Spectroscopy of Al VIII Produced by Low-Energy Charge-Changing Collisions

M. Mayo, D. Hitz, M. Druetta, S. Dousson,[a] J. P. Desclaux,[a] and S. Bliman
Association Grenobloise de Recherches Interdisciplinaires Plasmas et Physique Atomique, Centre d'Etudes Nucléaires de Grenoble, F-38041 Grenoble Cédex, France
(Received 1 October 1984)

Spectroscopy of emitted radiation following single-electron capture for 3-keV/u Al^{8+} ions on H_2 shows state-selective capture into the $n = 4$, 5, and 6 energy levels on the Al^{7+} ion. We report a relative measurement of transitions in Al VIII for $207 < \lambda < 800$ Å, and a multiconfiguration Dirac-Fock calculation of energy in levels in Al VIII is used to interpret the observed transitions.

PACS numbers: 32.30.Jc, 34.70.+e

This study of Al VIII provides spectroscopic data for transitions among energy levels of high principal quantum number n for which there is little existing energy-level and wavelength data.[1-5] Low-energy charge-exchange collisions can provide such data because an ion I^{Q+} of high charge Q incident at low energy on a neutral atom yields an ion $I^{(Q-1)+}$ in a few selected, predictable high-n states.[6,7] Because this process effects substantial radiation losses in fusion plasmas,[8] originating from high-Q impurity ions, final excited-state wavelength data for high-Q ions of heavier metallic elements are useful, and timely. The production for the first time of stable few-kiloelectronvolts/(atomic mass unit) Al^{Q+} ion beams ($Q \leq 13$) to do this study is an important and novel achievement for our electron cyclotron resonance (ECR) source, MINIMAFIOS.[9,10]

We report relative spectral measurements for $207 < \lambda < 800$ Å on the excited product states formed in $Al^{8+} + H_2 \rightarrow Al^{7+} + H_2^+$ collisions at 3 keV/u. We believe that the largest observed peaks originate from transitions in Al^{7+} seen here for the first time. We have calculated, using a multiconfigurational Dirac-Fock code,[11] Al^{7+} energy levels up to $n = 6$ for the configurations $1s^2 2s^2 2pnl$, and using them suggest the electron transitions observed.

We know the identity and excited-state composition of the incident ion beam as follows. Our apparatus[9,12] includes a two-magnet mass/charge (M/Q) analysis system. The first magnet can resolve two ions whose M/Q ratios differ by $\Delta(M/Q) = 3.6 \times 10^{-2}$ amu. With respect to the M/Q ratio for Al^{8+}, the closest M/Q ratios for ions of typical pollutants (e.g., O, N, C, Fe) have easily resolvable $\Delta(M/Q)$ values greater than 12.5×10^{-2} amu.

The Al^{8+} ion has a metastable excited state (^4P_J) with 11-, 41-, and 6-μs lifetimes for decay from the $J = \frac{5}{2}$, $\frac{3}{2}$, and $\frac{1}{2}$ sublevels, respectively, to the ground state ($^2P_{1/2}$).[13] For the metastable Al^{8+} fraction produced by our ion source, we estimate 12% after the measurements of Brazuk *et al.*[14] With use of the metastable lifetimes given above, and a statistical population of the J sublevels, and the distance (~ 600 cm with ~ 100-m mean free path) from ion extraction to target, then 54% of the extracted metastable fraction, or 6% (~ 18 nA) of the total beam reaches the target in the metastable state. We thus concluded that the most intense Al^{7+} transitions in our data originate from capture by ground-state Al^{8+} ions.

After electron capture (average Al^{8+} beam ~ 300 nA; target thickness $\leq 10^{13}$ cm^{-2}), emitted radiation from excited product ions is analyzed by a 3-m grazing-incidence (82°) spectrometer (300 lines/mm concave grating blazed at 552 Å) run with slits wide open (300 μm), and viewing the target at 25° from the forward beam direction. Data are corrected for the Doppler shift, $\Delta\lambda/\lambda = 2.3 \times 10^{-3}$. A Channeltron electron multiplier detected the radiation, and a multichannel analyzer (MCA) recorded counts. An MCA channel accumulated counts during the arrival time of a preselected constant number of projectiles (~ 30 μC). We recorded data for the first-order wavelength region $285 < \lambda < 790$ Å at intervals of about 0.8 Å. The spectrometer instrumental function is 3.5 Å at 600

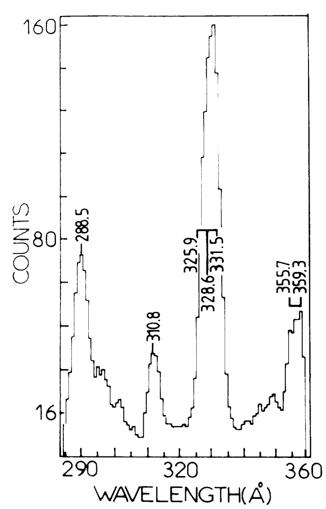

FIG. 1. Transitions in the range 285 to 360 Å observed following electron capture by 3-keV/amu Al^{8+} ions on H_2. Counts for constant incident beam intensity are uncorrected for spectrometer efficiency. Wavelengths are corrected for the Doppler shift.

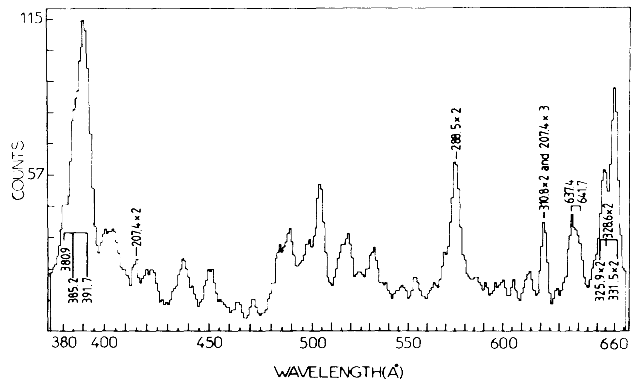

FIG. 2. The same as Fig. 1, but for transitions in the range 375 to 665 Å.

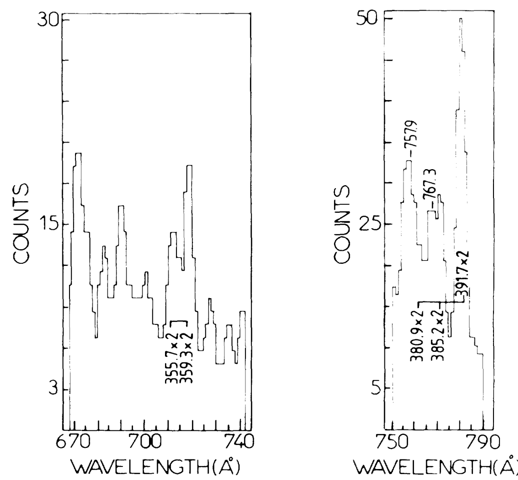

FIG. 3. The same as Fig. 1, but for transitions in the ranges 670 to 740 Å and 750 to 790 Å.

Å.

Figures 1, 2, and 3 are the smoothed[15] MCA output spectra. We deconvoluted the peaks adapting methods of Verma[16] and Sjontost.[17] To determine a wavelength we sought a better than 20% favorable comparison between the measured spectrometer relative efficiency ratio in two orders of a given wavelength and the observed ratio of counts in those two orders.

Table I gives the largest peaks with counts corrected for background and spectrometer efficiency. The wavelength error is ± 0.8 Å and includes both the data reproducibility and the wavelength reproducibility of a peak seen in two orders.

The third column of Table I is our suggested interpretation of the data. The Al^{7+} configurations $1s^2 2s^2 2pnl$ are the single-electron–capture product states for a low-energy ground-state Al^{8+} projectile.[18] Our calculated wavelengths for Al^{7+} $1s^2 2s^2 2pn'l' \rightarrow 1s^2 2s^2 2pnl$ transitions are summarized in Fig. 4 and noted there as $n'l' \rightarrow nl$. Calculated energy levels contain all leading relativistic effects and intrashell correlations. For sixteen transitions (with $\Delta n \neq 0$) tabulated by Kelly[2] around 50 Å, our calculation agrees to 2%. We conservatively estimate our calculated wavelengths for $\Delta n \neq 0$ transitions to be accurate to $\pm 10\%$ of the experimental value. Thus Table I can only be considered as suggestive: We chose transitions closest to observed peaks and closest to theoretical predictions.

Current theory and experiment[6,7,19,20] for a low-kiloelectronvolt/(atomic mass unit) $Q=8$ ion on a

TABLE I. Identification of some Al VIII transitions. The relative intensities are the counts of Figs. 1, 2, and 3 corrected for background and spectrometer efficiency.

λ (Å)	Relative intensity	Suggested transition	Other close transitions (within ∼5%×λ)
207.4	108	$5p \rightarrow 3d$	$4p \rightarrow 3s, 4d \rightarrow 3p, 5f \rightarrow 3d$
288.5	174	$4f \rightarrow 3d$	$4p \rightarrow 3d, 4s \rightarrow 3p$
310.8	53	$4p \rightarrow 3d$	$6p \rightarrow 4s$
325.9	69	$6p \rightarrow 4s$	
328.6	193	or	$6d \rightarrow 4p$
331.5	273	$4p \rightarrow 3d$	
355.7	55	Al VII	
359.3	66		
380.9	50		
385.2	94	$6f \rightarrow 4d$	$6p \rightarrow 4d, 6s \rightarrow 4p$
391.7	151		
637.4	36	$5d \rightarrow 4f$	$5s \rightarrow 4p, 5p \rightarrow 4d$
641.7	24		
757.9	23	$5d \rightarrow 4f$	$5p \rightarrow 4d$
767.3	21	$5d \rightarrow 4f$	$5p \rightarrow 4d$

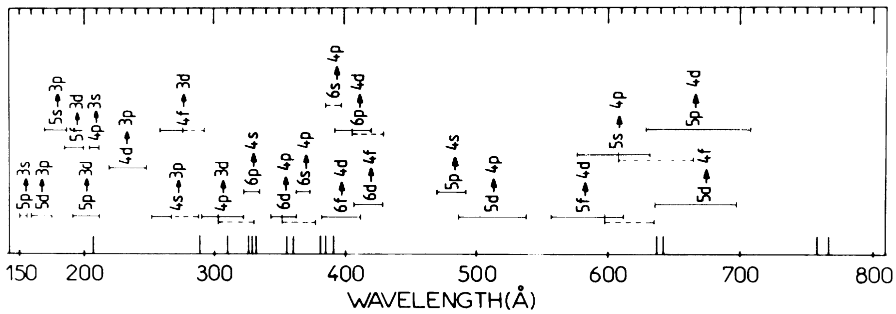

FIG. 4. Multiconfigurational Dirac-Fock code (Ref. 9) calculated Al VIII spectrum for $1s^2 2s^2 2pn'l' \rightarrow 1s^2 2s^2 2pnl$ transitions between 150 and 800 Å. Solid bar, includes all dipole allowed ${}^S L'_{J'} \rightarrow {}^S L_J$ transition terms for the given $n'l' \rightarrow nl$ transition; dashed bar, uniquely singlet transition terms; vertical lines are positions of reported experimental peaks.

neutral target predict electron capture on the ion dominantly into $n=5$, with $n=4$ and $n=6$ capture cross sections down by factors of 2 or more. Roughly, high-n selective capture results because the ion potential well is much deeper than the atom's, and large capture cross sections occur for quasiresonance between initial and final energy states.[6] For the present incident ion velocity of 0.345 a.u. theory predicts an almost statistical final l-state distribution for the captured electron ("intermediate mixing" of l states).[6] Thus, if our choice was ambiguous we chose the closest transition having $n=5$ capture, and in general we suggest, among the closest transitions, the one with the largest initial l.

Low spectrometer efficiency around 150 Å and low counting rates between 470 and 710 Å prevented reliable wavelength identification of most peaks in the very regions showing $n=5$ capture. Around 750 Å there are no calculated transitions closer than 10%; $n=6 \rightarrow 5$ transitions are of order 1000 Å. Around 328.6 Å we had no guide for choosing between $n=6$ or $n=4$ capture and/or cascade. The two peaks at 355.7 and 359.3 Å were also seen at 355.8 and 359.7 Å in our unpublished spectrum for 2.6-keV/amu $Al^{7+} + H_2 \rightarrow Al^{6+} + H_2^+$ collisions. The intensity ratios of the two peaks in both spectra are the same within 10%. We thus suggest that these peaks are Al^{6+} transitions; we do not have the calculated Al^{6+} transitions to identify them further. The present data correspond to no Al^{6+} transitions existing in Kelly's[2] tabulation.

To conclude we remark that this experiment was done primarily to prove the feasibility and reliability of our first metallic beams for atomic physics experiments. With higher resolution than we have here plus similar energy level calculations, low-kiloelectronvolt/(atomic mass unit) charge-exchange collisions with high-Q incident ions provide, as a result of state-selective capture, a new tool for spectroscopic studies of little known ion species. This is a departure from classical spectroscopic methods with beam foils and plasmas in which the resulting ion species are in several different charge states, and all energy levels are populated.

[(a)]Also at Département de Recherche Fondamentale, F-38041 Grenoble Cedex, France.

[1]W. C. Martin and R. Zalubas, J. Phys. Chem. Ref. Data **8**, 850 (1979).

[2]R. L. Kelly, *Atomic and Ionic Spectrum Lines Below 2000 Å* (Oak Ridge National Laboratory, Oak Ridge, 1982).

[3]Stanley Bashkin and John A. Stoner, Jr., *Atomic Energy Levels and Grotrian Diagrams* (American Elsevier, New York, 1975).

[4]B. Denne and E. Hinnov, Phys. Rev. A **29**, 3442 (1984).

[5]Kuniya Fukuda and Toshifumo Hasama, Jpn. J. Appl. Phys. **21**, 178 (1982).

[6]R. K. Janev, Phys. Scr. **T3**, 208 (1983).

[7]R. K. Janev and L. P. Presnyakov, Phys. Rep. **70**, 1 (1981).

[8]R. C. Isler *et al.*, Nucl. Fusion **23**, 1017 (1983).

[9]R. Geller and B. Jacquot, Phys. Scr. **T3**, 19 (1983).

[10]A. Chetoui *et al.*, to be published.

[11]J. P. Desclaux, Comput. Phys. Commun. **9**, 31 (1975).

[12]S. Bliman *et al.*, Phys. Scr. **T3**, 63 (1983).

[13]K. T. Cheng, Y. K. Kim, and J. P. Desclaux, At. Data Nucl. Data Tables **24**, 111 (1979).

[14]A. Brazuk *et al.*, J. Phys. B **17**, 2489 (1984).

[15]A. Savitzky and M. J. E. Golay, Ann. Phys. Chem. **36**, 1627 (1964).

[16]R. Verma, Nucl. Instrum. Methods **212**, 323 (1983).

[17]E. Sjontost, Nucl. Instrum. Methods **206**, 199 (1983).

[18]Hannspeter Winter, Phys. Scr. **T3**, 159 (1983).

[19]Hiroshi Ryufuku, Ken Sasaki, and Tsutomu Watanabe, Phys. Rev. A **21**, 745 (1980).

[20]R. Mann, F. Folkmann, and H. F. Beyer, J. Phys. B **14**, 1161 (1981).