Auger electron emission from Na-like Fe ions excited in collisions of 170-keV Fe^{17+} on He and Ne

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L Auger-electron emission from Na-like configurations populated in iron projectile ions have been measured with high-energy resolution. The Auger states have been formed in collisions of 170-keV Fe^{17+} ions with He and Ne target atoms. The dominant spectral structures are due to Auger decay of states with the configurations $1s^22s^22p^5nln'l'$ in Fe^{15+} and in particular from the $1s^22s^22p^53s3p\ ^4D_{7/2}$ metastable state. The absolute energy of the $3s3p\ ^4D_{7/2}$ level is measured, and its metastable nature is demonstrated. Line assignments are obtained by using calculated transition energies and rates and by comparison to previously measured optical spectra.

It has recently been demonstrated that ion-atom collisional excitation of specific Auger states in energetic highly charged ions reveals a wealth of atomic structure and collisional information (e.g., Ref. 1). This is particularly true when combined with high-resolution electron spectroscopy performed at 0° (forward) observation angle.[2–5] Zero-degree Auger spectroscopy with its various kinematic advantages is an excellent tool for investigating specific excitation mechanisms as well as for detailed spectroscopic studies. It has been shown that such studies can readily be performed not only at high-energy accelerators, which produce fast highly charged ions, but also using modern ion sources which produce slow highly charged ions. Auger states can selectively be produced in collisions with fast (~ 10 MeV/q) highly charged ions incident on light target atoms via ionization and/or excitation of projectile inner-shell electrons.[2,3] In slow collisions (~ 10 keV/q), the Auger states are predominantly produced via single- or multiple-electron capture[6–12] from the target gas.

In this work the method of zero-degree Auger spectroscopy is used to study the excitation and decay of Auger states formed in 170-keV Fe^{17+} ions in collision with He and Ne target atoms. *L*-shell Auger spectra from such high-*Z*, highly charged ions are reported here for the first time. The data provide new line assignments and demonstrate the possibility of studying specific decay channels of Auger states selectively populated in projectile ions with a defined high-charge state prior to the collision.

These experiments were performed at the ECR (electron cyclotron resonance) ion source at the Lawrence Berkeley Laboratory 88-in. cyclotron.[13,14] The apparatus consists of a scattering chamber and a hemispherical electrostatic analyzer combined with a 45° parallel-plate analyzer. Figure 1 shows a schematic of the experimental

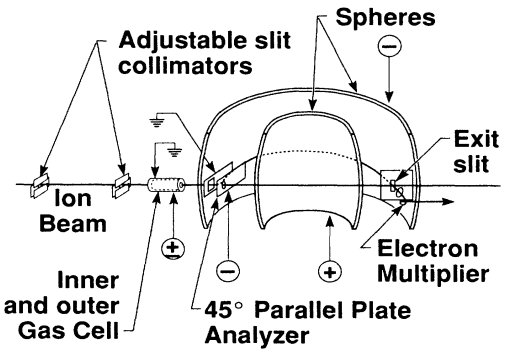

FIG. 1. Experimental arrangement for 0° electron spectroscopy using a collimated ion beam from the LBL ECR ion source. The beam passes through the gas cell and a 45° parallel-plate analyzer into the Faraday cup. Electrons emitted in the forward direction are deflected by the 45° analyzer into the high-resolution hemispherical instrument. Biasing the gas cell shifts the energy of electrons emitted inside the cell; those emitted from metastable states in the region between the cell and 45° analyzer are unshifted.

setup. The hemispherical analyzer[15] (a commercial instrument from the McPherson Company) and the scattering chamber[16] have been described in detail before. The 45° parallel-plate analyzer has been described both as a single-stage analyzer and recently in a tandemlike arrangement where two analyzers were used in order to perform zero-degree measurements.[4] The latter concept was adapted for the present experiment, where the hemispherical analyzer is used as the second stage.

In the following, the present setup for zero-degree measurements is outlined. The 170-keV Fe^{17+} ion beam passes through two sets of adjustable ("four-jaw") collimators where the upstream collimator was used to define a beam with an approximate spot size of 2×2 mm^2. The second collimator was used to eliminate slit-scattered particles. The collimated beam is then passed through a target cell of 40 mm length where He and Ne target gases of 99.99% purity were used. For the purpose of line energy measurements, typical pressures in the gas cell were some 10^{-3} Torr, while they were about 10^{-6} Torr outside the cell. However, to distinguish between multiple- and single-collision production processes, line intensities were measured for several target pressures between 0.23 and 1.0×10^{-3} Torr. Pressure in the gas cell was measured with a capacitance manometer. The gas cell consists of an outer cell and an inner cell insulated from each other.[5,15] Biasing of the inner cell allows one to shift the energy of the electrons present at the cell exit. This allows measurement of very-low-energy Auger lines and separation of lines from metastable excited states and prompt transitions (see also Fig. 3). Electrons coming from the target cell were analyzed by the 45° parallel-plate analyzer (first stage) 108 mm away from the cell. For the zero-degree arrangement, the ion beam was directed through the spectrometer by passing through four 4×4 mm^2 apertures in the gas cell and through a 3.5×10 mm^2 aperture and a 5-mm-diam aperture in the parallel-plate analyzer. For the 170-keV Fe^{17+} ion beam, a beam current of approximately 10 nA was detected in the Faraday cup and used for normalization. The rather large apertures, in the first analyzer stage, pass electrons with an energy resolution of about 9% (FWHM). These electrons then enter the wide acceptance cone of the hemispherical analyzer. This consists of two hemispheres with a mean radius of 36 cm (Ref. 15) and has a 0.2-mm exit slit, providing an energy resolution of 0.2% (FWHM). The solid angle of the total system is estimated to be about 10^{-4} sr. The kinematic effects associated with the zero-degree method are described in detail in various articles (see, e.g., Ref. 4). It should be noted that this particular arrangement reduces background due to stray electrons almost totally.

Figure 2 shows Fe L-Auger spectra from collisions of 170-keV Fe^{17+} on He and Ne; the energy scale and intensities have been transformed into the center-of-mass system. Figures 2(b) and 2(c) show spectra with He targets. Figure 2(d) is a background spectrum (no gas target). The spectrum in Fig. 2(c) is obtained by biasing the middle cell with -40 V which causes a shift of all spectral lines arising from prompt Auger decays inside the cell. Lines due to emission after the cell should therefore be unshifted (see Fig. 3). The spectra are dominated by a transition from an apparently metastable level with a measured energy of 253.9 eV. This energy is in good agreement with the calculated energy using the multiconfiguration Dirac-Fock model[18,19] (MCDF) for the Auger decay of the $2p^5 3s 3p\ ^4D_{7/2}$ level, Table I.

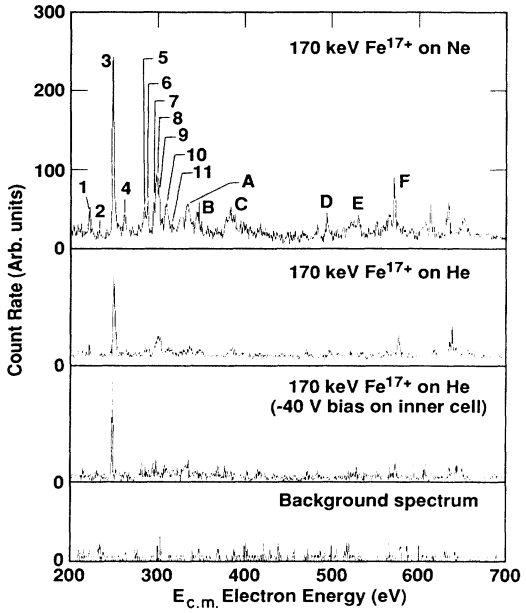

FIG. 2. (a)–(d) Fe^{15+} L-Auger spectra following 170-keV Fe^{17+} ion collisions with He and Ne gas atoms. The relative cross section is plotted vs the center-of-mass electron energy. (a) shows the spectrum following excitation in Ne. (b) and (c) show spectra following excitation in He. (d) is a background spectrum from residual gas pressure (3×10^{-7} Torr).

The quartet terms of the Na-like ions are forbidden to

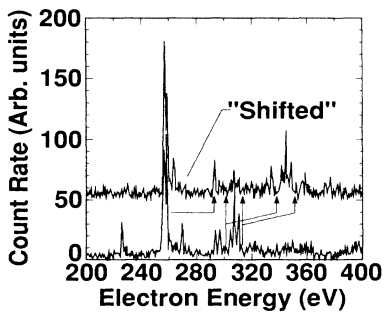

FIG. 3. The effect of the cell bias voltage is demonstrated for both metastable and quasimetastable levels. The $2p^5 3s 3p\ ^4D_{7/2}$ Auger decay line is left unaffected by the cell biasing of -40 V in the "shifted" spectrum. The feature at around 302.7 eV appears to have some metastability as shown by the arrows. The $3s3d\ ^4F_{9/2}$ level is known to be 49.9 eV above the $3s3d\ ^4D_{7/2}$ level (Ref. 22).

TABLE I. Comparison of experimental Auger energies with energies derived from the data in Ref. 21 and with theoretical energies. The absolute errors of the Auger energies are ±1 eV.

Number	Relative intensity	Experimental energy (eV)	Previous measurement[a] (eV)	Calculated energy (eV)	Initial state
1	54	226.5	226.5	224.1	$2p^5 3s^2\,{}^2P_{3/2}$
2	26	237.9	238.9	236.6	$2p^5 3s^2\,{}^2P_{1/2}$
3			252.4	251.7	$2p^5 3s 3p\,{}^4D_{5/2}$
				252.6	$2p^5 3s 3p\,{}^4D_{3/2}$
	241	253.9[b]		252.5	$2p^5 3s 3p\,{}^4D_{7/2}$
			254.8	254.2	$2p^5 3s(^1P)3p\,{}^2P_{1/2}$
4		267.1[c]		266.7	$2p^5 3s(^3P)3p\,{}^2D_{5/2}$
	45		266.7	266.5	$2p^5 3s 3p\,{}^4P_{3/2}$
			268.3	267.7	$2p^5 3s(^1P)3p\,{}^2D_{5/2}$
				268.9	$2p^5 3s(^1P)3p\,{}^2P_{3/2}$
5		289.9		286.9	$2p^5 3s(^3P)3p\,{}^2S_{1/2}$
				288.1	$2p^5 3p^2(^1D)\,{}^2P_{1/2}$
	54			289.0	$2p^5 3p^2(^3P)\,{}^4P_{5/2}$
				290.0	$2p^5 3p^2(^1D)\,{}^2F_{7/2}$
				290.5	$2p^5 3p^2(^3P)\,{}^4P_{3/2}$
6		293.7		292.7	$2p^5 3p^2(^1D)\,{}^2D_{5/2}$
				292.6	$2p^5 3p^2(^3P)\,{}^4P_{1/2}$
	62			292.8	$2p^5 3p^2(^3P)\,{}^2D_{3/2}$
				293.4	$2p^5 3p^2(^3P)\,{}^4D_{7/2}$
				293.6	$2p^5 3p^2(^3P)\,{}^2D_{5/2}$
7		300.0		300.4	$2p^5 3s(^3P)3d\,{}^4P_{1/2}$
				301.3	$2p^5 3s(^3P)3d\,{}^4P_{3/2}$
	59			299.4	$2p^5 3p^2(^3P)\,{}^4D_{1/2}$
			8	300.1	$2p^5 3p^2(^3P)\,{}^4S_{3/2}$
8		302.0	303.8[d]	302.9	$2p^5 3s(^3P)3d\,{}^4F_{9/2}$
			303.8	303.0	$2p^5 3s(^3P)3d\,{}^4P_{5/2}$
	98			302.9	$2p^5 3p^2(^3P)\,{}^4D_{3/2}$
				303.2	$2p^5 3p^2(^3D)\,{}^2F_{5/2}$
				303.8	$2p^5 3s(^3P)3d\,{}^4F_{7/2}$
9		306.2	306.6	306.2	$2p^5 3s(^3P)3d\,{}^4F_{3/2}$
			306.9	307.0	$2p^5 3s(^3P)3d\,{}^4D_{7/2}$
			307.1	307.5	$2p^5 3s(^1P)3d\,{}^2P_{1/2}$
	90		307.3	307.5	$2p^5 3s(^1P)3d\,{}^2F_{5/2}$
				305.1	$2p^5 3p^2(^1S)\,{}^2P_{3/2}$
				306.9	$2p^5 3p^2(^1D)\,{}^2D_{3/2}$
				307.1	$2p^5 3p^2(^3P)\,{}^2D_{5/2}$
10		312.9[c]		310.1	$2p^5 3s(^1P)3d\,{}^2P_{3/2}$
	54		312.2	311.2	$2p^5 3s(^3P)3d\,{}^4D_{1/2}$
			313.3	314.9	$2p^5 3s(^3P)3d\,{}^4D_{3/2}$
		315.3		316.0	$2p^5 3s(^3P)3d\,{}^2F_{7/2}$
				317.0	$2p^5 3s(^3P)3d\,{}^4F_{3/2}$
	59			317.2	$2p^5 3s(^3P)3d\,{}^4D_{5/2}$
				317.6	$2p^5 3s(^3P)3d\,{}^2D_{5/2}$
11		327.8	328.4	327.2	$2p^5 3s(^3P)3d\,{}^2P_{1/2}$
	32			329.1	$2p^5 3s(^3S)3d\,{}^4D_{1/2}$
		330.4[c]		329.4	$2p^5 3s(^3P)3d\,{}^2F_{5/2}$
	40			330.0	$2p^5 3p(^3S)3d\,{}^4D_{3/2}$
		331.9		331.5	$2p^5 3p(^3S)3d\,{}^4D_{5/2}$
	56			332.8	$2p^5 3s(^3P)3d\,{}^2P_{3/2}$
				333.3	$2p^5 3p(^3S)3d\,{}^4D_{7/2}$

[a] Reference 23.

[b] Newly assigned in this experiment, energy measured in biased spectrum.

[c] Blend.

[d] Derived from the $3s3p\,{}^4D_{7/2}-3s3d\,{}^4F_{9/2}$ energy given in Ref. 22 and our measured value for $3s3p\,{}^4D_{7/2}$.

TABLE II. Measured multiplet energies compared to calculated values. The bracketed number after the configuration is the number of levels calculated to contribute to the multiplet.

Multiplet	Experimental energy (eV)	Calculated	Initial configuration
A	338.3	338.5	$3p3d(6)$
B	351.0	351.0	$3p3d(7)$
C	387.5	387.7	$3d^2(7)$
D	498.2	498.4	$3s4d(3)$ $3p4s(4)$
E	533.8	533.3	$3p4d(14)$, $3p4f(5)$
F	574.6	574.6	$3d4p(8)$, $3d4d(23)$, $3p4f(2)$ $3d4s(1)$

Auger decay in the nonrelativistic *LS* coupling limit. Similarly they are *LS* forbidden to undergo an $E1$ transition to the $2p^6nl\,^2L$ system. The transition rates are thus strongly influenced by relativistic effects. This situation is similar to that encountered in the Li I sequence, see Refs. 20 and 21. Auger decay of the maximum j level of each configuration is even more forbidden due to the lack of a suitable doublet state to mix with; e.g., the $3s3p\,^4D_{7/2}$ and $3s3d\,^4F_{9/2}$ levels cannot Auger decay via the Coulomb or spin-orbit interactions. The $3s3d\,^4F_{9/2}$ level can, of course, undergo an $E1$ transition to the $3s3p\,^4D_{7/2}$ level; this transition has been studied along the Na-I sequence by Jupen *et al.*[22] The $3s3p\,^4D_{7/2}$ level has, however, no possibility to make a $\Delta n=0$ $E1$ transition—it Auger decays only through the spin-spin part of the Breit interaction. The calculated lifetime of the $2p^53s3p\,^4D_{7/2}$ level (MCDF including transverse Breit interaction) is 184 ns including the radiative $M2$ decay. The branching ratio for the $M2$ transition is calculated to be around 10^{-5}. For the beam velocity of 7.6×10^7 cm/s, the decay length for a 184-ns lifetime is 13.7 cm; thus a large fraction of ions in the $^4D_{7/2}$ state would leave the gas cell before decaying. It should be noted that the width of the unshifted line in the spectrum in Fig. 2(c) is somewhat narrower than the width observed in the Fig. 2(b) spectrum [2.4 eV compared to 3.1 eV full width at half-maximum (FWHM)]. This is most likely due to the shorter lifetime of the other (nonpure) components of the ^4D term. Intensity due to the prompt decay of these states would be shifted due to the application of the bias potential as described above.

The Auger spectra have been compared with the x-ray data on Fe XVI by Burkhalter *et al.*[23] and the results are tabulated in Table I. The spectra obtained in this work were calibrated to the $2p^53s^2\,^2P_{3/2}$ energy level from Ref. 23. Table II also contains a comparison with calculated energies, above 328 eV. No other experimental values are available in this energy range.

There two ways to produce the Auger states observed in this work. They are (a) double electron capture in a single collision, or (b) sequential capture of two electrons each of which originates from a different target atom. By careful pressure dependence studies we determined (a) to be the dominant mechanism in populating the states observed here. A similar but more detailed discussion for the collision systems Ar^{9+} and Ar^{8+} on He can be found in Ref. 9. The population of the $2p^53s3p\,^4D_{7/2}$ level could indicate evidence for a spin-flip collision. Such a collision requires that one of the captured electrons (antiparallel spins in He) flips its spin, i.e., both captured electrons have parallel spin. It is known,[6,7,9] however, that the cross section for double capture accompanied by "spin flip" is very small compared to capture without spin reorientation. It is likely, therefore, that double capture occurs in states of high n which are not pure spin states (but rather mixtures of $S=\frac{1}{2}$ and $\frac{3}{2}$ with the same total angular momentum); these states then populate $2p^53s3p\,^4D_{7/2}$ by a radiative cascade. It should be remembered that the "quartet" ($S=\frac{3}{2}$) notation has meaning for very few levels in high-Z ions.

In summary, Fe L-Auger transitions formed in 170-keV Fe^{17+} impact on He and Ne gas targets have been measured and assigned. The observed peaks are characteristic for the decay of Na-like Auger states in Fe projectile ions. The dominant lines are due to the decay of $1s^22s^22p^53s3p\,^4D$ and $1s^22s^22p^5nln'l'$ states. The observation of the metastable component ($2p^53s3p\,^4D_{7/2}$) will be the subject of further investigation regarding the lifetime, possible hyperfine quenching, and possible spin changing process for the state. This is a case where the magnetic spin-spin contribution in the Breit interaction can be tested in isolation from the Coulomb interaction which dominates allowed Auger decay.

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