{1/2}$–$3s3p^6\ ^2S_{1/2}$	317.50	317.48[f]	317.47

[a] Fawcett (1987).
[b] Goldsmith & Fraenkel (1970).
[c] Ryabtsev (1979).
[d] Gabriel et al. (1966).
[e] Fawcett & Hayes (1972).
[f] Fawcett & Hatter (1980).

Table 2. Solar wavelengths (in Å) for Ni XII lines.

Transition	Present measurement	Solar wavelength
$3s^23p^5\ ^2P_{3/2}$–$3s^23p^4(^3P)3d\ ^2D_{5/2}$	152.14	152.15[a] 152.15[b]
$3s^23p^5\ ^2P_{1/2}$–$3s^23p^4(^3P)3d\ ^2D_{3/2}$	152.90	152.84[b]
$3s^23p^5\ ^2P_{3/2}$–$3s^23p^4(^3P)3d\ ^2P_{3/2}$	154.17	154.18[a] 154.20[b]
$3s^23p^5\ ^2P_{3/2}$–$3s3p^6\ ^2S_{1/2}$	295.33	295.32[c] ?
$3s^23p^5\ ^2P_{1/2}$–$3s3p^6\ ^2S_{1/2}$	317.50	317.61[c] ?

[a] Behring, Cohen & Feldman (1972).
[b] Malinovsky & Heroux (1973).
[c] Unidentified line in Dere (1978).

($3s^2\ ^1S$–$3s3p\ ^1P$) feature. This is confirmed by our own line ratio calculations for the solar flare analysed by Dere. In this flare, the Fe XV line-emitting region has an electron density of $\sim 3\times10^{10}\,\mathrm{cm}^{-3}$ (Keenan et al. 1993), while the electron temperature of maximum Fe XV fractional abundance in ionization equilibrium is $T_\mathrm{e} = 2\times10^6\,\mathrm{K}$ (Mazzotta et al. 1998). For these plasma parameters, Keenan et al. derive an intensity ratio I(317.60 Å)/I(284.15 Å) $= 3.2\times10^{-5}$, confirming that the 317.61-Å line in the Dere spectrum is not the result of Fe XV.

The 295.32- and 317.61-Å line measurements by Dere (1978) were made from spectra recorded at different times during the solar flare. Hence the intensity ratio provided by Dere for these features ($\sim$1) does not reflect the true ratio, because of the time variability of the flare emission. However, by using the EUV light curve for this flare (Dere & Cook 1979), we can correct for the time dependence of the emission line intensities, and derive a true ratio of I(295.32 Å)/I(317.61 Å) $\simeq 3.0$. This compares favourably with the theoretical Ni XII ratio of I(295.33 Å)/I(317.50 Å) $= 2.5$ (Träbert 1996), indicating that the lines in the flare spectra are the result of the Ni XII $3s^23p^5\ ^2P_{1/2,3/2}$–$3s3p^6\ ^2S_{1/2}$ transitions. However, additional solar observations would be desirable in order to confirm these findings. We note that the lines are unfortunately not detected in high-resolution spectra from *SOHO* (Brooks et al. 1999). This is perhaps not surprising, as the *SOHO* spectra are of the quiet Sun, and the 295.32 and 317.61 Å features only appear to be measurable in flare observations.

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