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Oscillator strengths of the $2s\,^2S_{1/2}$-$2p\,^2P^o_{1/2,3/2}$ transitions in Fe XXIV and the $2s^2\,^1S_0$-$2s2p\,^3P^o_1$ transition in Fe XXIII

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We have used the beam-foil technique to measure the mean lives of the upper levels of: (i) the $2s\,^2S_{1/2}-2p\,^2P^o_{1/2,3/2}$ resonance transitions (at 255 and 192 Å) in lithiumlike Fe XXIV and (ii) the $2s^2\,^1S_0-2s2p\,^3P^o_1$ intersystem transition (at 264 Å) in berylliumlike Fe XXIII. The measured mean lives are $\tau(2p\,^2P^o_{1/2}) = 0.55 \pm 0.02$, $\tau(2p\,^2P^o_{3/2}) = 0.235 \pm 0.01$, and $\tau(2s2p\,^3P^o_1) = 13 \pm 4$ ns. Oscillator strengths derived from the Fe XXIV results are in good agreement with recent relativistic multiconfiguration Hartree-Fock (MCHF) "length" gauge calculations; the Fe XXIII result is not in agreement with these MCHF calculations, but appears to be in agreement with recent intermediate coupling calculations.

We report experimental values of the oscillator strengths of the lowest-lying resonance transitions, $2s\,^2S_{1/2}$-$2p\,^2P^0_{1/2,3/2}$, in lithiumlike Fe XXIV (Fe^{+23}); we also report a preliminary experimental value of the oscillator strength of the intersystem transition, $2s^2\,^1S_0$-$2s2p\,^3P^o_1$, in beryllium-like Fe XXIII (Fe^{+22}). Beam-foil[1] mean-life measurements performed at the Berkeley superheavy-ion linear accelerator (HILAC) on Fe beams passed through carbon foils provided the data from which these oscillator strengths were obtained.

Lines from low-lying transitions of highly charged ions of the Li and Be isoelectronic sequences appear prominently in the spectra of hot plasmas, both those of astrophysical interest associated with solar flares[2,3] and those associated with the controlled-fusion program.[4] Spectral wavelengths are used to identify the ions present; knowledge of oscillator strengths is required for determination of the ion concentration[5] and the electron temperature and density.[6] Further, these simple systems with small cores should be susceptible to successful theoretical treatment. In particular, for sufficiently high effective nuclear charge, relativistic contributions to calculated oscillator strengths are expected[7-11] to be large enough to be experimentally discernible. Calculated[7,8] oscillator strengths of the $2s\,^2S_{1/2}$-$2p\,^2P^o_{1/2,3/2}$ doublet in Li-like Fe XXIV contain relativistic contributions of 6% and 37%, respectively, of the nonrelativistic values; the nonzero oscillator strength of the $2s^2\,^1S_0$-$2s2p\,^3P^o_1$ transition in Be-like Fe XXIII is entirely due to relativistic effects. Hence, these measurements provide a test of whether these calculational techniques may be used with confidence in regions not presently accessible to experiment.

A 491-MeV Fe^{+17} beam (60 particle nA) from the Lawrence Berkeley Laboratory super-HILAC was magnetically deflected into our apparatus and passed through a carbon foil (206 $\mu g/cm^2$ for the Li-like Fe, and 40 $\mu g/cm^2$ for the Be-like Fe) mounted on a movable support that had about 0.5-m total travel. A 0.95-cm collimator mounted immediately upstream from the region viewed by the spectrometer (used in the standard "side-on" viewing configuration[1]) ensured that light detected by the spectrometer was emitted by ions that subsequently struck the downstream Faraday cup. The spectrometer (McPherson model No. 247, with stepping motor drive and a 2.2 m, 600 lines/mm grating) was operated with an 82° angle of incidence, a 3.17-mm-wide grating-mask slit, and a blaze wavelength of 210 Å; for an entrance slit width of 500 μm, the beam length viewed was 2.1 mm. The photon detector (Bendix Channeltron model No. 4700) was placed behind a repelling (−300 V) grid followed by a grounded grid to exclude charged particles. Calibration constants for the spectrometer were obtained from spectral scans over the 225–305 Å region containing the

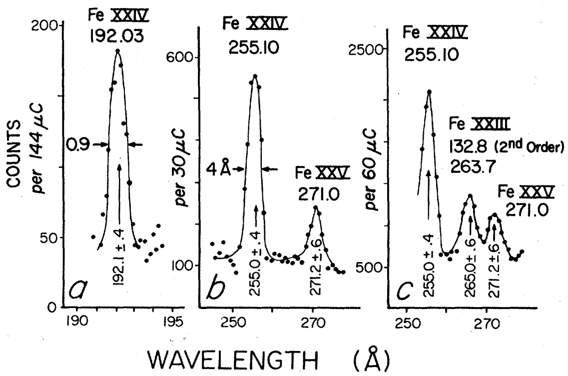

FIG. 1. Spectral scans of the post-foil beam for a 491-MeV Fe^{+17} beam incident on a carbon foil. (a) Scan of the $2s\ ^2S_{1/2}$-$2p\ ^2P^o_{3/2}$ resonance line from Li-like Fe XXIV (120 μm slits and 206 μg/cm²foil). (b) Scan of the $2s\ ^2S_{1/2}$-$2p\ ^2P^o_{1/2}$ resonance line from Fe XXIV and the previously unreported line at 271.2 ± 0.6 Å, which we attribute to the $1s2s\ ^3S_1$-$1s2p\ ^3P^o_2$ transition in He-like Fe XXV (500 μm slits and 206 μg/cm² foil). (c) Scan over the region shown in (b) (foil thickness of 40 μg/cm²). The feature at 265 Å is attributed to a blend of the first- and second-order lines from Be-like Fe XXIII (132.8 Å from $2s^2\ ^1S_0$-$2s2p\ ^1P^o_1$ and 263.7 Å from $2s^2\ ^3P^o_1$).

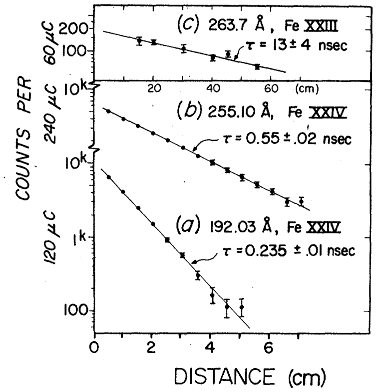

FIG. 2. Measured decay curves for determination of the mean lives of (a) the $2p\ ^2P^o_{3/2}$ level of Fe XXIV. (b) the $2p\ ^2P^o_{1/2}$ level of Fe XXIV, and (c) the $2s2p\ ^3P^o_1$ level of Fe XXIII.

first five members of the He II Lyman series from a stationary hollow-cathode source (calibration uncertainty of ± 0.2 Å).

Spectral scans over the regions of interest are shown in Fig. 1. These data were fitted[12] with Gaussian line shapes; the quoted uncertainties have been calculated from twice the statistical uncertainty (typically 0.3 Å) associated with the Gauss fitting added in quadruature to the 0.2 Å uncertainty associated with the calibration. There is good agreement with known accurate wavelengths obtained from solar-flare spectra.[3] We identify the line at 271.2 ± 0.6 Å as the previously unreported $1s2s\ ^3S_1$-$1s2p\ ^3P^o_2$ transition in He-like Fe XXV; a scaling of the terms used by Davis and Marrus[13] for Ar XVII yields[14] a predicted wavelength of 271.0 Å, in agreement with our measured value.

Typical decay curves from which the mean lives of the $2p\ ^3P^o_{1/2,3/2}$ levels in Fe XXIV were obtained as shown in Figs. 2(a) and 2(b) (each decay curve was measured three times). These data were obtained by the following procedure: for each foil position, with the spectrometer set on the particular spectral line center, the number of counts registered by the detector and the time elapsed during collection of a specified amount of charge in the Faraday cup were recorded (the dark current was ≈ 0.1 count/sec). At the same foil position, background data were acquired by making similar measurements about 10 Å above and below the line center. The number of detector counts recorded (corrected for average background and dark current) versus foil position is plotted in Figs. 2(a) and 2(b). A single exponential has been least-squares fitted[15] to the data in each case; the quoted uncertainties in the mean lives have been obtained by adding in quadrature the uncertainty (1%) in beam velocity and twice the statistical uncertainty (≈ 68% confidence level) associated with the least-squares fit. The effect of cascading from higher levels into the upper transition level is assumed to be negligible because (i) good fits to the data were obtained with single exponentials and (ii) such effects are expected to be negligible in these cases where the lifetimes of the higher levels (that have significant initial populations) are much shorter than those of the upper transition levels; possible effects of the resulting "growing in" cascades were eliminated by omitting from the fit data points taken within a few mm of the foil.

The results of these measurements are compared with theoretical predictions in Table I and Fig. 3. The absorption oscillator strengths, f_{ik}, were calculated using the usual formula[16]

$$f_{ik} = 1.50 \times 10^{-16} \lambda^2 (g_k/g_i) A_{ki} ,$$

where the transition wavelength[2] λ is in Å, g_k and g_i are the statistical weights of the upper and lower levels, respectively, and A_{ki} is the transition probability; in these cases, since the decay is unbranched, $A_{ki} = 1/\tau_k$, where τ_k is the mean life (in seconds) of the upper level measured in this work. It is apparent that the relativistic multiconfiguration Hartree-Fock (MCHF) calculations of Armstrong *et al.*[7] and Kim and Desclaux[8] in the dipole "length" gauge are in excellent agreement with our measurements.

The decay curve from which the mean life of the $2s2p\ ^3P^o_1$ level of Fe XXIII was obtained is shown in

TABLE I. Comparison of experimental and theoretical values of absorption oscillator strengths.

Ion	Transition observed	λ (Å)[a]	Measured lifetime (ns) of upper level[b]	Experimental oscillator strength[b]	Calculated relativistic oscillator strengths[c] f_L	f_V
Fe XXIV	$2s\,^2S_{1/2}$-$2p\,^2P^o_{1/2}$	255.10	0.55 ±0.02	0.018 ±0.001	0.018[d] (0.017)	0.020[e] (0.017)
Fe XXIV	$2s\,^2S_{1/2}$-$2p\,^2P^o_{3/2}$	192.03	0.235±0.01	0.047 ±0.002	0.048[d] (0.035)	0.053[e] (0.035)
Fe XXIII	$2s^2\,^1S_0$-$2s2p\,^3P^o_1$	263.74	13±4	0.0024±0.0007	0.0015[d,f]	0.0024[e]
					0.0017[g]	0.0015[f]
					0.0021[h]	

[a] Reference 2.

[b] This work.

[c] The symbols f_L and f_V denote results of length and velocity gauge calculations, respectively; values in parentheses are nonrelativistic (Refs. 7, 8, and 17).

[d] References 7 and 8; MCHF.

[e] Reference 7; MCHF.

[f] Reference 9; MCHF.

[g] Reference 10; intermediate coupling.

[h] Reference 11; intermediate coupling.

Fig. 2(c) (this decay curve was measured only one time). The data shown were obtained by a different procedure than that described above. At the spectral resolution (3.25 Å) used for this portion of the experiment the spectral line of interest at 263.7 Å from $2s^2\,^1S_0$-$2s2p\,^3P^o_1$ transition of Fe XXIII was blended with second order 132.8 Å from the $2s^2\,^1S_0$-$2s2p\,^1P^o_1$ transition of Fe XXIII [see Fig. 1(c)]. Spectral scans over the 263.7 Å line were obtained for foil locations of 0.6 to 55.5 cm from the observation region and were fitted[12] with Gaussian line shapes. The "wavelength" of this line depended upon foil location for small foil-to-observation-region distances, indicating a blend. For foil locations greater than 15 cm the line wavelength was stable at 263.7±1.0 Å. Spectral line peak amplitudes produced by the Gaussian fits are plotted versus foil location in Fig. 2(c) and have been least-squares fitted[15] to a single exponential to yield the mean life indicated; the quoted uncertainty was obtained by the method described above. No cascade analysis was attempted in this case. The first of the arguments presented earlier against the necessity of a cascade analysis does not apply in this instance (owing to the poor quality of the data); however, the second argument should hold here also. It should be noted that we regard our measured value in this case to be much less reliable than those given above owing to the obvious shortcomings of poor statistics, the small number of data points, and the fact that we followed the decay curve for less than one mean life; we report the result because it appears to be of considerable interest.

The result of our measurement is compared with theory in Table I. The relativistic MCHF "velocity" gauge calculation of Armstrong *et al.*[7] appears to be in good agreement with our measurement. This agreement may be misleading in view of the fact that a similar relativistic calculation by Cheng and Johnson[9] (which includes certain "exchange overlap" terms neglected by

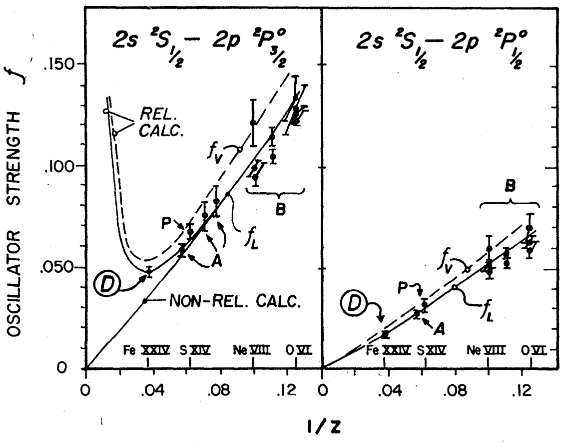

FIG. 3. Comparison of theoretical and experimental oscillator strengths for the $2s\,^2S_{1/2}$-$2p\,^2P^o_{1/2,3/2}$ resonance transitions for ions of the Li isoelectronic sequence. The theoretical curves are results of multiconfiguration Hartree-Fock calculations (relativistic—Refs. 7 and 8, nonrelativistic—Refs. 7, 8, and 11); relativistic and nonrelativistic results appear the same on the scale shown for the $^2S_{1/2}$-$^2P^o_{1/2}$ transition; subscripts V and L denote results of velocity and length gauge calculations, respectively. The experimental points are D (this work), P (Ref. 18), A (Ref. 19), and B (Ref. 20) (Z is the atomic number).

Armstrong *et al.*) obtains good agreement between oscillator strengths calculated in the length and velocity gauges. Their results do not agree with our measurements but do agree with the length gauge calculations of Armstrong *et al.*[7] and Kim and Desclaux[8]; thus, it appears there is disagreement between the relativistic MCHF calculation and experiment in this instance. The results of two relativistic intermediate-coupling calculations (Weiss[10] and Victorov and Safronova[11]) are also listed in Table I; these results are in agreement with our measurement.

In summary, we have obtained experimental oscillator strengths for the $2s\,^2S_{1/2}$-$2p\,^2P^o_{1/2,3/2}$ transitions in Li-like Fe XXIV; the relativistic MCHF calculations of Armstrong *et al.*[7] and Kim and Desclaux[8] are in excellent agreement with our results. We have also obtained a preliminary value for the oscillator strength of the $2s^2\,^1S_0$-$2s2p\,^3P^o_1$ intersystem transition in Be-like Fe XXIII; in this instance the relativistic MCHF calculations[7-9] are not in agreement with our experimental result; instead, relativistic intermediate-coupling calculations[10,11] appear to agree with experiment in this case.

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