SEMIEMPIRICAL STUDIES OF
ATOMIC STRUCTURE: Progress Report
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*Reprints removed for
Separate processing*

1 DIRECTORY OF APPENDED REPRINTS

Invited Review Article

- A0. L.J. Curtis, "Precision Oscillator Strength and Lifetime Measurements," Chapter in Atomic, Molecular and Optical Physics Handbook" (AIP Press, NY, 1996), Chapter 17, pp 206-12. [Appendix pp. 1-8]

Measurement and Data-Based Specification of Line Strengths

- A1. L.J. Curtis, D.G. Ellis, and I. Martinson, "Precise Data-Based Predictions of Line Strengths in Alkalilike Isoelectronic Sequences," Phys. Rev. A **51**, 251-6 (1995). [Appendix pp. 9-14]
- A2. L.J. Curtis, "A Predictive Data-Based Exposition of $nsnp\ ^1,^3P_1$ Lifetimes in the Cd and Hg Isoelectronic Sequences," J. Phys. B: At. Mol. Opt. Phys. **26**, L589-94 (1993). [Appendix pp. 15-20]
- A3. M. Henderson and L.J. Curtis, "Lifetime Measurements in Tl II," J. Phys. B: At. Mol. Opt. Phys. (in press, 1996). [Appendix pp. 21-26]
- A4. L.J. Curtis and D.G. Ellis, "Predictive Systematization of Line Strengths for the $2s^2$ - $2s2p$ Resonance and Intercombination Transitions in the Be Isoelectronic Sequence," J. Phys. B: At. Molec. and Opt. Phys. **29**, 645-54 (1996). [Appendix pp. 27-36]
- A5. L.J. Curtis, S.T. Maniak, R.W. Ghrist, R.E. Irving, D.G. Ellis, M. Henderson, M.H. Kacher, E. Träbert, J. Granzow, P. Bengtsson, and L. Engström, "Measurements and Data-Based Predictions for $\Delta n=1$ Resonance and Intercombination Transitions in the Be and Ne Sequences," Phys. Rev. A **51**, 4575-82 (1995). [Appendix pp. 37-44]
- A6. M. Henderson, L.J. Curtis, D.G. Ellis, R.E. Irving and G. M. Wahlgren, "Lifetimes and Oscillator Strengths for the $6s7p\ ^3P_{0,1}$ Levels in Bi II," Astrophys. J. (December 1996). [Appendix pp. 45-50]

Lifetime Measurements in Few Times Ionized Atoms

- A7. S.T. Maniak, L.J. Curtis, R.E. Irving, I. Martinson and R. Hellborg, "Lifetimes of the $7p$ Levels in Hg II," *Phys. Lett. A* **182**, 114-9 (1993). [Appendix pp. 51-56]
- A8. S.T. Maniak, L.J. Curtis, C.E. Theodosiou, R. Hellborg, S.G. Johansson, I. Martinson, R.E. Irving and D.J. Beideck, "Lifetimes of Excited Levels in Y III," *Astron. Astrophys.* **286**, 978-82 (1994). [Appendix pp. 57-62]
- A9. R.E. Irving, S.T. Maniak, D.J. Beideck, P. Bengtsson, L.J. Curtis, R. Hellborg, G. Kalus, and I. Martinson, "Lifetimes of the $4d^9 5p$ Levels in Ag II," *Physica Scripta* **51**, 351-3 (1995). [Appendix pp. 63-66]
- A10. M. Henderson, P. Bengtsson, J. Corcoran, L.J. Curtis, R.E. Irving and S.T. Maniak, "Lifetimes of the $4d^9 5p$ Levels in Cd III," *Physica Scripta* **53**, 309-11 (1996). [Appendix pp. 67-70]
- A11. M. Henderson, L.J. Curtis, and R.E. Irving, "Lifetimes of the $4d^9 5p$ Levels in In IV," *Physica Scripta* **53**, 557-9 (1996). [Appendix pp. 71-74]
- A12. P. Bengtsson, L.J. Curtis, M. Henderson, R.E. Irving and S.T. Maniak, "Lifetime Measurements in N III using the Beam-Foil Technique and Cascade Corrections," *Physica Scripta* **52**, 506-10 (1995). [Appendix pp. 75-80]

Polarizabilities

- A13. L.J. Curtis and C.E. Theodosiou, "A Comment on the Dipole Polarizability of the Zn^+ Ion," *J. Opt. Soc. Am. B* **12**, 175-7 (1995). [Appendix pp. 81-84]
- A14. C.E. Theodosiou, L.J. Curtis, and C.A. Nicolaides, "Determination of Dipole Polarizabilities for Mg^+ and Ca^+ from Precision Lifetime Measurements and Transition Moment Cancellations," *Phys. Rev. A* **52**, 3677-80 (1995). [Appendix pp. 85-88]

Spectroscopic Classification and Intensity Studies

- A15. C. Jupén and L.J. Curtis, "Isoelectronic Comparison of the Al-like $3s^2 3p^2 \ ^2P - 3s 3p^2 \ ^4P$ Transitions in the Ions P III - Mo XXX," *Physica Scripta* **53**, 312 (1996). [Appendix pp. 89-94]
- A16. L. Engström, M. Kirm, P. Bengtsson, S.T. Maniak, L.J. Curtis, E. Träbert, J. Doerfert and J. Granzow, "Extended Analysis of Intensity Anomalies in the Al I Isoelectronic Sequence," *Physica Scripta* **52**, 516-21 (1995). [Appendix pp. 95-100]

Highly Ionized Two-Electron Systems

- A17. R.W. Dunford, H.G. Berry, D.A. Church, M. Hass, C.J. Liu, M.L.A. Raphaelian, B.J. Zabransky, L.J. Curtis, and A.E. Livingston, "Forbidden Transitions in One- and Two-Electron Nickel," *Phys. Rev. A* **48**, 2729-45 (1993). [Appendix pp. 101-118]
- A18. A.E. Livingston, K.W. Kukla, C.M. Vogel Vogt, H.G. Berry, R.W. Dunford, D.S. Gemmell, E.P. Kanter, J. Suleiman, R. Ali, S. Cheng and L.J. Curtis, "Fine Structure Energies for the $1s2s \ ^3S - 1s2p \ ^3P$ transition in Helium-Like Ions, *Nucl. Instr. Meth. in Phys. Res. B* **98**, 28-32 (1995). [Appendix pp. 119-124]
- A19. K.W. Kukla, A.E. Livingston, J. Suleiman, H.G. Berry, R.W. Dunford, D.S. Gemmell, E.P. Kanter, S. Cheng and L.J. Curtis, "Fine Structure Energies for the $1s2s \ ^3S - 1s2p \ ^3P$ Transition in Helium-like Ar^{16+} ," *Phys. Rev. A* **51**, 1905-17 (1995). (Appendix pp. 125-138]
- A20. S. Cheng, R.W. Dunford, C.J. Liu, B.J. Zabransky, A.E. Livingston, and L.J. Curtis, "M1 Decay of the $2 \ ^3S_1$ State in Heliumlike Krypton," *Phys. Rev. A* **49**, 2347-53 (1994). [Appendix pp. 139-146]
- A21. R. Ali, I. Ahmad, H.G. Berry, R.W. Dunford, D.S. Gemmell, E.P. Kanter, P.H. Mokler, A.E. Livingston, S. Cheng and L.J. Curtis, "Spectral Distribution of the Two-Photon Decay of He-like Krypton," *Nucl. Instr. Meth. in Phys. Res. B* **98**, 69-73 (1995). [Appendix pp. 147-152]

2 SCOPE OF INVESTIGATIONS

The atomic structure and properties of highly-ionized many-electron systems are studied through the combined use of sensitive semiempirical data systematizations, precision experimental measurements, and specialized theoretical computations. Measurements are made primarily through the use of fast ion beam excitation methods, which are combined with available data from laser- and tokamak-produced plasmas, astrophysical sources, and conventional light sources. The experimental studies are supported and interpreted through *ab initio* calculations. Large blocks of data are systematized and parametrized along isoelectronic, homologous, isoionic, Rydberg, and yrast series.

The use of spectroscopic line intensities as diagnostics for determining thermonuclear plasma temperatures and densities requires laboratory observation and analysis of the spectra of these systems, and computer modeling of both astrophysical and laboratory plasmas requires a comprehensive knowledge of the atomic structure parameters for highly ionized complex systems. Spectroscopic classifications require accuracies exceeding parts per million, which cannot be achieved by standard *ab initio* methods for these highly relativistic many electron systems. Semiempirical systematizations of high precision data can provide these accuracies, and an increasingly large base of such data is becoming available. This program seeks to acquire, systematize, and parametrize large blocks of data to expose and exploit predictive empirical regularities. Trends revealed are tested through well chosen experimental measurements, and theoretical methods are used to gain quantitative understanding of the empirical regularities.

Spectroscopic techniques now permit measurements of unprecedented precision for highly ionized, highly excited and highly complex systems. This has pressed the use of quantum defect analyses, core polarizations, and screening parameter formulations into new regimes, and has revealed both new systematic trends and the breakdown of regularities present for lower ionicities. Laser techniques, fast-ion-beam excitation, tokamak-produced plasmas, and advances in the detectability of astrophysical light sources have provided access to high Rydberg states and to multiply excited states, brought about MHz accuracies in the specification of differential energy levels, and yielded spectra for atoms ionized through one electron uranium. Through the acquisition and systematization of empirical data, methods have been developed as part of this project that parametrize and precisely predict excitation en-

ergies, transition wavelengths, transition probabilities, level lifetimes, ionization potentials, core polarizabilities, and core penetrabilities for large classes of atomic systems. Furthermore, this precision is sharpened with the subsequent measurements that are motivated by the predictions themselves.

A number of different methods have been utilized, some of which will be described below.

3 SIGNIFICANT RESULTS

Since it was begun in 1980, results obtained in this project has been reported in 102 published papers [1-102]. Of these, 21 [82-102] were produced during the three-year funding period covered by this Report. These papers provide the best context for a description of the significant results of the program, and a set of reprint copies of these 21 publications is attached as Appendix A (henceforth designated as Papers [A1]-[A21]). The project has proceeded through a number of separate but complementary investigations, which can be broken down into specific topics. To facilitate the description, the appended papers have been placed in subjective groupings, rather than in the chronological order given in the bibliography. Thus the 21 latest publications, together with a related Invited Review Paper which was prepared for the AIP, are arranged in the following categories: Invited Review Article [Paper A0]; Data-Based Isoelectronic Studies of Line Strengths [Papers A1-A6]; Lifetime Measurements in Few Times Ionized Systems [Papers A7-A13]; Precision Determination of Ionic polarizabilities [Papers A14-A15]; Spectroscopic Classification and Systematization [Paper A16]; and Studies of Highly Ionized Two Electron Systems [Papers A17-A21].

Measurements have been made using a large number of facilities. Fast ion beam measurements were carried out using: the 330 kV Heavy Ion Accelerator at the University of Toledo; the 3 MV Tandem Pelletron Accelerator at the University of Lund in Sweden; the ATLAS Linear Accelerator System at Argonne National Laboratory; and the 4 MV Dynamitron Accelerator at the University of Bochum in Germany. Spectroscopic measurements were also made using the sliding spark light source at the University of Lund, and the JET Tokamak in Abingdon England. New measurements have been made for the 32 ions listed in Table 1. Semiempirical systematizations have also utilized data obtained from other measured sources as well as from theoret-

Table 1: Ions for which new measurements have been made

Sequence	Ions
H	Ni ²⁷⁺
He	Ar ¹⁶⁺ , Ni ²⁶⁺ , Kr ³⁴⁺
Be	C ²⁺ , N ³⁺ , O ⁴⁺ , F ⁵⁺
B	N ²⁺
Ne	Ne, Na ⁺ , Mg ²⁺ , Al ³⁺ , Si ⁴⁺ , P ⁵⁺
Al	Si ⁺ , P ²⁺ , S ³⁺ , Cl ⁴⁺ , K ⁶⁺ , Sc ⁸⁺ , Fe ¹³⁺ , Ni ¹⁵⁺ , Kr ²³⁺ , Mo ²⁹⁺
Rb	Y ²⁺
Pd	Ag ⁺ , Cd ²⁺ , In ³⁺
Au	Hg ⁺
Hg	Tl ⁺
Pb	Bi ⁺

ical calculations. Short descriptions of some of these studies will be given below.

3.1 Invited Review Article

A comprehensive summary which describes and contrasts the precision lifetime measurements carried out in this program is presented in Paper [A0], which is a Chapter in a book on Atomic, Molecular, and Optical Physics prepared at the invitation of the American Institute of Physics. The book is intended as an encyclopedic description of the subject, which can serve as a guide to graduate students entering the field, a cross-. specialty guide to workers in the field, and as a general information resource.

3.2 Line Strength Isoelectronic Extrapolations.

When measurements exist for both the lifetimes τ_i and the branching fractions B_{ik} for transitions in an isoelectronic sequence, a reduction of these quantities to the line strength $S_{ik} = (\lambda_{ik}/1265)^3 g_i B_{ik} / \tau_i$ can often yield an exposition that is regular and slowly varying. This systematization permits the measurements for different ions in the same sequence to be: examined for consistency; smoothed to increase the individual accuracies; predictively interpolated and extrapolated; and sensitively compared with theoretical pre-

dictions. We have applied these methods to a variety of systems, with successful and often insightful results.

3.2.1 Resonance Transitions in Alkalilike Sequences

The results of earlier studies in this project [43,45,63] have established that experimental $ns\ ^2S_{1/2} - np\ ^2P_{1/2,3/2}$ transition line strengths in alkalilike isoelectronic sequences are well represented for moderate stages of ionization by the empirical relationship

$$Z^2 S = S_0 + b/(Z - C). \quad (1)$$

In the nonrelativistic one electron case, $Z^2 S$ has the hydrogenic value $S_H = \frac{3}{4}n^2(n^2 - 1)g_i$, and is constant and independent of Z over the entire hydrogen-like isoelectronic sequence. Thus, the quantities b and C can be interpreted as characterizing the screening by the core electrons. By examination of the data for the Li, Na, and Cu isoelectronic sequences, we demonstrated in Paper A1 that, for a $\Delta n=0$ transition, the low Z data extrapolate to the hydrogenic value $S_0 \cong S_H$. The linearizing exposition of the trend of Eq.(1) toward the high Z limit S_H is of utilitarian value for the precise interpolation and extrapolation of measured data, and the high degree of experimental linearity (which is not always exhibited by *ab initio* calculations), raises intriguing theoretical questions. If the linearity is valid, then measurements at lower Z can be used to predict those at the high Z end of the sequence, where lifetimes become very short.

Because the $^2S_{1/2} - ^2P_{1/2}$ interval becomes much smaller than the $^2S_{1/2} - ^2P_{3/2}$ interval at high Z , the $^2P_{3/2}$ lifetime becomes immeasurably small, but the $^2P_{1/2}$ lifetime is lengthened by λ^3 the factor, and is thus accessible to measurement. A test of this extrapolative approach was made possible by a measurement [Schweppe *et al.*, PRL 66, 1434 (1991)] for the lifetime of the $np\ ^2P_{1/2}$ level in Li-like Uranium. This yielded a result that was significantly lower than the value predicted by this extrapolation procedure. Such a discrepancy could arise from either: (a) a breakdown in the validity of the representation of the core screening given in Eq.(1); or (b) a relativistic breakdown in the constancy of the one-electron line strength given by S_H . To test these two alternatives, we performed a relativistic calculation [Paper

A1] of the line strength of the hydrogen atom, which is of the form

$$S'_H = S_H[1 - \sum_i a_i(\alpha Z)^{2i}] \quad (2)$$

with the coefficients a_i computed from hydrogenlike Dirac wave functions. We then tested this with the existing data base for alkalilike isoelectronic sequences, and found that the linearity of the extrapolation can be preserved to high Z over these sequences by using the parametrization

$$Z^2 S/[1 - \sum_i a_i(\alpha\{Z - C\})^{2i}] = S_H + b/(Z - C). \quad (3)$$

With this correction, the low Z trends have been found in Paper A1 to extrapolate precisely to the non-relativistic hydrogenic value in the $1/(Z - C)=0$ limit. These results were also used to make predictions for the Ag sequence.

3.2.2 Intrashell Resonance and Intercombination Transitions in Alkaline Earthlike Sequences

As part of this project, we have earlier [58] developed an extension of this isoelectronic extrapolation of line strengths to $ns^2\text{-}n\text{-}sn\text{-}p$ transitions in two valence electron sequences. To account for the effects of intermediate coupling, an empirical data reduction is used that treats measured transition probabilities for the resonance and intercombination lines as conjugate quantities. The reduction is formulated through a singlet-triplet mixing angle θ that is deduced from measured spectroscopic energy level data to produce effective reduced line strengths. These are found to have an isoelectronic behavior that can be linearized through a screening parametrization. In this approach the line strengths obtained from measured transition probabilities of the resonance and intercombination lines $S(Res)$ and $S(Int)$ are converted to values reduced for spin mixing effects by dividing by the appropriate empirical mixing angle quantity to obtain $S_r(Res) \equiv S(Res)/\cos^2 \theta$ and $S_r(Int) \equiv S(Int)/\sin^2 \theta$. The resonance and intercombination data can thus be presented in a common exposition very similar to that described above for the alkali isoelectronic sequences, which exhibit a regularity that has been observed to persist even in the presence of strong perturbations. It

can also be linearized through simple screening parametrizations that permit quantitative interpolation, extrapolation and smoothing

$$Z^2 S_r(Res) = S_0 + b_R/(Z - C); \quad Z^2 S_r(Int) = S_0 + b_I/(Z - C). \quad (4)$$

This permits data over a wide range of charge states to be merged. Time-of-flight methods are limited to lifetimes that produce a measurable decay length, and often the intercombination transitions are immeasurably long-lived at low Z while the resonance transitions are immeasurable short-lived at high Z .

- *Cd and Hg sequences*

We have earlier applied these methods to use spectroscopic energy level data to systematize lifetime data for the strong low lying intrashell resonance and intercombination lines of the ns^2 - $nsnp$ transitions in the Be ($n=2$) [58], Mg ($n=3$), and Zn ($n=4$) [67,72] isoelectronic sequences. In Paper A2 we have extended the application of this approach to both the Cd and the Hg isoelectronic sequences. There exist both experimental measurements and theoretical calculations for these sequences. The calculations that are in best agreement with experiment take into account core polarization, but these calculations are available only for the lower members of the sequence where spectroscopic energy level data can be utilized. This exposition reveals shortcomings in some of the theoretical calculations both in specific values and in isoelectronic trends.

We have made lifetime measurements [Paper A3] for the $6s6p$ 1P_1 , $6s6p$ 3P_1 , $6s6d$ 1D_2 , and $6s7s$ 1S_0 levels in singly ionized thallium in the mercury isoelectronic sequence. Oscillator strength data for Tl II are needed for many specific applications. Spectral lines from Tl II have been identified in astrophysical observations of Hg-Mn type stars made using the Goddard High Resolution Spectrograph on board the Hubble Space Telescope. Because it can be confined in an ion trap and possesses a very long-lived metastable $6s6p$ 3P_0 level, Tl II can be utilized as a high accuracy atomic clock. In terms of fundamental theory, the eighty electron Hg isoelectronic sequence provides a severe challenge to existing calculational methods, which can only be tested by acquiring a base of reliable measurements. Earlier curve fitting studies have been made for the 1P_1 , 1D_2 and 1S_0 levels, but this is the first lifetime

measurement of the 3P_1 level, and the first cascaded-correlated lifetime measurement of the 1P_1 level. The values obtained were $\tau(^1P_1)=0.59\pm0.02$ ns, $\tau(^3P_1)=39\pm2$ ns, $\tau(^1D_2)=6.5\pm0.5$ ns, and $\tau(^1S_0)=3.0\pm0.4$ ns.

• *High Z limit for the $2s^2$ - $2s2p$ transitions in the Be sequence*

We have sought to apply the same high Z tests to this parametrization as were described above for the alkalilike sequences. We have begun this through a study of the $2s^2\ ^1S_0 - 2s2p\ ^1,^3P_1$ transitions in the Be isoelectronic sequence in Paper A4.

For the ns - np alkalike sequences we have shown [Paper A1] that measured data for the line strengths converge to values $Z^2 S_r \cong S_H$. Within the framework of $1/Z$ perturbation theory, it is clear that the unscreened hydrogenic line strength is also relevant to the high- Z limit of the alkaline earthlike sequences, with two caveats. First, there may be effects due to the high- Z asymptotic degeneracy of levels in the same complex, which causes strong configuration mixing that is zeroth order in $1/Z$, such as between $2s^2$ and $2p^2$ in the Be sequence. (For alkalilike sequences, the hydrogenic value S_H is independent of such asymptotic mixing, since levels of the same parity with different ℓ cannot have the same J .) Second, the relativistic effects are more complicated in these two-electron spectra. For example the asymptotic degeneracy is now between $2s_{1/2}^2$ and $2p_{1/2}^2$ only, and the Breit interaction should be included. However these relativistic effects are not relevant to our analysis of the available data in the present case.

In the alkaline earthlike case, there will be configuration mixing at high Z (where states of the same J and parity but differing L become degenerate), and the interpretation of the high Z "hydrogenic" value S_H is more complicated, and involves all levels (equivalent at high Z) of the complexes of the upper and lower configurations. Thus the high Z limit of the nominally $2s^2$ - $2s2p$ transition will involve a coherent mixture of $2s^2$ and $2p^2$ configurations in the lower $n=2$ even parity complex. If ϕ denotes the mixing angle of the $2s^2$ and $2p^2$ configurations, we have shown that, in the limit of high Z ,

$$Z^2 S_r(Res) \cong Z^2 S_r(Int) \Rightarrow \frac{2}{3}(\sqrt{3} \cos \phi - \sin \phi)^2 S_H. \quad (5)$$

We computed this high Z limit by diagonalizing the 2×2 matrix of the Coulomb repulsion using standard Slater-integral methods and unscreened hydrogenic radial wavefunctions, and obtained $\phi = 13^\circ$. Combining this with

the $n=2$, $J=1$ hydrogenic value $S_H = 27$ yields an asymptotic value for the LHS of Eq.(5) of 38.5. As can be seen from Fig.2 of Paper A4 the trend of the data is consistent with this limit. We performed a critical evaluation of all available lifetime data, which was reduced to the appropriate exposition, parametrized, and interpreted. In this way we have obtained an appropriate means of determining the limiting value S_H from theoretical considerations, which permits lifetime measurements made at low and intermediate Z to be accurately extrapolated to relatively high Z .

3.2.3 Intershell resonance and intercombination transitions in alkaline earthlike and inert gaslike sequences

Many experimental studies of line strengths for $^1S_0 - ^1,^3P_1$ resonance and intercombination lines exist for intrashell $ns^2 - nsnp$ transitions in alkaline earthlike isoelectronic sequences, but few data exist for these line strengths for intershell $ns^2 - nsn'p$ ($n' > n$) transitions. This is because lifetime data can be converted directly to line strengths for the unbranched $\Delta n=0$ case, but the $\Delta n > 0$ cases have branched decays, and virtually no experimental branching ratio data exist for charged ions in any isoelectronic sequence. This extension to intershell transitions provides a stringent test for the method, since it introduces complications from plunging configuration interaction, transition integral cancellations, and multiple exit channels, that are not present in the case of the intrashell transitions.

We have identified two examples for which line strengths can be deduced from measured $\Delta n > 0$ lifetime data. These are the $2s^2 - 2s3p$ transitions in the Be isoelectronic sequence and the $2p^6 - 2p^53s$ transitions in the Ne sequence. In the Be sequence case, a method utilizing differential lifetime measurements within the triplet permits a determination of the branching ratio for the intercombination decay, and the dominance of the resonance decay over competing branches permits accurate theoretical estimates of its branching ratio to be made. In the Ne sequence case, the electron-hole nature of the levels causes these intershell transitions to be unbranched. Paper A5 reports a systematic study of these two $\Delta n > 0$ systems, in which we performed lifetime measurements of both the singlets and triplets, as well as measurements and theoretical estimates of the branching ratios.

- *Be sequence $2s^2 - 2s3p$*

We have earlier [68] applied this semiempirical formulation to a study of the resonance and intercombination lines of the $2s^2$ - $2s3p$ and $3s^2$ - $3s4p$ transitions in the Be and Mg isoelectronic sequences. These transitions permit branched transition probabilities to be determined from lifetime measurements through a novel experimental technique which we developed earlier [19]. This permits the determination of intercombination transition probabilities through differential decay curve measurements that exploit the J dependence of the exit channels of the triplet levels.

Supplementing our earlier measurements of lifetimes and branching ratios of the intercombination line strengths for N IV, OV, F VI, and Ne VII in the Be sequence, in Paper A4 we added new measurements for the intercombination line strength, for the resonance line strengths in C III, N IV, O V and F VI, and theoretical estimates of the branching fractions for the resonance transitions.

The linear trends in the measured data for both the resonance and intercombination line strengths tend to converge toward the high Z hydrogenic limit $S_H(2s-3p)=18.79$. These results greatly sharpen the predictive accuracy of the parametrization, and indicate that existing measurements for the intercombination transitions in Na VIII, Al X and Si XI are contrary to the general trends and should be remeasured.

- *Ne sequence $2p^6$ - $2p^53s$*

Because of the strong radiative decay of the $2p^6$ - $2p^53s$ transitions in the Ne isoelectronic sequence, it is possible to create a population inversion between the $2p^53s$ and $2p^53p$ levels which can produce XUV laser amplification action. Modeling studies have demonstrated that amplification is optimal near $Z=36$, leading to applications in Se and Y plasmas. The lifetimes of these levels are too short for time-of-flight measurements at $Z=36$, but we have developed methods that permit reliable semiempirical extrapolation if precise results at lower Z are available.

For the Ne sequence we have measured lifetimes [Paper A5] for the resonance lines for Ne I, Na II, Mg III, Al IV, Si V, and P VI, and for the intercombination lines for Ne I, Na II, and P V. The line strengths so determined were corrected for the effects of intermediate coupling using the

singlet-triplet mixing angle formalism. Again in this case the linear trends of the measured data for both the resonance and intercombination line tended to converge at high Z toward the hydrogenic limit $S_H(2p-3s)=1.761$. This also sharpens the predictive accuracy for this sequence, and suggests that the values for the line strengths of the intercombination transitions in S VII and Cl VIII are off the general trend, and should be remeasured.

- *Mixing angles in both initial and final states: Bi II*

Bismuth represents the last element in the chain of neutron capture nucleosynthesis that is radioactively stable, and its abundance in stellar atmospheres presents a constraint on the theories of nucleosynthesis for the very heavy elements. However, observations of its spectral lines in astronomical spectra have been limited to IUE and HST observations of a few chemically peculiar stars, which indicate abundances as high as six orders of magnitude greater than in the solar system. Quantitative stellar abundance analyses are hindered by the limited number of lines for which oscillator strength data exist, which motivated our study of Bi II [Paper A6].

We have made lifetime measurements and empirical branching ratio estimates for the $6p7s$ 3P_0 and 3P_1 levels in Bi II, and performed supporting theoretical calculations. We have combined these results to obtain absorption oscillator strengths between these levels and those of the $6p^2$ ground configuration. The results have applications in the interpretation of spectroscopic data obtained from orbiting telescopes.

We have determined oscillator strengths for $6s^26p^2 - 6s^26p7s$ transitions in Bi II from our lifetime measurements of the $6p7s$ $^3P_0^o$ and $^3P_1^o$ levels and our empirical estimates (based on measured energy level data) of the branching ratios of the $6p7s$ $^3P_1^o$ to the $6p^2$ 3P_0 , 3P_1 , 3P_2 , 1D_2 and 1S_0 ground configuration levels. We used theoretical calculations to examine the single configuration intermediate coupling approximation, and to determine the extent to which these levels are affected by configuration interaction. The empirical approach was used to characterize intermediate coupling in both the upper and lower levels through singlet-triplet mixing amplitudes determined from experimental energy level data.

In this system both the ground and the excited configurations are affected by singlet-triplet mixing. The sp and p^2 configurations have at most two normalized mixing amplitudes for a given value of J , which can be characterized

by a singlet-triplet mixing angle θ_J . Thus we characterize the mixing between the $sp\ ^3P_1$ and 1P_1 states by θ_1 , between the $p^2\ ^3P_0$ and 1S_0 states by θ_0 , and between the $p^2\ ^3P_2$ and 1D_2 states by θ_2 . By a formalism we developed earlier [58], these mixing angles are first extracted from measured energy level data and then used to predict transition probabilities. For a p^2 - sp manifold, the transitions from the upper level $sp\ ^3P_1^o$ to the levels of the ground configuration p^2 can be deduced [58] using the LS coupling angular transition matrices to obtain

$$\langle\ ^3P_0\ |\mathbf{r}|\ ^3P_1^o\rangle = -\sqrt{20}\cos(\theta_1 + \theta_0)\langle\ p^2|r|sp\rangle\quad (6)$$

$$\langle\ ^3P_1\ |\mathbf{r}|\ ^3P_1^o\rangle = \sqrt{15}\cos\theta_1\langle\ p^2|r|sp\rangle\quad (7)$$

$$\langle\ ^3P_2\ |\mathbf{r}|\ ^3P_1^o\rangle = 5(2\sin\theta_1\sin\theta_2 + \cos\theta_1\cos\theta_2)\langle\ p^2|r|sp\rangle\quad (8)$$

$$\langle\ ^1D_2\ |\mathbf{r}|\ ^3P_1^o\rangle = -5(2\sin\theta_1\cos\theta_2 - \cos\theta_1\sin\theta_2)\langle\ p^2|r|sp\rangle\quad (9)$$

$$\langle\ ^1S_0\ |\mathbf{r}|\ ^3P_1^o\rangle = -\sqrt{20}\sin(\theta_1 + \theta_0)\langle\ p^2|r|sp\rangle\quad (10)$$

The transition probabilities can then be obtained from

$$A_{ik} = \frac{1}{3}[1265.38/\lambda(\text{\AA})]^3|\langle k|\mathbf{r}|i\rangle|^2,\quad (11)$$

and used to specify the branching fractions

$$B_{ik} = A_{ik} / \sum_{k'} A_{ik'}\quad (12)$$

The branching fractions can then be used to compute convert the lifetime measurements to transition probabilities and to the corresponding oscillator strengths.

Our mixing angle reductions of the measured energy level data base yielded the values $\theta_1=33.15^\circ$, $\theta_0=-24.15^\circ$, and $\theta_2=42.83^\circ$. Our lifetime measurements for the $6p7s\ ^3P_J$ levels yielded $\tau(J=0)=1.56\pm0.15$ ps and $\tau(J=1)=1.24\pm0.08$ ps. These were reduced to produce values of absorption oscillator strengths.

3.3 Lifetime measurements in few times ionized states.

A number of specialized lifetime measurements have been made for few times ionized atoms using the University of Toledo heavy ion accelerator. The study

of Bi II has already been discussed in the section above on isoelectronic systematization of line strengths. Other studies have utilized the ANDC method to account for cascade repopulations, and still others have traced lifetimes both homologously and isoelectronically.

3.3.1 Hg II in the Au sequence.

We have measured [Paper A7] the lifetimes of the $7p$ levels of Hg II in the Au sequence using joint cascade analysis of its decay curve with those of the $7d$ and $8s$ levels by the ANDC method. Transitions in this system have applications, *e.g.*, in the development of CW rare-gas/metal-vapor lasers and in the plasma dynamics of stellar atmospheres. Theoretical computations indicate that this unusually large J dependence occurs because of the combined influence of a near-lying cancellation node and CI-induced decay to the $5d^96s^2$.

Heavy cancellation effects in a specific transition probability do not usually lead to a large anomaly in the lifetime of the upper level, since these cancellations occur only for $\Delta n \neq 0$ transitions (which possess multiple decay branches), and f sum rules tend to redistribute the missing oscillator strength among other exit channels. However, we have shown earlier [61] that such lifetime anomalies are to be expected for $6s$ - $7p$ transitions in the Au isoelectronic sequence. The effect is expected to be largest in Pb IV, and a measurement [Pinnington *et al.* Can.J.Phys. **69**, 594 (1991)] for that system has exhibited an anomaly in which the $7p\ ^2P_{1/2}$ level has a lifetime six times longer than that of the $7p\ ^2P_{3/2}$.

We found that similarly severe cancellation effects for the $6s$ - $7p$ transitions in Hg II. Although not quantitatively reliable for these sensitive conditions, our theoretical calculations qualitatively indicated that there should be a large J dependence to these lifetimes as a consequence of a nearly complete cancellation in the $6s$ - $7p$ radial transition moment for the $J = \frac{1}{2}$ level (*cf.* Fig.1 of Ref.[61]), coupled with fortuitous λ^3 factors which suppress the decay to $7s$, $6d$, and $6s$. Our measurements (made utilizing the ANDC method) yielded lifetimes 14.5 ± 1.0 ns and 1.2 ± 0.2 ns for the $J = \frac{1}{2}$ and $\frac{3}{2}$ levels, so the J dependence is even stronger here (a factor 12) than was observed for Pb IV.

3.3.2 Y III in the Rb sequence

We have also made the first measurements of lifetimes for Y III [Paper A8] in the Rb sequence. These measurements also utilized the ANDC method to account for cascade repopulation through the joint analysis of the decay curves of the $5p$ levels with those of the $5d$ and $6s$ levels. Although the structure of these levels is dominated by configurations with one electron outside a closed $4p$ subshell, our measurements indicated lifetimes about 30% longer than some existing *ab initio* calculations. However, our results are in good agreement with semiempirical CAHS calculations that include core polarization effects.

3.3.3 N III in the B sequence.

We have made lifetime measurements for several levels in the $2s2p3p$, $2s2p3d$, $2s2p^2$, $2p^3$ configurations of B-like N III [Paper A12]. Beam-foil excitation methods were used with cascade repopulation corrections made by the correlated decay curve ANDC technique. A small but significant J -dependence in the lifetimes of the $3d\ ^4F$ levels was observed. The experimental lifetimes for the levels in the $2s2p^2$ and $2p^3$ were found to be in good agreement with recent theoretical results.

Experimental studies of the lifetime differences among the individual fine structure levels within a term system provide a sensitive test of atomic structure calculations. Even for term systems that are in other ways accurately described by LS coupling, very small changes in the wave function composition can produce substantial J -dependent lifetime variations by, *e.g.*, opening additional decay channels. Such a J -dependence in the measured lifetimes of the $2s2p3p\ ^4D$ and $2s2p3d\ ^4F$ levels have been observed in F V [Engström *et al.*, Phys.Scri. **44**, 548 (1991)] and O VI [Westerlind *et al.*, J.Phys.B **27**, 877 (1994)], but similar studies in N III [Kotzé *et al.*, PR A **44**, 4180 (1991)] revealed no significant J -dependent variations. We have therefore also investigated the decay rates of $2s2p^2$ and $2p^3$ levels in N III, which are of recent interest as a result of their application to the determination of the abundance of nitrogen in stars and in the interstellar medium.

We observed a pronounced J -dependence in the lifetimes of the $3d\ ^4F$ levels in N III, similar to those reported earlier for F V and O IV. Theoretical explanations for these effects have been given and involve the opening of

additional decay channels to certain levels as a result of two types of intermediate coupling. This investigation has shown that, except for the $2s2p3d\ ^4F$ levels, there is good agreement between the available calculations in the sequence and the observed lifetime data. For the $3d\ ^4F$ levels a systematic discrepancy exists, whereby the differences among the lifetimes agree with theory but the absolute values do not. While agreement is good for F V, the calculated values for the lifetimes in O IV and N III become increasingly longer than the measured values, which motivates additional calculations.

3.3.4 Ag II, Cd III, and In IV in the Pd sequence.

We have continued our studies of lifetimes in few times ionized members of the Pd and Rb isoelectronic sequences. Our earlier studies of lifetimes of $5d^96p$ levels in the Pt sequence have been homologously extended to the $4d^96p$ levels of the Pd sequence. Our studies of the Pt-like Au II and Hg III were motivated by their observation in spectra from the Hubble Space Telescope, and our new measurements in Pd-like Ag II [Paper A9], Cd III [Paper A10], and In IV [Paper A11] permits us to compare trends in experiment and theory for which differ only in principal quantum number and number of core electrons.

3.4 Determination of Dipole Polarizabilities from Precision Lifetime Measurements and Transition Moment Cancellations.

Traditionally, the most accurate determinations of ionic dipole polarizabilities α_d have been made using spectroscopic data for high Rydberg levels. For states of sufficiently high n and ℓ , the active electron and passive core are essentially coupled only by central interactions, and the term values can be approximated by a model in which the inner electrons are represented by a deformable core of charge. Although the high precision attainable in spectroscopic term analysis can provide similarly high accuracy in the polarizabilities so determined, distortions due to effects such as core penetration require that the Rydberg states have very high values of both n and ℓ . We have developed an alternative method, based on the fact that the dipole polarizability can be written as a summation over wavelength-weighted absorption oscillator strengths from the ground state to all excited bound and

continuum states. Thus, the ground state dipole polarizability α_d can be expressed in the form

$$\alpha_d = 4R^2 \left[\sum_{n'} \frac{f_{nn'}}{(E_{n'} - E_n)^2} + \int_0^\infty \frac{df/dE}{(E - E_n)^2} dE \right] \quad (13)$$

where $f_{nn'}$ is the absorption oscillator strength for a transition from an ns $^2S_{1/2}$ ground state to an $n'p$ $^2P_{J'}$ excited state, $E_{n'} - E_n \equiv E_{nn'}$ is the corresponding excitation energy, and R is the Rydberg constant. (Both the sum and the integral include an implicit sum over the fine structure levels of the excited states.)

In alkalilike systems, the lowest lying ns - np oscillator strength is unbranched and can be determined from a precision lifetime measurement. It also tends to be close to unity, and thus dominates this sum. Moreover, there is a tendency for singly ionized members of alkalilike isoelectronic sequences to have ns - $n'p$ ($n' > n$) transition moments that are in virtually complete cancellation [2,8,61]. If the sum is dominated by the $n'=n$ term, a lower limit for the dipole polarizability can be deduced directly from the precisely measured lifetime of the ns - np transition through its oscillator strength and transition energy

$$\alpha_d \geq f_{nn}(2R/E_{nn})^2. \quad (14)$$

The uncertainties inherent in this inequality can be accurately estimated by propagating the tolerances in the lifetime measurement, and combining these with theoretical estimates of the magnitudes and uncertainties in the specification of the $n' > n$ transitions. Moreover, the contributions due to higher terms in the summation could also be examined in the context of the Thomas-Reiche-Kuhn sum rule

$$N = \sum_{n'} f_{nn'} + \int_0^\infty \frac{df}{dE} dE \quad (15)$$

where N is the effective number of active electrons (unity in the single particle approximation).

We have made theoretical estimates of the contributions of higher n transitions using energy level data and the semiempirical Coulomb approximation, with a central potential to represent the core (CACP). We adopted the approach of explicitly calculating the oscillator strengths for $n' \leq 20$,

estimating the contributions with $20 < n' < \infty$ by an accurate Padé extrapolation, and calculating the transitions to continuum states up to about 500 eV above threshold. This approach was applied to make determinations of α_d in several ions, as described below.

3.4.1 Polarizability of the Zn^+ ion.

We have performed a study [Paper A13] of the dipole polarizability of Zn using a procedure that combine the use of spectroscopic energy level data, lifetime measurements, and semiempirical calculations. One portion involved the analysis of available spectroscopic measurements for the $4snf$ levels in neutral Zn to specify the effective polarizabilities of its Zn^+ core. Another portion involved the use of existing precision lifetime measurements for the $4s-4p$ transitions in Zn^+ , and new computations of the $4s-np$ transition probabilities. These calculations demonstrated the existence of strong cancellation effects in these transitions for $n \geq 5$, which provided the error bounds described above. A critical evaluation of the results obtained from the spectroscopic and lifetime data yielded $\alpha_d = 15.4 \pm 0.5 a_0^3$.

3.4.2 Polarizability of the Mg^+ ion.

The dipole polarizability for Mg^+ has earlier been determined through its application in the identification of lines from neutral Mg in the far infrared solar spectrum. The observation in 1981 of two strong unidentified solar emission lines in the 120 μm region was initially puzzling because the lines were narrow, had a large Zeeman sensitivity, and (unlike most magnetically sensitive visible solar lines) were chromospheric rather than photospheric. Speculations concerning the origin of these lines ended when Chang and Noyes [Ap. J. **275**, L11 (1983)] used the core polarization model (and calculations for $\alpha_d(\text{Mg}^+)$ made earlier on this project) to identify these lines as the $6h-7i$ and $6g-7h$ transitions in Mg I. In Paper [A14] we report a new and accurate determination of $\alpha_d(\text{Mg}^+)$.

The oscillator strengths for the $3s \ ^2S_{1/2} - 3p \ ^2P_{1/2}$ and $3s \ ^2S_{1/2} - 3p \ ^2P_{3/2}$ transitions have been determined through high precision lifetime measurements [Ansbacher *et al.*, Phys. Lett. A **139**, 165 (1989)] which yielded $\tau(^2P_{1/2}) = 3.854 \pm 0.030$ ns and $\tau(^2P_{3/2}) = 3.810 \pm 0.040$ ns, in good agreement with CACP values of 3.929 ns and 3.898 ns which we have made. We

have extended these calculations up to $n' = 20$, using Ritz parameter extrapolations of measured energy level data. The oscillator strengths are given in Table II of Paper [A14]. The calculated oscillator strengths for $4 \leq n' \leq 20$ make a negligible contribution to α_d since over 85% of the contribution to the sum rule is contained in the $3s$ - $3p$ transitions. Our calculation of the contribution for $n' > 3$ is ± 0.13 (0.4%). Uncertainties in the measured lifetimes introduce a corresponding uncertainty of ± 0.26 (0.7%) into the determination of α_d . The final result was $\alpha_d(\text{Mg}^+) = 34.62 \pm 26 a_o^3$.

3.4.3 Polarizability of the Ca^+ ion.

Lines in the Ca I spectrum which have been produced using both multiphoton laser excitation and microwave spectroscopy have been classified by Chang [J. Phys. B **16**, L539 (1983)] using the core polarization model with the aid of calculations for $\alpha_d(\text{Ca}^+)$ obtained earlier as part of this project. Chang then inverted these classifications to obtain experimental values for $\alpha_d(\text{Ca}^+)$.

The lifetimes for the $4s\ ^2S_{1/2} - 4p\ ^2P_{1/2}$ and $4s\ ^2S_{1/2} - 4p\ ^2P_{3/2}$ transitions in Ca^+ have been measured [Jin and Church, PRL **70**, 3213 (1993)] to be $\tau(^2P_{1/2}) = 7.098 \pm 0.020$ ns and $\tau(^2P_{3/2}) = 6.924 \pm 0.019$ ns. These values also agree well calculations of 7.105 ns and 6.909 ns which we have made as part of this study. Our calculations indicate branching fractions to $3d\ ^2D_J$ levels of 6.0% for $^2P_{1/2}$ and 6.1% for $^2P_{3/2}$.

In view of the apparent accuracy of our semiempirical lifetime values, we treated our semiempirical branching ratios as essentially exact to deduce the principal transition absorption oscillator strengths from the measured lifetime values. We have extended our CACP calculations up to $n' = 20$ using measured energy levels and Ritz parametrization extrapolations. The oscillator strengths corresponding to this measurement, together with our calculated values, are given in Table III of Paper A14.

The calculated oscillator strengths for $5 \leq n' \leq 20$ make a contribution of only 3 parts in 10^3 to α_d , and the experimentally determined oscillator strengths of the $4s$ - $4p$ transitions alone sum to 0.9424 ± 0.0002 , indicating a possible breakdown of the single active electron model. Assuming uncorrelated uncertainties in the measurements of the two lifetimes, they introduce a primary uncertainty of ± 0.15 (0.2%) into the determination of α_d . Contributions from higher n' are less than 0.285 (0.4%), and sum rules thus set brackets of very small width. The result was $\alpha_d(\text{Ca}^+) = 70.89 \pm 15 a_o^3$.

3.5 Spectra and Intensity Ratio Studies in the Al Isoelectronic Sequence

Two separate studies were made on Al isoelectronic sequence: one involved high wavelength resolution term analysis with laser and tokamak sources, the other involved relative intensity measurements with a fast ion beam source.

3.5.1 Wavelength measurements and isoelectronic specification of energy levels in the Al sequence with $Z=15-42$.

We have made new observations [Paper A15] of the $3s^23p^2\ ^2P - 3s3p^2\ ^4P$ intercombination transitions Cl V, Kr XXIV and Mo XXX using spark spectra obtained at the University of Lund and tokamak spectra obtained at the JET Joint European Torus. Through semiempirical parametrizations we were able to interpolate the available data base to obtain precise recommended values for all ions from P III to Mo XXX.

In formulating the isoelectronic systematization of the observed data, we sought one-to-one mappings that reduce the raw data to a linearized exposition, which can be specified by a number of empirical parameters that is much smaller than the number of data points. We found that this could be done very effectively by independently considering the quantities A , B and C

$$A \equiv 3s^23p^2\ ^2P_{1/2} - 3s3p^2\ ^4P_{1/2} \quad (16)$$

$$B \equiv 3s3p^2\ ^4P_{1/2} - 3s3p^2\ ^4P_{3/2} \quad (17)$$

$$C \equiv 3s3p^2\ ^4P_{1/2} - 3s3p^2\ ^4P_{5/2} \quad (18)$$

These were compared to Multiconfiguration Dirac-Fock (MCDF) calculations of interval A , and the fine structure of the ground term,

$$GFS \equiv 3s^23p^2\ ^4P_{1/2} - 3s^23p^2\ ^4P_{5/2} \quad (19)$$

which is accurately known. We found that very accurate linear parametrizations could be obtained by plotting $A(\text{Meas}) - A(\text{MCDF})$ vs $(\alpha Z)^6$, $GFS(\text{Meas}) - B(\text{Meas})$ vs $(Z-12)^{5/2}$, and by performing a Sommerfeld screening parameter reduction of the interval $C(\text{Meas})$. In this manner we obtained a reliable base of data for the $3s3p^2\ ^4P$ levels in this sequence. While the utility of this smoothing procedure does not rely on the fundamental correctness of

the mapping functions, it permits accurate interpolations and the ability to recognize inconsistent data. However, the degree of linearity is so striking in this case that it may suggest the origin of flaws in existing theoretical calculations and point to large scale trends that could be used to test subsequent calculations.

3.5.2 Studies of relative intensities of fine structure transitions in the Al sequence for $Z=14-28$.

We have made an extended investigation [Paper A16], using beam foil excitation, of the intensity ratio of the fine structure components of the $3s^23p\ ^1P_{1/2,3/2} - 3s3p^2\ ^2S_{1/2}$ and $^2P_{1/2}$ resonance transitions along the Al isoelectronic sequence. These intensity ratios are strongly influenced by cancellation and enhancement effects arising from spin-orbit induced level mixings, and are thus sensitive probes of the detailed atomic structure. New measurements have been made for Al-like Si, P, S, K, Sc, Fe and Ni using the accelerators at the Universities of Lund and Bochum. By studying these results together with earlier data, significant deviations from theoretical predictions have been revealed.

3.6 Experimental studies of energy levels and lifetimes in very highly ionized two electron systems.

We have also continued our studies of highly ionized one and two electron systems. These systems are a valuable testing ground for *ab initio* calculations of the fully relativistic electromagnetic interaction between charged particles, and provide one of the simplest systems for which the quantum field theoretical treatment of a bound system of many particles still poses interesting unsolved problems. Several measurements have been carried out at the Argonne National Laboratory ATLAS accelerator facility in collaboration with the ANL and Notre Dame groups.

3.6.1 Lifetime measurements of forbidden transitions in H-like and He-like Ni.

A number of lifetime measurements of forbidden transitions in one- and two-electron nickel have been reported in Paper [A17]. These included the $2\ ^3S_1$

level in hydrogenlike nickel with a lifetime 217.1 ± 1.8 ps and the 2S_0 and 2P_0 A levels in heliumlike nickel with lifetimes 156.1 ± 1.6 and 70 ± 3 ps. We also studied the phenomenon of hyperfine quenching in the He-like 2P_0 level by comparing decay curves for the isotopes Ni and Ni. The lifetime of the 2P_0 level in Ni was 470 ± 50 ps.

3.6.2 Fine structure energies for the $1s2s\ ^3S - 1s2p\ ^3P$ transitions in Ar^{16+} .

The $2\ ^3S_1 - ^3P_1$ energy interval in highly ionized heliumlike atoms has recently provided an important test of *ab initio* calculations. Benchmark calculations by Drake differ for this interval by more than twice the theoretical tolerances. Johnson and Sapirstein have made relativistic MBPT calculations that exhibit a similar discrepancy with Drake's calculations for this interval, that grow approximately as $2.9(Z/10)^4$ for $Z > 12$, which they attribute the omission of relativistic corrections to the second-order energy and of the Breit-Breit interaction, both of which grow as $(\alpha Z)^4$. We have undertaken [Papers A18 and A19] a test of these results through precise measurements of this interval in highly ionized systems.

We have measured the wavelengths of the $1s2s\ ^3S_1 - 1s2p\ ^3P_{0,2}$ transitions in the heliumlike Ar^{16+} ion with a precision < 30 ppm. The experimental results are sensitive to recently calculated $(\alpha Z)^4$ -dependent relativistic corrections to the $n=2$ state energies that represent a new benchmark to our knowledge of the atomic structure of heliumlike ions. Our measurements of the fine structure transition energies, coupled with the accurate new calculations of nonradiative contributions and the existing lower order QED calculations, establish an upper limit to the magnitude of uncalculated higher-order QED corrections for $Z=18$. Our results suggest that the inclusion of higher order terms will reduce the calculated QED contributions to the $1s2s\ ^3S_1$ energy for Ar^{16+} by about 4.5×10^{-5} au is $0.15(\alpha Z)^4$ au. This modification of the QED correction for the $1s2s\ ^3S_1$ state is consistent with the results of new QED calculations for then $n=1$ and $n=2$ singlet states in heliumlike ions.

3.6.3 M1 decay of the $2\ ^3S_1$ state of Kr^{34+} .

Theoretical and experimental studies of the lifetime of the $1s2s\ ^3P_1$ level in He-like ions have been important testing grounds for atomic theory. Unlike the case of the H-like $2s\ ^2S_{1/2}$ level, in which the two-photon mode dominates over M1 decay, for the He-like 3P_1 levels the relativistic M1 decay mode is orders of magnitude greater than the two-photon decay mode. The lowest order matrix element for the $1s^2\ ^1S_0 - 1s2s\ ^3S_1$ transition vanishes in a lowest order, since the operator involves only angular factors and the radial wave functions of the initial and final state are orthogonal. Thus the calculation requires a relativistic theory, and other factors such as electron correlation, nuclear motion, and higher order relativistic corrections must be taken into account. Experimental work exists for a wide variety of ions from $Z=2$ to $Z=42$, which suggest that corrections of order $(\alpha Z)^2$ or higher to existing calculations may be needed.

In an earlier study [53] we obtained a 3% measurement of the lifetime of the 3P_1 level in Br^{33+} . Since the recent addition of an ECR source on the ATLAS facility provides access to intense Kr beam, we have extended this study of the lifetime of the level in Kr^{34+} [Paper A20]. We obtained a result 171.1 ± 2.2 ps, which is in reasonable agreement with current theoretical calculation, but also follows the trend of existing measurements at higher Z that indicate a need for relativistic corrections of order $(\alpha Z)^2$.

3.6.4 Preliminary measurements of the spectral distribution of the two photon decay of $2\ ^1S_0$ in Kr^{34+} .

The $2\ ^1S_0$ state in heliumlike ions is forbidden to decay to the ground state by the emission of a single photon so the dominant decay mode is emission of two E1 photons. The energies of the individual photons have a continuous distribution with a broad peak at half the transition energy and the sum of the energies of the two photons is equal to the transition energy. Calculations of the two-photon decay rate and the spectral distribution have been made by several authors, and indicate that electron correlations give rise to a dependence of the spectral shape on nuclear charge. Relativistic corrections to the spectral shape have not been calculated for the He-like systems, but fully relativistic calculations for corresponding two photon decay of the $2\ ^2S_{1/2}$ level in H-like ions, which indicate that the relativistic effects also lead to a

dependence of the shape on nuclear charge. While the two photon decay rate has been measured for a number of He-like ions, no detailed measurement of the spectral shape has been made for such ion. We have therefore undertaken a series of measurements of the spectral shape of the $2\ ^1S_0$ in Kr^{34+} in order to test existing nonrelativistic calculations and to provide sensitivity to the relativistic corrections.

Our preliminary measurements [Paper A21] of this spectral shape demonstrates that our apparatus is sensitive to photon energies down to about 1 keV, and our rate of detection of two-photon events is sufficient to provide a detailed comparison between experiment and theory. A Monte Carlo program has been developed that allows us to account for many details and imperfections in the apparatus and provides a means for detailed comparisons with theory. A number of problems remain which must be overcome before a comparison with theory can be made. We must eliminate spurious events arising from the interactions of the beam with the aperture that shields the detector from X-rays the target. One of the serious sources of background involves cascade coincidences. While these do correspond to true coincidences, they do can be reduced by the additional constraint imposed by the correct sum-energy. We also need additional calibration sources for the determination of detector efficiencies at the low energy end of the spectrum. Additional run time has been requested at the ATLAS accelerator to complete the measurements.

4 COMPLIANCE WITH CONTRACT STIPULATIONS

4.1 Travel:

4.1.1 Overseas

Two trips to Sweden were made by the PI during this funding cycle. Both trips involved both research collaborations and participation in other research related activities. The first trip was made in the period 19 June 1994 - 4 July 1994 (and thus overlapped with the previous funding cycle). This coincided with an International Conference on "Iron Group Atoms in the Laboratory and in Space" at the University of Lund on 28-29 June 1994. The PI presented an invited talk entitled "Lifetime and Oscillator Strength Measurements in Few Times Ionized Atoms" at this conference, which was attended by over 50 scientists from Sweden, Germany, England, Ireland, France, Lithuania, Japan, Venezuela, and the US. A second trip was made during the period 7-19 December 1995. The PI was invited by the Royal Swedish Academy of Sciences to attend the Nobel Prize Presentations and Ceremonial Banquet in Stockholm (Martin Perl, co-recipient of this year's Physics Prize, was a graduate research mentor of the PI at the University of Michigan). This trip also included a visit to the University of Lund where the PI participated in a Doctoral Thesis Defense. Both trips involved research on Grant related matters, and the first trip was partially supported by Grant Funds, but the second trip was supported entirely by funds from other sources.

4.1.2 Domestic

During this period the PI was also supported by the Grant for attendance at three meetings of the Division of Atomic, Molecular, and Optical Physics (DAMOP) of the American Physical Society. The meetings took place in Crystal City, Virginia (18-20 April 1994), Toronto, Ontario (16-19 May 1995), and Ann Arbor, Michigan (17-19 May 1996). Support was also provided to attend the three DOE/BES Atomic Physics Workshops, held at the University of Kentucky in Lexington (1994), arranged by the University of Texas and held in San Antonio (1995), and held at the University of California

in Fullerton, California (1996). Numerous working visits were also made to Argonne National Laboratory, as well as to the University of Notre Dame.

4.2 Time and Effort Reports:

Time and Effort Reports have been submitted to the University of Toledo Grants Accountant which indicate that 25% of the principal investigator's full time activity is released and charged to the University of Toledo for cost sharing of the project during the 9 month academic year. During the 2 month summers 100% of the principal investigator's full time activity is charged to the grant. For the graduate assistant, 50% of full time activity during the 9 month academic year and 100% during the 2.5 summer months are devoted to this project and charged to the grant.

4.3 Support of Students

The grant has provided various levels of support to three Graduate Students (Richard E. Irving, Murray Henderson, and Rasa Matulioniene), one Undergraduate Student (Michael Kacher), and two Post Doctoral Associates (Steven T. Maniak and Peter Bengtsson). Maniak was supported as a Research Assistant during the previous funding cycle, and his PhD was conferred in December 1993. He received Post Doctoral support from other sources within Department until he accepted a permanent position in the computer industry in 1994. Irving was supported by University funds and received his PhD in August 1996. Henderson was supported as a Research Assistant in 1994-95, and is currently employed full time as accelerator technician in the THIA laboratory. Matulionione was supported as a Research Assistant during the summer of 1996, and she continues to work on project related research. Irving and Henderson have both received support for travel to the National DAMOP meetings, and Maniak, Irving, Henderson, and Kacher have all used equipment purchased under this Grant in the pursuit of thesis or project research.

5 BIBLIOGRAPHY OF PUBLICATIONS PRODUCED IN THIS PROJECT

1980

1. L.J. Curtis, and D.G. Ellis, "Alkali Spectra in the Promethium Isoelectronic Sequence," *Phys. Rev. Lett.* **45**, 2099-2102 (1980).
2. L.J. Curtis and D.G. Ellis, "Cancellations in Transition Probabilities of the K I Isoelectronic Sequence," *J. Phys. B: Atom. Mol. Phys.* **13**, L431-5 (1980).
3. L.J. Curtis and I. Martinson, "Recent Progress in Atomic-Structure Investigations with Fast-Ion Beams," *Comments on Atomic and Molecular Physics* **10**, 1-8 (1980).
4. R.L. Brooks, J.E. Hardis, H.G. Berry, L.J. Curtis, K.T. Cheng, and W. Ray, "Radiation from the Negative Lithium Ion," *Phys. Rev. Lett.* **45**, 1318-22 (1980).

1981

5. L.J. Curtis, "Theoretical Estimates of Quadrupole Polarization and Dynamical Correlation Effects in Single-Valence-Electron Ions," *Phys. Rev. A* **23**, 362-5 (1981).
6. L.J. Curtis, "An Explicit Empirical Formula for Fine-Structure Separations of $^2P^o$ and 2D Terms for Ions in the Cu Isoelectronic Sequence," *J. Phys. B: Atom. Mol. Phys.* **14**, 631-40 (1981).
7. L.J. Curtis, "A Semi-Classical Formula for the Term Energy of a Many Electron Atom," *J. Phys. B: Atom. Mol. Phys.* **14**, 1373-86 (1981).
8. L.J. Curtis, "Cancellations in Atomic Dipole Transition Moments in the Cu Isoelectronic Sequence," *J. Opt. Soc. Am.* **71**, 566-8 (1981).

9. L.J. Curtis, and P.S. Ramanujam, "Semi-Empirical Calculations of Fine Structure Splittings and Ionisation Potentials in the Mg I Isoelectronic Sequence," *Physica Scripta* **23**, 1043-6 (1981).

10. L.J. Curtis and P.S. Ramanujam, "Semiclassical Parameterization of the $\ell \geq 3$ Energy Levels in Cs I," *J. Opt. Soc. Am.* **71**, 1315-7 (1981).

1982

11. L.J. Curtis, "Semiempirical Regularities in the Spectra and Transition Probabilities of Heavy and Highly Ionised Atoms," *Nucl. Instr. Meth.* **202**, 333-8 (1982).

12. L.J. Curtis and P.S. Ramanujam, "A Semiclassical Formulation of Term Energies and Electrostatic Intervals in He I," *Phys. Rev. A* **25**, 3090-6 (1982).

13. L.J. Curtis and P.S. Ramanujam, "Ground State Fine Structures for the B and F Isoelectronic Sequences Using the Extended Regular Doublet Law," *Phys. Rev. A* **26**, 3672-5 (1982).

14. D.G. Ellis, and L.J. Curtis, "Closed N-Shell Alkali Spectra," *Nucl. Instr. Meth.* **202**, 339-40 (1982).

15. B.M. Johnson, K.W. Jones, T.H. Kruse, L.J. Curtis, and D.G. Ellis, "Search for Promethiumlike Gold Lines and Other Transitions of Interest to Fusion Research," *Nucl. Instr. Meth.* **202**, 53-8 (1982).

1983

16. L.J. Curtis and P.S. Ramanujam, "Isoelectronic Wavelength Predictions for the Magnetic Dipole, Electric Quadrupole, and Intercombination Transitions in the Mg Sequence," *J. Opt. Soc. Am.* **73**, 979-84 (1983).

17. L.J. Curtis and P.S. Ramanujam, "Isoelectronic Predictions for Ground State 2P Fine Structures Using the Extended Regular Doublet Law," *Physica Scripta* **27**, 417-21 (1983).

18. L.J. Curtis, P.S. Ramanujam, and C.E. Theodosiou, "Semiclassical Parametrization of the $6snh-6sni-6snk$ Intervals in Ba I," *Phys. Rev. A* **28**, 1151-3 (1983).

19. J.E Hardis, L.J. Curtis, P.S. Ramanujam, A.E. Livingston, and R.L. Brooks, "Measurement of the Transition Probability of the $2s^2\ ^1S_0 - 2s3p\ ^3P_1$ Intercombination Line in Ne VII," Phys. Rev. A **27**, 257-61 (1983).

1984

20. L.J. Curtis, "Lifetime Measurements in Highly Ionised Atoms," Physica Scripta T **8**, 77-83 (1984).
21. L.J. Curtis and R.R. Silbar, "Self-Consistent Core Potentials for Complex Atoms: A Semiclassical Approach," J. Phys. B: Atom. Molec. Phys. **17**, 4087-101 (1984).
22. L.J. Curtis, J. Reader, S.J. Goldsmith, B. Denne and E. Hinnov, " $4s^24p\ ^2P$ Intervals in the Ga Isoelectronic Sequence from Rb^{6+} to In^{18+} " Phys. Rev. A **29**, 2248-50 (1984).
23. L.J. Curtis, I. Martinson, J.A. Leavitt, D.D. Dietrich, S. Bashkin and B. Denne, "Wavelength of the $4s^2\ ^1S - 4s4p\ ^3P$ Intercombination Line in Br VI," Phys. Lett. A **105**, 212-4 (1984).
24. J.A. Hardis, H.G. Berry, L.J. Curtis, and A.E. Livingston, "The $1s2s2p^2\ ^5P_{1,2,3} - 1s2p^3\ ^5S_2$ Transition in Ne VII," Physica Scripta **30**, 189-93 (1984).
25. A.E. Livingston, J.E. Hardis, L.J. Curtis, R.L. Brooks and H.G. Berry, "Observation of Quartet State Fine Structure and Lifetimes in Lithium-like Ne VIII," Phys. Rev. A **30**, 2089-92 (1984).
26. H. Cederquist, S. Mannervik, M. Kisielinski, P. Forsberg, I. Martinson, L.J. Curtis and P.S. Ramanujam, "Lifetimes of Some Excited Levels in Cu I and Cu II," Physica Scripta T **8**, 104-6 (1984).

1985

27. L.J. Curtis, "Semiempirical Methods for Systematization of High Precision Atomic Data," *Comments on Atomic and Molecular Physics* **16**, 1-19 (1985).
28. L.J. Curtis, Isoelectronic Studies of the $4s4p\ ^3P_J$ Energy Levels in the Zn Sequence," *J. Opt. Soc. Am. B* **2**, 407-10 (1985).
29. L.J. Curtis, "Some Current Problems in Beam Foil Spectroscopy," *Nucl. Instr. Meth. in Phys. Res. B* **9**, 565-71 (1985).
30. L.J. Curtis, "Explicit Functional Approximation for the αZ Dependence of Self-Energy Radiative Corrections in Hydrogenlike Atoms," *J. Phys. B: Atom. Molec. Phys.* **18**, L651-6 (1985).
31. E. Träbert and L.J. Curtis, "Comment on Fine Structure Data of Three-Electron Quartet States," *Physica Scripta* **32**, 599-601 (1985).

1986

32. L.J. Curtis, Isoelectronic Studies of the $5s^2\ ^1S_0 - 5s5p\ ^1,^3P_J$ Intervals in the Cd Sequence," *J. Opt. Soc. Am.* **3**, 177-82 (1986).
33. L.J. Curtis, "Alkaline Earthlike Spectra in Highly Ionized Members of the Sm Isoelectronic Sequence," *J. Opt. Soc. Am. B* **3**, 1102-6 (1986).

1987

34. L.J. Curtis, "Fine-structure Intervals for the Lowest P terms in the Cu, Zn, Ga, and Br Isoelectronic Sequences for $Z \leq 92$," *Phys. Rev. A* **35**, 2089-5 (1987).
35. L.J. Curtis, "Bengt Edlén's Handbuch der Physik Article - 26 Years Later," *Physica Scripta* **35**, 805-10 (1987).
36. L.J. Curtis, R.R. Haar, and M. Kummer, "An Expectation Value Formulation of the Perturbed Kepler Problem," *Am. J. Phys.* **55**, 627-31 (1987).

37. L.J. Curtis and L.S. Anderson, editors, "Proceedings of Colloquium on Atomic Spectra and Oscillator Strengths for Astrophysics and Fusion Research, Physica Scripta RS 5, 1-95 (1987).
38. R.R. Haar and L.J. Curtis, "The Thomas Precession Gives g_e-1 , Not $g_e/2$," Am. J. Phys. 55 , 1044-5 (1987).
39. R.R. Haar, L.J. Curtis, N.Reistad, C. Jupén, B.M. Johnson, K.M. Jones and M. Meron, "On the $3s-3p$ and $3p-3d$ Transitions in Ne-like Ni XIX," Physica Scripta 35, 296-9 (1987).

1988

40. L.J. Curtis, "Semiempirical Formulations of Spectroscopic Data and Calculations," Nucl. Instr. Meth. in Phys. Res. B 31, 146-52 (1988).
41. L.J. Curtis, R.R. Haar and I. Martinson, "Multiconfiguration Dirac-Fock Calculations of Energy Levels and Transition Probabilities in Ne-like S VII, Cl VIII and Ar IX," Nucl. Instr. Meth. in Phys. Res. B 31, 280-3 (1988).
42. I. Martinson, L.J. Curtis, R.R. Haar, M.L.A. Raphaelian, H.G. Berry, and C. Kurtz, "Doubly-Excited Levels in Al III," Nuc. Instr. Meth. in Phys. Res. B 31, 188-90 (1988).
43. C.E. Theodosiou and L.J. Curtis, "Accurate Calculations of $3p$ and $3d$ Lifetimes in the Na Sequence," Phys. Rev. A 38, 4435-45 (1988). [Document DOE/ER/13958-3]
44. R.W. Dunford, H.G. Berry, K.O. Groeneveld, M. Hass, E. Bakke, M.L.A. Raphaelian, A.E. Livingston, and L.J. Curtis, "Lifetime of the 2^1S_0 State in Ni^{26+} ," Phys. Rev. A 38, 5423-5 (1988). [DOE/ER/13958-4]

1989

45. L.J. Curtis and C.E. Theodosiou, "Comprehensive Calculations of $4p$ and $4d$ Lifetimes for the Cu Sequence," Phys. Rev. A 39, 605-15 (1989). [DOE/ER/13958-5]

46. L.J. Curtis, "Computation of M1 Decay Rates in Intermediate Coupling Using Empirical Spectroscopic Data," J. Phys. B: Atomic, Molecular and Optical Physics **22**, L267-71 (1989). [DOE/ER/13958-6]
47. L.J. Curtis, "Semiempirical Confrontations between Theory and Experiment in Highly Ionised Complex Atoms," Physica Scripta **39**, 447-57 (1989). [DOE/ER/13958-7]
48. I. Martinson and L.J. Curtis, "Spectroscopic Studies of the Structure of Highly Ionised Atoms," Contemporary Physics **30**, 173-85 (1989). [DOE/ER/13958-8]
49. R.W. Dunford, M. Hass, E. Bakke, H.G. Berry, C.J. Liu, M.L.A. Raphaelian, and L.J. Curtis, "Lifetimes of Two-Photon-Emitting States in Heliumlike and Hydrogenlike Nickel," Phys. Rev. Lett. **62**, 2809-12 (1989). [DOE/ER/13958-9]
50. L.J. Curtis, "Semiempirical Specification of Singlet-Triplet Mixing Angles, Oscillator Strengths, and g-factors in $ns\ n'\ell$, $ns\ n'p^5$, np^2 , and np^4 Configurations," Phys. Rev. A **40**, 6958-68 (1989). [DOE/ER/13958-10]
51. R.R. Haar, T.J. Kvale, D.G. Ellis, I. Martinson, L.J. Curtis and D.J. Beideck, "J-Dependent Lifetimes of Quintet Levels in Neutral Carbon," Phys. Lett. A **141**, 131-4 (1989). [DOE/ER/13958-11]

1990

52. S.T. Maniak and L.J. Curtis, "Labeling Conventions in Isoelectronic Sequences," Phys. Rev. A **42**, 1821-3 (1990). [DOE/ER/13958-12]
53. R.W. Dunford, D.A. Church, C.J. Liu, H.G. Berry, M.L.A. Raphaelian, M. Hass and L.J. Curtis, "Lifetimes of the $2\ ^3S_1$ State of Heliumlike $^{79}\text{Br}^{33+}$," Phys. Rev. A **41**, 4109-11 (1990). [DOE/ER/13958-13]
54. L.J. Curtis, "Semiempirical Formulations of Line Strengths Using Singlet-Triplet Mixing Angles," in *Atomic Spectroscopy and Oscillator Strengths for Astrophysics and Fusion Research*, ed. J.E. Hansen, (North Holland Publ., Amsterdam, 1990), pp. 134-5. [DOE/ER/13958-14]

55. R.R. Haar, T.J. Kvale, D.G. Ellis, I. Martinson and L.J. Curtis, "Lifetime Measurements of Core-Excited Levels in Carbon I," in *Atomic Spectroscopy and Oscillator Strengths for Astrophysics and Fusion Research*, ed. J.E. Hansen, (North Holland Publ., Amsterdam, 1990), pp. 178-9. [DOE/ER/13958-15]
56. L.J. Curtis and I. Martinson, "Lifetime Measurements in Multiply Ionized Atoms," *Comments in Atomic and Molecular Physics* **24**, 213-33 (1990). [DOE/ER/13958-16]

1991

57. L.J. Curtis, "Classical Mnenonic Approach for Obtaining Hydrogenic Expectation Values of r^p ," *Phys. Rev. A* **43**, 568-9 (1991). [DOE/ER/13958-17]
58. L.J. Curtis, "Isoelectronic Smoothing of Line Strengths in Intermediate Coupling," *Physica Scripta* **43**, 137-43 (1991). [DOE/ER/13958-18]
59. R.R. Haar, L.J. Curtis, T.J. Kvale, D.J. Beideck, I. Martinson and R. Hellborg, "Lifetimes of Excited Levels in Neutral Carbon," *Astronomy and Astrophysics* **243**, 321-6 (1991). [DOE/ER/13958-19]
60. R. Hellborg, I. Martinson, S.T. Maniak, R.E. Irving, R.R. Haar, L.J. Curtis and D.J. Beideck, "Variations of Carbon Foil Lifetimes under Bombardment by N^+ , Ne^+ , Ar^+ and Zn^+ Ions," *Physica Scripta* **43**, 262-5 (1991). [DOE/ER/13958-20]
61. L.J. Curtis, "Cancellation Effects in Alkalilike Doublets," *Can. J. Phys.* **69**, 668-70 (1991). [DOE/ER/13958-21]
62. L.J. Curtis, Z.B. Rudzikas, and D.G. Ellis, "Empirical Determination of Intermediate Coupling Amplitudes and Transition Rates from Spectroscopic Data," *Phys. Rev. A* **44**, 776-9 (1991). [DOE/ER/13958-22]
63. C.E. Theodosiou, L.J. Curtis, and M. El-Mekki, "Calculations of $2p$ Lifetimes in the Li Sequence," *Phys. Rev. A* **44**, 7144-57 (1991). [DOE/ER/13958-23]

64. A.E. Livingston, F.G. Serpa, A.S. Zacarias, L.J. Curtis, H.G. Berry and S.A. Blundell, "Lifetime Measurements in Highly-Ionized Silicon, Phys. Rev. A **44**, 7820-2 (1991). [DOE/ER/13958-24]
65. R.W. Dunford, C.J. Liu, J. Last, N. Berrah-Mansour, R. Vondrasek, D.A. Church, and L.J. Curtis, "Direct Observation of Hyperfine Quenching of the $2\ ^3P_0$ Level in Heliumlike Nickel," Phys. Rev. A. **44**, 764-7 (1991). [DOE/ER/13958-25]
66. R.W. Dunford, H.G. Berry, D.A. Church, T.P. Dineen, M. Hass, C.J. Liu, N. Berrah-Mansour, R.C. Pardo, M.L.A. Raphaelian, L. Young, B.J. Zabransky, and L.J. Curtis, "Precision Spectroscopic Measurements in Few-Electron Ions," Z. Physik D **21**, S13-16 (1991). [DOE/ER/13958-26]

1992

67. L.J. Curtis, "Empirical Lifetimes for $4s4p\ ^1,^3P$ Levels in the Zn Isoelectronic Sequence," J. Opt. Soc. Am. B **9**, 5-9 (1992). [DOE/ER/13958-27]
68. L.J. Curtis, "A Predictive Systematisation for ns^2 - $nsn'p$ Line Strength Data," J. Phys.B: Atomic, Molecular and Optical Physics **25**, 1425-35 (1992). [DOE/ER/13958-28]
69. M. Westerlind, L. Engström, P. Bengtsson and L.J. Curtis, "Experimental Lifetimes of the $2p3s\ ^1P_1$ and 3P_1 Levels in Ne-like Sulfur and Chlorine," Phys. Rev. A **45**, 6198-201 (1992). [DOE/ER/13958-29]

1993

70. D.J. Beideck, L.J. Curtis, R.E. Irving, S.T. Maniak, R. Hellborg, S.G. Johansson, A.A. Joueizadeh, I. Martinson, and T. Brage, "Lifetimes of $5d^96p$ and $5d^86s6p$ Levels in Hg III," Phys. Rev. A **47**, 884-889 (1993). [DOE/ER/13958-31]
71. D.J. Beideck, L.J. Curtis, R.E. Irving, S.T. Maniak, R. Hellborg, S.G. Johansson, I. Martinson, and M. Rosberg, "Lifetimes of $5d^86p$ levels in Au II," J. Opt. Soc. Am. B **10**, 977-981 (1993). [DOE/ER/13958-32]

72. R.R. Haar and L.J. Curtis, "ACCEL, A Program for Data Acquisition," Nucl. Instr. Meth. in Phys. Res. B **79**, 746-8 (1993). [DOE/ER/13958-33]
73. S.T. Maniak, E. Träbert, and L.J. Curtis, "Beam-Foil Lifetime Measurements of Low-Lying Levels in Si IV," Phys. Lett. A **173**, 407-410 (1993). [DOE/ER/13958-34]
74. R.R. Haar, D.J. Beideck, L.J. Curtis, T.J. Kvale, A. Sen, R.M. Schectman, and H. Stevens, "The Toledo Heavy Ion Accelerator," Nucl. Instr. Meth. in Phys. Res. B. **79**, 782-4 (1993). [DOE/ER/13958-35]
75. S. Cheng, H.G. Berry, R.W. Dunford, D.S. Gemmell, E.P. Kanter, B.J. Zabransky, A.E. Livingston, L.J. Curtis, J. Bailey, and J.A. Nolen, Jr., "Branching Ratio for the M1 Decay of the $2^2S_{1/2}$ State in One-Electron Krypton," Phys. Rev. A **47**, 903-910 (1993). [DOE/ER/13958-36]
76. E. Träbert, J. Suleiman, S. Cheng, H.G. Berry, R.W. Dunford, E.P. Kanter, C. Kurtz, A.E. Livingston, K.W. Kukla, F.G. Serpa, and L.J. Curtis, Experimental Transition Probabilities of Intercombination Transitions in Mg-like and Al-like Ions of Bromine," Phys. Rev. A **47**, 3805-3809 (1993). [DOE/ER/13958-37].
77. L.J. Curtis, "Data-Based Methods for Isoelectronic Prediction of Atomic Lifetimes and Energy Levels," Physica Scripta **48**, 559-66 (1993). [DOE/ER/13958-38]
78. E. Träbert and L.J. Curtis, "Intercombination and Resonance Transitions in the Zn Isoelectronic Sequence: Problems in Experiment and Theory," Physica Scripta **48**, 559-66 (1993). [DOE /ER/13958-39]
79. S. Cheng, R.W. Dunford, E.P. Kanter, H.G. Berry, D.S. Gemmell, B.J. Zabransky, A.E. Livingston, L.J. Curtis, J. Bailey, and J.A. Nolen, Jr., "Lifetime of the $2^2S_{1/2}$ State in Hydrogenlike Krypton," AIP Conf. Proceed. No. 274, 394-397 (1993). [DOE/ER/13958-40]
80. K.W. Kukla, A.E. Livingston, F.G. Serpa, A.S. Zacarias, H.G. Berry, R.W. Dunford, E. Kanter, S. Cheng, J. Suleiman, L.J. Curtis, and

- E. Träbert, "Spectroscopy of Highly-Ionized Atoms Using Position-Sensitive Detection," in *The Physics of Highly-Charged Ions*, AIP Conf. Proceed. No. 274, 398-401 (1993). [DOE/ER/13958-41]
81. R.W. Dunford, S. Cheng, E.P. Kanter, H.G. Berry, C. Kurtz, B.J. Zebransky, A.E. Livingston, and L.J. Curtis, "Two-Photon Decay of the $2\ ^1S_0$ State in Heliumlike Bromine," *Phys. Rev. A* **48**, 1929-36 (1993). [DOE/ER/13958-42]
 82. L.J. Curtis, "A Predictive Data-Based Exposition of the $nsnp\ ^1,^3P_1$ Lifetimes in the Cd and Hg Isoelectronic Sequences," *J. Phys. B: At. Mol. Opt. Phys.* **26**, L589-94 (1993). [DOE/ER/14461-3]
 83. S.T. Maniak, L.J. Curtis, R.E. Irving, I. Martinson, and R. Hellborg, "Lifetimes of the 7p Levels in Hg II," *Phys. Lett. A* **182**, 114-9 (1993). [DOE/ER/14461-4]
 84. R.W. Dunford, H.G. Berry, D.A. Church, M. Hass, C.J. Liu, M.L.A. Raphaelian, B.J. Zabransky, L.J. Curtis, and A.E. Livingston, "Forbidden Transitions in One- and Two-Electron Nickel," *Phys. Rev. A* **48**, 2729-45 (1993). [DOE/ER/14461-5]

1994

85. S.T. Maniak, L.J. Curtis, C.E. Theodosiou, R. Hellborg, S.G. Johansson, I. Martinson, R.E. Irving and D.J. Beideck, "Lifetimes of Excited Levels in Y III," *Astron. Astrophys.* **286**, 978-82 (1994). [DOE/ER/14461-6]
86. S. Cheng, R.W. Dunford, C.J. Liu, B.J. Zabransky, A.E. Livingston, and L.J. Curtis, "M1 Decay of the $2\ ^3S_1$ State in Heliumlike Krypton," *Phys. Rev. A* **49**, 2347-53 (1994). [DOE/ER/14461-7]

1995

87. L.J. Curtis and C.E. Theodosiou, "A Comment on the Dipole Polarizability of the Zn^+ Ion," *J. Opt. Soc. Am. B* **12**, 175-7 (1995). [DOE/ER/14461-8]

88. L.J. Curtis, D.G. Ellis, and I. Martinson, "Precise Data-Based Predictions of Line Strengths in Alkalilike Isoelectronic Sequences," *Phys. Rev. A* **51**, 251-6 (1995). [DOE/ER/14461-9]
89. L.J. Curtis, S.T. Maniak, R.W. Ghrist, R.E. Irving, D.G. Ellis, M. Henderson, M.H. Kacher, E. Träbert, J. Granzow, P. Bengtsson, and L. Engström, "Measurements and Data-Based Predictions for $\Delta n=1$ Resonance and Intercombination Transitions in the Be and Ne Sequences," *Phys. Rev. A* **51**, 4575-82 (1995). [DOE/ER/14461-10]
90. C.E. Theodosiou, L.J. Curtis, and C.A. Nicolaides, "Determination of Dipole Polarizabilities for Mg^+ and Ca^+ from Precision Lifetime Measurements and Transition Moment Cancellations," *Phys. Rev. A* **52**, 3677-80 (1995). [DOE/ER/14461-11]
91. P. Bengtsson, L.J. Curtis, M. Henderson, R.E. Irving and S.T. Maniak, "Lifetime Measurements in N III using the Beam-Foil Technique and Cascade Corrections," *Physica Scripta* **52**, 506-10 (1995). [DOE/ER/14461-12]
92. R.E. Irving, S.T. Maniak, D.J. Beideck, P. Bengtsson, L.J. Curtis, R. Hellborg, G. Kalus, and I. Martinson, "Lifetimes of the $4d^9 5p$ Levels in Ag II," *Physica Scripta* **51**, 351-3 (1995). [DOE/ER/14461-13]
93. L. Engström, M. Kirm, P. Bengtsson, S.T. Maniak, L.J. Curtis, E. Träbert, J. Doerfert and J. Granzow, "Extended Analysis of Intensity Anomalies in the Al I Isoelectronic Sequence," *Physica Scripta* **52**, 516-21 (1995). [DOE/ER/14461-14]
94. K.W. Kukla, A.E. Livingston, J. Suleiman, H.G. Berry, R.W. Dunford, D.S. Gemmell, E.P. Kanter, S. Cheng and L.J. Curtis, "Fine Structure Energies for the $1s2s\ ^3S - 1s2p\ ^3P$ Transition in Helium-like Ar^{16+} ," *Phys. Rev. A* **51**, 1905-17 (1995). [DOE/ER/14461-15]
95. R. Ali, I. Ahmad, H.G. Berry, R.W. Dunford, D.S. Gemmel, E.P. Kanter, P.H. Mokler, A.E. Livingston, S. Cheng and L.J. Curtis, "Spectral Distribution of the Two-Photon Decay of He-like Krypton," *Nucl. Instr. Meth. in Phys. Res. B* **98**, 69-73 (1995). [DOE/ER/14461-16]

96. A.E. Livingston, K.W. Kukla, C.M. Vogel Vogt, H.G. Berry, R.W. Dunford, D.S. Gemmell, E.P. Kanter, J. Suleiman, R. Ali, S. Cheng and L.J. Curtis, "Fine Structure Energies for the $1s2s\ ^3S - 1s2p\ ^3P$ transition in Helium-Like Ions, Nucl. Instr. Meth. in Phys. Res. B **98**, 28-32 (1995). [DOE/ER/14461-17]

1996

97. L.J. Curtis and D.G. Ellis, "Predictive Systematization of Line Strengths for the $2s^2-2s2p$ Resonance and Intercombination Transitions in the Be Isoelectronic Sequence," J. Phys. B: At. Molec. and Opt. Phys. **29**, 645-54 (1996). [DOE/ER/14461-18]
98. C. Jupén and L.J. Curtis, "Isoelectronic Comparision of the Al-like $3s^23p\ ^2P - 3s3p^2\ ^4P$ Transitions in the Ions P III - Mo XXX," Physica Scripta **53**, 312-6 (1996). [DOE/ER/14461-19]
99. M. Henderson, L. J. Curtis, and R. E. Irving, "Lifetimes of the $4d^95p$ Levels in In IV," Physica Scripta **53**, 557-9 (1996). [DOE/ER/14461-20]
100. M. Henderson, L.J. Curtis, D.G. Ellis, R.E. Irving and G.M. Wahlgren, "Lifetimes and Oscillator Strengths for the $6s7p\ ^3P_{0,1}$ Levels in Bi II," Astrophys. J. (December 1996). [DOE/ER/14461-21]
101. M. Henderson, P. Bengtsson, J. Corcoran, L.J. Curtis, R.E. Irving and S.T. Maniak, "Lifetimes of the $4d^95p$ Levels in Cd III," Physica Scripta **53**, 309-11 (1996). [DOE/ER/14461-22]
102. M. Henderson and L.J. Curtis, "Lifetime Measurements in Tl II," J. Phys. B: At. Mol. Opt. Phys. (in press, 1996). [DOE/ER/14461-23].

DOE INTERNAL REPORTS

Oak Ridge Operations Number: DOE/ER/13958-n

1. Progress Report: 1 July 1988 - 1 April 1989
2. Progress Report: 1 July 1989 - 15 Jan. 1990
3. Ref. 43 above.
4. Ref. 44 above.
5. Ref. 45 above.
6. Ref. 46 above.
7. Ref. 47 above.
8. Ref. 48 above.
9. Ref. 49 above.
10. Ref. 50 above.
11. Ref. 51 above.
12. Ref. 52 above.
13. Ref. 53 above.
14. Ref. 54 above.
15. Ref. 55 above.
- 16a. Progress Report: 1 July 1988 - 1 Jan. 1991.
- 16b. Ref. 56 above.
17. Ref. 57 above.
18. Ref. 58 above.
19. Ref. 59 above.
20. Ref. 60 above.
21. Ref. 61 above.
22. Ref. 62 above.
23. Ref. 63 above.
24. Ref. 64 above.
25. Ref. 65 above.
26. Ref. 66 above.
27. Ref. 67 above.
- 28a. Progress Report: 1 September 1990 - 1 March 1992.
- 28b. Ref. 68 above.
29. Ref. 69 above.
30. Progress Report: 1 March 1992 - 15 December 1992.
31. Ref. 70 above.
32. Ref. 71 above.

33. Ref. 72 above.
34. Ref. 73 above.
35. Ref. 74 above.
36. Ref. 75 above.
37. Ref. 76 above.
38. Ref. 77 above.
39. Ref. 78 above.
40. Ref. 79 above.
41. Ref. 80 above.
42. Ref. 81 above.
43. Progress Report: 1 July 1991 - 15 December 1993.
44. Progress Report: 1 October 1993 - 1 March 1995.
45. Progress Report: 1 July 1994 - 1 October 1996
- Argonne Operations Number: DOE/ER/14461-n**
1. Progress Report: 1 March 1995 - 15 February 1996.
2. Progress Report: 1 July 1994 - 1 October 1996
3. Ref. 82 above.
4. Ref. 83 above.
5. Ref. 84 above.
6. Ref. 85 above.
7. Ref. 86 above.
8. Ref. 87 above.
9. Ref. 88 above.
10. Ref. 89 above.
11. Ref. 90 above.
12. Ref. 91 above.
13. Ref. 92 above.
14. Ref. 93 above.
15. Ref. 94 above.
16. Ref. 95 above.
17. Ref. 96 above.
18. Ref. 97 above.
19. Ref. 98 above.
20. Ref. 99 above.
21. Ref. 100 above.
22. Ref. 101 above.
23. Ref. 102 above.

*Reprints removed for
separate processing*

6 APPENDIX A: REPRINTS OF PAPERS PUBLISHED AS PART OF THIS PROJECT

- Paper A0: 1-8
- Paper A1: 9-14
- Paper A2: 15-20
- Paper A3: 21-26
- Paper A4: 27-36
- Paper A5: 37-44
- Paper A6: 45-50
- Paper A7: 51-56
- Paper A8: 57-62
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- Paper A11: 71-74
- Paper A12: 75-80
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- Paper A15: 89-94
- Paper A16: 95-100
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- Paper A19: 125-138
- Paper A20: 139-146
- Paper A21: 147-152