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Final Report

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Project Title: "Line Identification and Lifetime Measurements
In the XUV and Soft X-Ray Regions"

by

The University of Tennessee
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A. Introduction

An accurate summary of the voluminous data acquired concerning line identification and lifetime measurements in the xuv and soft x-ray regions for a wide variety of both resonance transitions and forbidden transitions in ions of astrophysical interest during the period of this grant is provided in the detailed list of publications supported in part by this grant in Section C. We call particular attention to a few papers among the many we have listed which have appeared in the *Astrophysical Journal*. These are of special relevance to specific astrophysical data needs.

We also note the many experiments completed in areas related to but somewhat outside the confines of the project title. These areas include: 1) the charge state dependence of innershell ionization cross-sections for very highly ionized beams incident on lighter targets; 2) the measurement of the mean lives of metastable states of few-electron ions; 3) the electron spectroscopy of autoionizing states of highly ionized ions and associated Auger lifetimes; 4) the discovery of coherent electron density distribution oscillation in charge transition excitation of the $n=2$ hydrogen levels; 5) the measurement of the charge states of energetic ions while inside solid targets; 6) the measurement of production cross-sections for characteristic x-ray production in the region connecting the adiabatic and sudden collision regimes; 7) the measurement of directional anisotropies of non-characteristic x-rays emitted in heavy ion collisions; 8) electron emission spectroscopy on optically inaccessible autoionizing states of the alkali metals; 9) the measurement of differences in the production

of non-characteristic radiation in solids vs. gas targets; 10) study of the forward peak of electrons accompanying projectile ions with the same vector velocity subsequent to both ion-atom and ion-solid collisions; 11) study of the breakdown of one-electron molecular orbital transition models in ion-atom collisions.

In Section B, many of the lifetime data concerning soft x-ray and for uv transitions studied in our experiments appear in convenient tabular form.

In Section D, a listing of resident and visiting scientists, postdoctoral research associates, and graduate students (including two who received Ph.D. degrees during the grant period) is provided.

B. Summary of Principal Transitions Studied

Table 1. Radiative Lifetimes (nsec) of the 2p Levels of Li-like Ions

Level	Al XI	Si XII	S XIV	Cl XV	Fe XXIV
$(1s^2 2p)^2 P_{1/2}$	1.35 ± 0.06^a	—	0.92 ± 0.09	0.95 ± 0.05	0.55 ± 0.02^b
$(1s^2 2p)^2 P_{3/2}$	1.19 ± 0.05^a	1.01 ± 0.10	0.77 ± 0.04	0.76 ± 0.04	0.235 ± 0.01^b
	1.12 ± 0.10				

^aMeasurements made in Uppsala, Sweden. (A collaboration of the Uppsala-Lund-Tennessee Groups.)

^bMeasurement made in Berkeley-Superhilac. (A collaboration of the Berkeley-Arizona-BNL-Tennessee Groups.)

Table 2. Oscillator Strengths for the 2s-2p Principal Resonance Transitions in Li-like Ions

Transition	Al XI	Si XII	S XIV	Cl XV	Fe XXIV
$(2s)^2 S_{1/2} - 2p^2 P_{1/2}$	0.036	—	0.032	0.028	0.018
$(2s)^2 S_{1/2} - 2p^2 P_{3/2}$	0.076	0.074	0.068	0.057	0.047

Fractional errors on f value entries are estimated to be the same as for the lifetimes in Table 1. (All wavelengths have been measured to much higher accuracy.)

Table 3. Radiative Lifetimes (nsec) of the $n=2$ Levels of Be-like Ions

Level	Al X	Si XI	P XII	S XIII	Cl XIV
$(1s^2 2s 2p) ^1P_1$		0.18 ± 0.03	0.17 ± 0.03	0.16 ± 0.03	0.15 ± 0.03
$(1s^2 2p^2) ^1D_2$	1.03 ± 0.05^a	0.76 ± 0.04	—	0.69 ± 0.04	0.60 ± 0.06
$(1s^2 2p^2) ^1S_0$	—	—	—	0.079 ± 0.02	0.067 ± 0.01
$(1s^2 2s 2p) ^3P_2$	0.19 ± 0.03^a	0.19 ± 0.01	0.18 ± 0.01	0.17 ± 0.01	0.16 ± 0.01

^aMeasurements made in Uppsala, Sweden. (A collaboration of the Uppsala-Lund-Tennessee Groups.)

Table 4. Oscillator Strengths for $\Delta n=0$ Transitions ($n=2$) in Be-like Ions

Transition	Al X	Si XI	P XII	S XIII	Cl XIV
$(2s^2) ^1S - (2s 2p) ^1P$	—	0.23	0.21	0.19	0.17
$(2s 2p) ^1P - 2p^2 ^1D$	0.11	0.12	0.10	0.091	0.088
$(2s 2p) ^1P - 2p^2 ^1S$	—	—	—	0.057	0.058
$(2s 2p) ^3P - 2p^2 ^3P$	—	0.105	0.094	0.085	0.076

Fractional uncertainties on f value entries same as for lifetime entries of Table 3.

Table 5. Radiative Lifetimes (nsec) of the $n=3$ Levels of Na-like Ions

Level	Ni XVIII	Cu XIX	Br XXV
$(3p) ^2P_{1/2}$	0.14 ± 0.01	0.085 ± 0.02	0.11 ± 0.03
$(3p) ^2P_{3/2}$	0.11 ± 0.01	0.085 ± 0.01	0.062 ± 0.01
$(3d) ^2D_{3/2}$	0.066 ± 0.007	0.051 ± 0.005	0.042 ± 0.005
$(3d) ^2P_{3/2}$	—	0.054 ± 0.006	—

All measurements made at Brookhaven National Laboratory. (A collaboration of the BNL-Tennessee Groups.)

Table 6. Oscillator Strengths for $\Delta n=0$ Transitions ($n=3$) in Na-like Ions

Transition	Ni XVIII	Cu XIX	Br XXV
$(3s) ^2S_{1/2} - 3p ^2P_{1/2}$	0.11	0.16	0.072
$(3s) ^2S_{1/2} - 3p ^2P_{3/2}$	0.24	0.26	0.17
$(3p) ^2P_{3/2} - 3d ^2D_{3/2}$	0.19	0.22	0.15

Accuracy of f value entries is estimated to be at same level as lifetime entries of Table 5.

Table 7. Summary of Those Wavelengths of Those Classified Lines of Br Investigated

Transition	Wavelength (Å)	
	Present Result [†]	Edlén*
$3^2S_{1/2} - 3^2P_{1/2}$	229.0 ± 0.2	229.194
$3^2S_{1/2} - 3^2P_{3/2}$	189.6 ± 0.1	189.593
$3^2P_{3/2} - 3^2D_{5/2}$	166.8 ± 0.1	166.726

[†]Corrected for first and second order Doppler Effect.

*Reference: *Physica Scripta* 17, 565 (1978); semi-empirical extrapolation from measured wavelengths of other Na-like ions.

Table 8. Radiative Lifetimes and Oscillator Strengths for Allowed $\Delta n=0$ Transitions in Multiply Charged Chlorine Ions

Ion	Wavelength (Å)	Transition	Lifetime of Upper Level (nsec)	Multiplet Oscillator Strengths	
				Present	Theory
Cl XV	384.0	$(2s)^2S_{1/2} - (2p)^2P_{3/2}$	$0.76 \pm .04$		
	415.6	$(2s)^2S_{1/2} - (2p)^2P_{1/2}$	$0.95 \pm .05$	$0.085 \pm .004$	$0.090^a, 0.087^d, 0.082^e$
Cl XIV	277.9	$(2s2p)^1P_1 - (2p^2)^1S_0$	$0.067 \pm .010$	$0.058 \pm .009$	$0.052^b, 0.049^e$
	458.4	$(2s2p)^1P_1 - (2p^2)^1D_2$	$0.60 \pm .06$	$0.088 \pm .009$	$0.082^b, 0.078^e$
	237.8	$(2s^2)^1S_0 - (2s2p)^1P_1$	$0.15 \pm .03$	$0.17 \pm .03$	$0.22^b, 0.21^d, 0.21^e, 0.22^f$
	286.1	$(2s2p)^3P_2 - (2p^2)^3P_2$	$0.16 \pm .01$	$0.076 \pm .004$	0.079^e
Cl XIII	215.3	$(2s2p^2)^2D_{5/2} - (2p^3)^2P_{3/2}$	$0.055 \pm .006$	—	—
	272.9	$(2s2p^2)^2S_{1/2} - (2p^3)^2P_{3/2}$			
	419.5	$(2s^22p^2)^2P_{3/2} - (2p^3)^2D_{5/2}$	$0.12 \pm .01$	—	—
	209.9	$(2s^22p^2)^2P_{1/2} - (2s2p^2)^2S_{1/2}$	$0.080 \pm .008$	$0.029 \pm .003$	$0.026^b, 0.029^c, 0.026^e$
	205.5	$(2s^22p^2)^2P_{3/2} - (2s2p^2)^2P_{1/2}$	$0.058 \pm .006$	$0.10 \pm .01$	$0.137^b, 0.14^c, 0.14^e$
	264.6	$(2s^22p^2)^2P_{1/2} - (2s2p^2)^2D_{3/2}$	$0.33 \pm .03$	$0.057 \pm .006$	$0.054^b, 0.054^c, 0.053^e$
	224.6	$(2s2p^2)^4P_{3/2} - (2p^3)^4S_{3/2}$	$0.053 \pm .005$	$0.047 \pm .005$	$0.055^c, 0.052^e$
Cl XII	197.5	$(2s2p^3)^3D_1 - (2p^4)^3P_1$	$0.035 \pm .004$	—	—
	197.6	$(2s2p^3)^3D_2 - (2p^4)^3P_1$			
	202.5	$(2s2p^3)^3D_1 - (2p^4)^3P_2$			
	202.6	$(2s2p^3)^3D_3 - (2p^4)^3P_2$	$0.033 \pm .004$		
	174.4	$(2s^22p^2)^3P_1 - (2s2p^3)^3S_1$	$0.027 \pm .005$	$0.055 \pm .010$	$0.077^b, 0.075^e$
	223.2	$(2s^22p^2)^3P_1 - (2s2p^3)^3P_0$	$0.13 \pm .01$	$0.058 \pm .003$	$0.064^b, 0.062^e$
	223.1	$(2s^22p^2)^3P_1 - (2s2p^3)^3P_1$			
	262.4	$(2s^22p^2)^3P_1 - (2s2p^3)^3D_2$			
	262.2	$(2s^22p^2)^3P_1 - (2s2p^3)^3D_1$	$0.32 \pm .01$	$0.055 \pm .003$	$0.055^b, 0.058^e$
	271.2	$(2s2p^3)^1D_2 - (2p^4)^1D_2$	$0.051 \pm .005$	—	—
	175.8	$(2s^22p^2)^1D_2 - (2s2p^3)^1P_1$	$0.028 \pm .003$		
	199.3	$(2s^22p^2)^1D_2 - (2s2p^3)^1D_2$	$0.070 \pm .004$	$0.085 \pm .004$	$0.085^b, 0.145^e$
Cl XI	195.6	$(2s2p^4)^2D_{5/2} - (2p^5)^2P_{3/2}$	$0.026 \pm .005$		
	192.1	$(2s^22p^3)^2P_{3/2} - (2s2p^4)^2S_{1/2}$	$0.040 \pm .004$	$0.046 \pm .005$	$0.049^b, 0.049^e$
	166.1	$(2s^22p^3)^2D_{3/2} - (2s2p^4)^2P_{3/2}$			
	166.6	$(2s^22p^3)^2D_{5/2} - (2s2p^4)^2P_{3/2}$	$0.022 \pm .005$	—	—
Cl XI	209.9	$(2s^22p^3)^2D_{5/2} - (2s2p^4)^2D_{5/2}$			
	209.4	$(2s^22p^3)^2D_{3/2} - (2s2p^4)^2D_{3/2}$	$0.064 \pm .06$		
	242.7	$(2s^22p^3)^4S_{3/2} - (2s2p^4)^4P_{3/2}$	$0.18 \pm .02$	$0.15 \pm .015$	$0.141^b, 0.149^e$
Cl X	215.7	$(2s2p^5)^1P_1 - (2p^6)^1S_0$	$0.033 \pm .007$	$0.11 \pm .02$	0.133^e
	164.5	$(2s^22p^4)^1D_2 - (2s2p^5)^1P_1$	$0.024 \pm .005$	$0.10 \pm .015$	$0.116^b, 0.120^e$
	205.4	$(2s^22p^4)^3P_2 - (2s2p^5)^3P_2$	$0.062 \pm .009$		
Cl IX	180.7	$(2s^22p^5)^2P_{3/2} - (2s2p^6)^2S_{1/2}$	$0.030 \pm .006$	$0.055 \pm .01$	$0.063^b, 0.071^e$

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^bRef. 2 O. Sinanoglu, in *Beam-Foil Spectroscopy* (edited by S. Bashkin), Springer-Verlag, Berlin (1976).

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^dRef. 4 L. Armstrong, Jr., W. R. Fielder, and D. L. Lin, *Phys. Rev.*, A14, 1114 (1970).

^eRef. 5 U. I. Safronova, A. N. Ivanova, and V. N. Kharitonova, *Theor. and Expt. Chem.*, 5, 325 (1969).

^fRef. 6 K. T. Cheng and W. R. Johnson, *Phys. Rev.*, A15, 1326 (1977).

C. Publications

C.1. List of Publications on Research Accomplished under NASA Support, 1974 to date (present grant period):

Books, General Articles, Reviews:

"Ions," to be published in the McGraw-Hill Annual Yearbook of Science and Technology, 1978, D. Lapedes, ed., McGraw-Hill Book Co., New York (1978).

Structure and Collisions of Ions and Atoms, I. A. Sellin, ed. (Springer Verlag, Heidelberg, 1978).

Op. cit., Chapter 6, "Extensions of Beam Foil Spectroscopy."

"Optical, X-ray, and Auger Beam Foil Studies," in Methods of Experimental Physics, Vol. 14, P. Richard, ed. (Academic Press, New York), to be published in 1979.

"The Violent Many-Electron Chemistry of Highly Charged Ions," in Physics News - 1977, G. Present, ed. (American Institute of Physics, New York), p. 18 (1977).

Beam Foil Spectroscopy: Vol. 1, Atomic Structure and Lifetimes, Vol. 2, Collisional and Radiative Interactions, I. A. Sellin and D. J. Pegg, eds., Plenum Press, New York (1976).

"Highly Ionized Ions," in Advances in Atomic and Molecular Physics, Vol. 12, D. R. Bates and B. Bederson, eds., Academic Press, New York (1976), p. 215.

"Measurement of Auger Lifetimes and Energy Levels by Projectile Electron Spectroscopy," in Topics in Current Physics, Vol I: Beam-Foil Spectroscopy, S. Bashkin, ed., Springer-Verlag, Heidelberg (1976), Chap. 10, p. 265.

Articles in Major Journals and Proceedings:

"Z, Velocity, and Target-Material Dependence of Convoy Electrons from Solids." Phys. Rev. Lett. 41, 712 (1978).

"Observation of Oscillatory (Interference?) Structure in the Forward Peak from Fast-Projectile Electron Loss," Phys. Rev. Lett. 41, 399, (1978).

"Continuum Electron Capture Dependence on Projectile Z and Velocity," Z. Physik A 286, 233 (1978).

"Z, Velocity, and Charge Dependence of Zero-Degree Electron 'Cusps' from Charge Transfer to Continuum States of Bare and Highly Ionized Projectiles," Phys. Rev. Lett. 40, 1020 (1978).

Invited paper, "Electron 'Cusp' Spectroscopy of the Forward Peak in Continuum Electron Capture and Loss in Gases and Solids," to be published in the Proceedings of the International Conference on Fast Ion Spectroscopy, Université de Lyon, by the Journal de Physique in 1979.

"Oscillator Strength Determinations for $\Delta n = 0$ Transitions in Be-like Ions of the Third Period Elements," to be published in the Proceedings of the Fifth International Conference on Beam-Foil Spectroscopy. Université de Lyon, by the Journal de Physique in 1979.

"Coherent Electron Density Distribution Oscillations in Electron Capture by Fast Protons in He," to be published in Z. Physik-Short Notes (1978).

"Electron 'Cusp' Spectroscopy of the Forward Peak in Continuum Electron Capture and Loss in Gases and Solids," to be published in the Proceedings of the International Conference on Fast Ion Spectroscopy, Université de Lyon, by the Journal de Physique (1979).

"Electron Capture Collisions at keV Energies of Boron and Other Multiply Charged Ions with Atoms and Molecules, I: Ar, H₂, and He," submitted to Phys. Rev. A.

"Delayed Coincidence Auger Electron Lifetime Measurements," to be published in the Proceedings of the International Conference on Fast Ion Spectroscopy, Université de Lyon, by the Journal de Physique (1979).

"Orbital Angular Momentum State Coherence in Charge Transfer to the $n=2$ Hydrogen Levels by Fast Protons in Gases," to be published in the Proceedings of the International Workshop on Coherence and Correlation in Atomic Collisions, Plenum Press, New York, 1979.

"A Systematic Study of the $2s^2 2p^k - 2s 2p^{k+1} - 2p^{k+2}$ Transitions in Multiply-Charged Cl Ions," to be published in the Proceedings of the Fifth International Conference on Beam-Foil Spectroscopy, Université de Lyon, by the Journal de Physique in 1979.

"Radiative Lifetimes of Highly Ionized and Foil-Excited Al," to be published in the Proceedings of the Fifth International Conference on Beam-Foil Spectroscopy, Université de Lyon, by the Journal de Physique in 1979.

"Observation of Mixed Parity Electric Dipole Oscillations in Charge-Transfer to the $n=2$ Hydrogen Levels by Fast Protons in Gases," submitted to Phys. Rev. Lett.

Invited Paper, "Electron Capture to Continuum States," to be published in the Proceedings of the Fifth Conference on Application of Small Accelerators, North Texas State University, November 6-8, 1978, in the February 1979 issue of IEEE Transactions on Nuclear Science.

Invited Paper, "Failure of Single Electron Descriptions of Molecular Orbital Collision Processes," to be published in the Proceedings of the Fifth Conference on Application of Small Accelerators, North Texas State University, November 6-8, 1978, in the February 1979 issue of IEEE Transactions on Nuclear Science.

Invited Paper, "A Scanning Proton Microprobe for Trace Element Analysis," to be published in the Proceedings of the Fifth Conference on Application of Small Accelerators, North Texas State University, November 6-8, 1978, in the February 1979 issue of IEEE Transactions on Nuclear Science.

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"Many-Electron Aspects of Molecular Promotion in Ion-Atom Collisions: Production of Core-Excited States of Li in $Li^+ - He$ Collisions," submitted to Phys. Rev. A.

"Spin-dependent Excitation of Autoionizing States of Li Produced in Collisions with Noble Gas Targets," in Proceedings, Tenth International Conference on the Physics of Electronic and Atomic Collisions, M. Barat, J. Reinhardt, and G. Watel, eds. (Commissariat a l'Energie Atomique, Paris), p. 1014 (1977).

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D. List of Personnel Associated with the University of Tennessee/Oak Ridge National Laboratory Accelerator-based Atomic and Molecular Physics Collaboration

D. 1. Personnel who have regularly participated in the collaboration

<u>Name</u>	<u>Title</u>
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S. B. Elston*	Visiting Assistant Professor
J. P. Forester [†]	Assistant Professor (UT-Chattanooga)
G. A. Glass*	Graduate Research Assistant
P. M. Griffin	Physicist, ORNL
K. O. Groeneveld	Visiting Professor (Germany)
H. H. Haselton	Section Head (ORNL Fusion Energy Division)
H. Hayden	Visiting Associate Professor (Univ. of Conn.)
R. Laubert	Visiting Professor (N.Y.U.)
K. H. Liao	Postdoctoral Research Associate
J. R. Mowat	Assistant Professor (North Carolina State Univ.)
D. J. Pegg*	Associate Professor
R. S. Peterson§	Visiting Assistant Professor (Univ. of Conn.)
I. A. Sellin*	Professor
S. Schumann	Postdoctoral Research Associate (Germany)
M. Suter*	Postdoctoral Research Associate (Switzerland)
R. S. Thoe*	Assistant Professor
C. R. Vane*	Graduate Research Assistant
J. Wright	Visiting Associate Professor (Univ. of New Hampshire)
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James Bayfield	Professor, University of Pittsburgh
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J. Cecci	Physicist, Princeton Plasma Physics Laboratory
D. Crandall	Physicist, Oak Ridge National Laboratory
S. Datz	Associate Director, Chemistry Division, Oak Ridge National Laboratory
D. Dietrich	Postdoctoral Research Associate, LBL
B. L. Donnally	Dean, Lake Forest College
H. J. Frischkorn	Graduate Research Assistant, Univ. of Frankfurt/M
L. Gardner	Postdoctoral Research Associate, Univ. of Pittsburgh
H. Gould	Physicist, LBL
B. Johnson	Physicist, BNL
K. Jones	Physicist, BNL
R. Kauffman	Physicist, Bell Telephone Laboratories
H. Kim	Physicist, Oak Ridge National Laboratory
T. Kruse	Professor, Rutgers University
P. Koch	Assistant Professor, Yale University
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R. Marrus	Professor, University of California at Berkeley
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W. W. Smith	Professor, University of Connecticut
R. R. Turtle	Postdoctoral Research Associate, Univ. of Tennessee