PROGRESS REPORT

for

GRANT NO: DE-FG02-86ER13491

REPORTING PERIOD: FY-95

Submitted to

U. S. DEPARTMENT OF ENERGY

Title: "ATOMIC PHYSICS WITH HIGHLY CHARGED IONS"

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September 1995

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INTRODUCTION:
During the last year we have made much progress in our investigations of high energy collisions and low energy collisions involving multiply charged ions, and in our investigations of the theory of structure and collisions of highly charged ions. The work from previous years has resulted in the publication of 27 papers in refereed journals during the last twelve months.

HIGH ENERGY COLLISIONS WITH MULTIPLY CHARGED IONS:
In the area of high energy collisions involving multiply charged ions, we continue to develop and use the methods of electron emission spectroscopy, recoil momentum spectroscopy, and ion-molecule collision spectroscopy. The primary goal in these experiments is to refine the measurement techniques to better obtain a complete description of the collision. This has allowed us to isolate such important information as collision mechanisms and cross sections for well defined processes.

Electron emission spectroscopy has allowed us to study electron-electron and electron-nuclear excitation mechanisms, to study direct ionization test cases for theory, to study the production of binary encounter electrons in the field of a screened nucleus, which is equivalent to studying electron-ion elastic scattering, to study Coster-Kronig transitions of doubly excited states, which is equivalent to investigations of electron-ion inelastic resonance (REDA) scattering, and to study Compton profiles of molecules and molecular clusters.

In electron spectroscopy, we have recently completed the measurement of the double differential cross sections, DDCS, for 2.5 MeV/u C6+ on H2 from 0.1 eV to 300 eV electron energy and for angles from 15° to 160°. This is an important test case for detailed comparisons with theories such as the continuum distorted wave. This experiment is a warm-up for the ultimate experiment of electron production from bare ions on atomic hydrogen which is just now beginning. One interesting application of the electron DDCS data is the construction of the recoil longitudinal momentum distribution directly from the electron DDCS cross sections. We have also investigated the relative roles of electron-electron vs. electron-nucleus interactions in one electron excitation of Li-like highly charged ions by multi-electron neutral targets including Ne, Ar, Kr and Xe. During the last few months we have observed for the first time a shift from a normal projectile q scaling to an inverted projectile q scaling of the binary encounter electron production cross section as the projectile energy is increased. In inverted projectile q scaling the cross section decreases as the charge of the projectile increases. These effects can be explained in terms of screened potential scattering of the target electron by the projectile ion. We have also measured the Compton profile of C60 (buckyballs) using the binary encounter electron spectroscopy method.

The method of recoil momentum spectroscopy with high velocity highly charged projectiles was performed with a cooled supersonic He jet. The jet has an effective temperature of 0.4 K transverse to the jet corresponding to a resolution in recoil momentum of 0.15 a.u. The great detection efficiency of this method allows one to easily obtain charge separated projectile-recoil ion and electron-recoil ion coincidences. The resolution obtained in the transverse and longitudinal momentum directions allows
one to separate ionization by electron-electron interactions from ionization by electron-nucleus interaction. The recoil momentum spectroscopy method also allows one to study single electron capture and transfer ionization.

The recoil momentum spectroscopy method has been used in several studies during the last year. They include the study of electron capture and transfer ionization in 10-15 MeV F$^8+$ on He. Capture channels separated in Q value by 20 eV could be resolved. This method allows one to obtain capture cross sections to various (n,\epsilon) states free of fluorescence and/or Auger yields and cascading effects present in x-ray and Auger electron measurements. The transfer ionization requires the measurement of the electron momentum which is being done by using a projection electron spectrometer immersed in a longitudinal magnetic field. The ratio of transfer ionization to capture has been measured by the recoil ion-projectile coincidences using primarily the recoil longitudinal momentum information for projectiles between C$^8+$ to Ti$^{88+}$. In one study recently completed, we addressed the question "How are the impact parameter and the transverse recoil moment related to each other in inelastic collisions?" The impact parameter dependence of the four inelastic channels of single ionization, double ionization, single capture and transfer ionization determined from a deflection function based on a static screening potential gives a consistent agreement with calculations based on the Independent Electron Approximation.

The ion-molecule collision spectroscopy method has allowed us to determine mechanisms leading to breakup following high energy highly charged ion collisions with diatomic molecules. We have measured the kinetic energy release in the breakup channels. We have also performed experiments and calculations on the mean lifetime of long-lived doubly charged molecular ions.

During the last year we measured the double-to-single ionization ratio of H$_2$ molecules caused by fast proton impact for 5 to 24 a.u. ion velocities using coincidence time-of-flight. The ratio levels off at $\sim$0.13% at the high velocities which is smaller than that produced by electrons. The ratio was also measured at 1 MeV/u for Li$^{(2-3)+}$ and F$^{(4-9)+}$ and found to be much larger than for H$^+$ impact (e.g., $\sim$6% for F$^{8+}$). The ratio of ionization-excitation to single ionization of H$_2$ was also determined by taking advantage of the fact that all the electron states of H$_2^+$ are dissociative in the Franck-Condon region. This ratio is 2% for H$^+$ and 30% for F$^{8+}$ projectiles.

We have measured the lifetimes of the following long-lived doubly charged molecules: $^4$HeH$^2+$, $^3$HeD$^2+$, $^4$HeD$^2+$, $^{22}$Ne$^{40}$Ar$^2+$, and $^3$He$^4$He$^2+$.

LOW ENERGY COLLISIONS INVOLVING MULTIPLY CHARGED IONS

The ion-ion collision facility at KSU has been completed and the test reaction of He$^{2+}$ from the ECR source capturing from He$^+$ from a penning ion source is under study. A vacuum of 10$^{-10}$ torr in the interaction region has been achieved. Electrostatic and magnetic analysis of the reaction products, with the use of UHV compatible position sensitive detectors, allow a sensitive separation of reaction products from capture in the background gas from those from the colliding beams.

We have used a simple projection spectrometer to measure the momentum distributions for slow bare H, C, O, and Ne ions on He. The results for the highly charged projectiles show that the longitudinal momentum of the electrons is much larger than the transverse momentum, showing a near confinement in velocity space to a line
extending from target to projectile. For highly charged projectiles, the center of the longitudinal momentum distribution lies nearer the projectile velocity than the target. No saddle point feature is seen.

The single and double photoionization of He is being investigated using recoil momentum spectroscopy with a cooled supersonic He gas jet at the Advanced Light Source. The momentum of the He ions is measured with a precision of typically 0.1 a.u. For single ionization, determination of this momentum is sufficient to kinematically completely determine the final state of the reaction, whereas for double ionization the momentum of one of the electrons must be measured as well. In experiments carried out to date, the ratio of single-to-double ionization of He for Eγ between 79 and 400 eV has been measured. Multiply differential cross sections for single and double ionization have been measured for Eγ for 1, 6, 20, and 80 eV above the He double ionization threshold.

We have studied projectile neutralization and K x ray emission in grazing collisions of slow Ar ions with graphite. Ar4+ through Ar17+ with velocities between 0.15 and 0.62 a.u. have been scattered from highly oriented (±0.4 deg mosaicity) pyrolytic graphite under a grazing scattering angle of initially 1.6 deg. The electrically analyzed reflected ions and atoms yield approximately 80% complete neutralization, 20% Ar1+, and 2% of Ar2+ for a velocity of 0.22 a.u., almost independent of the initial charge state. The fraction of completely neutralized ions decreases, while the fraction of the incompletely neutralized ions increases approximately linearly with the ion velocity, independent of the initial ion charge state.

We have measured capture cross sections in collisions of slow highly charged ions with a laser-excited Rydberg target. We have continued our collaborative measurements of absolute capture cross sections for slow highly charged ions incident on a laser-excited rubidium Rydberg target. Using the KSU CRYEBIS to produce beams of Xe4+ (q=4-40) at velocities between 0.1 and 0.6 atomic units, we have measured absolute total capture cross sections for a rubidium target which has been put into a 10f state via a resonant, 3 photon (3 color) excitation scheme (supplied in a collaborative effort by Colorado State University). These results have been published. In an attempt to determine capture cross sections differential in final n and ℓ, a novel approach was undertaken in which a fourth laser was used to probe the projectile following charge capture.

In order to probe more deeply the mechanism for "soft" capture of electrons from C60 by slow multiply-charged ions, we have measured the angular distributions of the projectiles resulting from the capture. For such a process, the very large polarizability of the C60 is expected to play an important role in determining the trajectory of the projectile during the capture. The experiment uses a C60 jet crossed with a 2.4 keV Ar3+ beam from the KSU EBIS and measures the projectiles scattered at a known angle in coincidence with charged C60 ions produced in the capture.

The gain of Multi-channel-plates (MCP) in a Chevron arrangement has been determined for 1.5 to 150 keV/q Ar with charge states q = +3 to +16+ by measuring the initial ion beam current as well as the electron current collected at the output of the second MCP.
THEORY OF STRUCTURE AND COLLISIONS OF HIGHLY CHARGED IONS

The total and differential excitation cross sections for the electron impact excitation of hydrogen-like carbon for the transitions 1s $^2$S $\to$ 2s $^2$S and 2p $^2$P were calculated. These calculations were performed for electron-impact energies ranging from 28.2 to 29.5 Rydbergs with an energy mesh of 0.0025 Ry using the close-coupling R-matrix method. This energy region was chosen because in addition to the direct excitation of 2s and 2p, there is a sizable contribution to the excitation cross section from the doubly excited two electron states (3\(\varepsilon\)3\(\varepsilon'\)) which decay predominantly to n=2 via autoionization. The differential cross section at the resonance energy and at ±0.01 Ry with respect to the resonance energy show the sensitivity of the DCS. The resonance contribution including the Fano-type profile are strongly dependent on the observation angle. The impulse approximation was used to calculate DDCS for C\(^{5+}\)(1s)+H\(_2\) $\to$ C\(^{5+}\)(2\(\varepsilon\))+H\(_2^+\) and these DDCS were found to qualitatively reproduce the resonant structure observed in a recent experiment reported by Hvelplund et al. (Phys. Rev. A 49, 2535 (1949). Calculations of the differential electron elastic scattering cross sections from several ions were performed with the Hartree-Fock atomic model. These results were then used to calculate the double differential BE electron production cross sections, and compared with the data obtained at KSU.

We have performed two-center close-coupling calculations to obtain ionization cross sections of He by highly charged C\(^{6+}\), N\(^{7+}\), and O\(^{8+}\) ions at velocities between 1 and 2 a.u. The dependence of ionization cross sections on the projectile charge state and velocity was studied. It was found that the observed rapid increase in ionization cross section in this velocity region was due to electron capture into projectile continuum. Two-center close-coupling calculations were performed to obtain cross sections for single and multiple electron transitions in collisions of He with Be\(^{9+}\) and B\(^{10+}\) ions at energies between 10-500 keV/amu. We studied the collision between elliptic Rydberg states and singly charged ions to examine how the charge transfer and ionization cross sections depend on the orientation and the alignment of the elliptic states.

A dynamical over-barrier model for long-range charge exchange was developed to simulate the population dynamics during the interaction of slow, highly charged ions with C\(_{60}\). The model has been applied to 80 keV Ar\(^{8+}\) and 50 keV N\(^{5+}\) projectiles. Occupation evolutions of all strongly coupled levels, final charge states, and energy-resolved Auger spectra were simulated. Calculated cross sections and final charge-state distributions agree reasonably well with recent experiments. In a comparative study, two different electronic structure calculations for C\(_{60}\), a LDA-type approach and a new Dirac-Fock-Slater (DFS) calculation were used within the dynamical over-barrier model.
1. "Angular Distribution of $\delta$ Electrons Emitted in Collisions of 1.0-MeV/u F$^+$ (q=4,6,8,9) with Molecular Hydrogen"

2. "Evidence for Population of Highly Asymmetric States in Double-Electron Capture by O$^{7+}$ and N$^{7+}$ Colliding with He at Low to Intermediate Velocities"

3. "Electron Capture from Elliptic Rydberg States"
   M.F.V. Lundsgaard, N. Toshima, Z. Chen, and C. D. Lin

4. "Charge Exchange and Electro Emission in Slow Collisions of Highly Charged Ions with C$_{60}$"
   Uwe Thumm

5. "Methods for Measuring Mean Lifetimes of Long Lived Molecular Ions Formed in Fast Collisions"
   I. Gertner, B. Rosner, and I. Ben-Itzhak

6. "Charge State Equilibration Length of a Highly Charged Ion Inside a Carbon Solid"
   R. Herrmann, C. L. Cocke, J. Ullrich, S. Hagmann, M. Stöckli, and H. Schmidt-Böcking

7. "Scaling of Single Ionization Cross Sections of Molecules with the Charge of Fast Projectiles"
   Vidhya Krishnamurthi, I. Ben-Itzhak, K. D. Carnes, and B. M. Barnes

8. "Relationship Between the Born and Impulse Approximations for the Antiscreening Process"
   E. C. Montenegro and T.J.M. Zouros

9. "Excitation and Ionization of H(2s) by Proton Impact"
   Z. Chen, B. D. Esry, C. D. Lin, and R. D. Piacentini

10. "Scaling of Mean Lifetimes of Metastable Molecular States with Angular-Momentum and Vibrational Quantum Numbers"
    I. Ben-Itzhak, Z. Chen, and C. D. Lin

11. "Energy-Transfer Processes During Xe$^{30+}$-Ar Collisions for Projectile Velocities Between 0.3 and 1.0 a.u."
    M.L.A. Raphaelian, M. P. Stöckli, W. Wu, and C. L. Cocke
12. "Kinetic-Energy Release in CO Dissociation Caused by Fast F$^{4+}$ Impact"
   I. Ben-Itzhak, S. G. Ginther, Vidhya Krishnamurthi, and K. D. Carnes

    D. C. Parks, R. Bastasz, R. W. Schmieder, and M. Stöckli

14. "Electron Capture in K$^+$ Ion Collisions with Na(4d)"
    M.F.V. Lundsgaard, Z. Chen, and C. D. Lin

15. "L-Subshell Vacancy Production of Fast Argon Ions in Solids"

16. "Search for Inelastic Electrons Scattered Off Ions in Energetic Ion-Atom Collisions"

17. "Two-Electron Excitation to Rydberg Levels in Fast I$^{6+}$"

18. "Diffraction Structures in Binary Encounter Electron Spectra: A Dominant Feature for Projectiles Above C$^+$ and a Tool to Study the Ionization Mechanism"

19. "Single Capture and Transfer Ionization in Collisions of C$^+$ Projectile Ions Incident on Helium"

20. "One and Two Electron Processes in Fast Collisions Between Protons and Hydrogen Molecules"
    I. Ben-Itzhak, Vidhya Krishnamurthi, K. D. Carnes, H. Aliabadi, H. Knudsen, and U. Mikkelson


22. "Recoil Longitudinal Momentum and Q-Value Measurements in Electron-Capture Processes of Fast Multiply Charged Ions Colliding with He"
    W. Wu, K. L. Wong, C. L. Cocke, J. P. Giese, and E. C. Montenegro
   C. P. Bhalla, S. R. Grabbe, and A. K. Bhatia
24. "Search for Inelastic Electrons Scattered Off Ions in Energetic Ion-Atom Collisions"
26. "Recoil Momentum Dynamics for the Antiscreening Process"
   E. C. Montenegro, W. Wu, K. L. Wong, and C. L. Cocke

ABSTRACTS FOR GRANT PERIOD

13th International Conference on the Application of Accelerators in Research and Industry, Denton, Texas (November 7-10, 1994)

1. "One and Two Electron Processes in Fast Collisions Between Protons and Hydrogen Molecules"
   I. Ben-Itzhak
2. "A Method for Measuring Mean Lifetimes of Short-Lived (nanosecond region) Molecular Ions Formed in Fast Collisions"
   B. Rosner and I. Ben-Itzhak
3. "q-Dependence of Zero Degree Binary Encounter Electron Production in 30 MeV O^q+ Collisions with H_2, He, and Ne"
   C. P. Bhalla, S. Grabbe, P. Richard, and T.J.M. Zouros
4. "q-Dependence of Zero Degree Binary Encounter Electron Production for Si^q+, C^q+, and Cu^q+ on H_2"
   P. Richard, C. P. Bhalla, S. Grabbe, and H. I. Hidmi
5. "Final Charge State Distributions of Close Collisions of Slow-Highly Charged Ions with C_60"
   Bernhard P. Walch and C. Lewis Cocke
6. "Electron Capture from Circular Rydberg Atoms"
   M.F.V. Lundsgaard, Z. Chen, and C. D. Lin
7. "Absolute 1s→2p Excitation Cross Sections of 4P and 2P States for 30 MeV O^{5+} Projectiles"
   G. Toth, P. Richard, and E. C. Montenegro
8. "An Apparatus for the Study of Ion-Ion Collisions"
   C. Y. Chen, A. Landers, J. P. Giese, F. Melchert, and M. Stöckli
   Jiyun Kuang and C. D. Lin
10. "Large Angle Scattering of 100 keV C⁴⁺ and C⁴⁺ on He Without Charge Exchange"
    W. Winecki, R. Ali, C. L. Cocke, M.L.A. Raphaelian, P. Richard,
    H. Schmidt-Böcking, H. Schone, and M. P. Stöckli
11. "Single Capture and Transfer Ionization in Collisions of C⁶⁺ Projectile Ions Incident on Helium"
    K. L. Wong, W. Wu, C. L. Cocke, J. Giese, I. Ben-Itzhak, E. C.
    Montenegro, V. Krishnamurthi, and P. Richard
13. "Quasi-Resonant Charge Exchange in Collisions Between B⁺ and C²⁺ Ions"
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    Y. Zou, Y. Awaya, C. P. Bhalla, T. Kambara, Y. Kanai, M. Oura,
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15. "Q-Dependence of Molecular Ionization and Fragmentation"
    V. Krishnamurthi, I. Ben-Itzhak, and K. D. Carnes
16. "Resonant Inelastic Scattering of Quasifree Electrons on Ions"
    S. Grabbe (with C. P. Bhalla)
17. "Nanometer-size Surface Modification Produced by Single, Low Energy, Highly Charged Ions"
    Martin P. Stöckli (with D. Parks, R. W. Schmieder, and R. Bastasz)
18. "Target Ionization by Highly Charged Ions at Low Velocities"
    Wuchun Wu (with C. L. Cocke, J. P. Giese, F. Melchert, M.L.A.
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    J. P. Giese (with M. Schulz, H. Schone, A. Landers, C. Y. Chen,
    F. Melchert, C. L. Cocke, and H. V. Needham)
20. "Recoil Momentum Dynamics for the Antiscreening Interaction"
    E. C. Montenegro (with W. Wu, K. L. Wong, and C. L. Cocke)

Annual DOE Workshop on Atomic Physics, Lexington, Kentucky (October 13-14, 1995)

21. "High Energy Collisions Involving Multiply Charged Ions"
    J. R. Macdonald Laboratory Personnel
22. "Low Energy Collisions Involving Multiply Charged Ions"
    J. R. Macdonald Laboratory Personnel
23. "Theory of Structure and Collisions of Highly Charged Ions"
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24. "Diffraction of Quasi-Free Electrons in Potentials of Highly Charged Ions"
   S. Hagmann (with C. Liao, P. Richard, C. P. Bhalla, S. Grabbe, and
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25. "J. R. Macdonald Laboratory USER Facility for Ion-Atom Collisions"
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26. "Electron Capture from H(n=4) Stark States"
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27. "Advances in Ion-Ion Collision System at KSU"
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28. "Angular Distribution of Electrons for Heavy Ions on C and Au Targets"
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29. "Observation of Direct Ionization of He by Highly Charged Ions at
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   and M. P. Stöckli
30. "Target-Electronic Structure Dependence in Highly Charged Ion C_{60} Collisions"
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   P. Richard, T. N. Tipping, B. Walch, and S. Winecki
33. "Suppression of He^{+} Production via Single Electron Capture by High q
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   P. Richard, I. Ben-Itzhak, C. L. Cocke, E. C. Montenegro,
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34. "I onization and Excitation of Hydrogen Molecules by Fast Proton Impact"
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   H. Knudsen, and U. Mikkelson
35. "Mean Lifetimes of HeH^{2+} and its Isotopes"
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36. "Inclusive Multi-Channel Measurement of the Impact Parameter Distribution
    in Collisions of Swift Heavy Ions with He"
   I. Ben-Itzhak, K. L. Wong, W. Wu, E. C. Montenegro, C. L. Cocke,
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37. "Separation of Target and Projectile Ionization in Diffraction Extrema of
    δ-Electron Spectra Emitted in 0.3 MeV/u Cu^{4+} \rightarrow H_{2}"
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38. "Transition from $q_2$ Scaling to an Inverted Scaling of the Cross Section for 0 Degree BE Emission in Ion Atom Collisions"
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40. "Ionization of Helium Atoms by Highly Charged Ions at Low Velocity"
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41. "Angular Distributions of Inelastically Scattered Electrons from Hydrogen-Like Carbon"
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42. "Analysis of Hyperspherical Channels of Three-Electron Atomic Systems"
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43. "A New Diabatic-by-Sector MO/AO Matching Method for Ion-Atom Collisions"
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44. "The KSU-CRYEBIS: A User Facility for Low Energy, Highly Charged Ions"

XIX International Conference on the Physics of Electronic and Atomic Collisions,
Whistler, Vancouver, British Columbia, Canada (July 26-August 1, 1995)

45. "Study of Aligned States in Ion-Atom Collisions"
46. "The KSU-CRYEBIS: A User Facility for Low-Energy Highly-Charged Ions"
47. "Recoil Longitudinal Momentum Spectroscopy of Electron Capture from He by O$^7+$ and F$^8+$"
   W. Wu, K. L. Wong, C. L. Cocke, J. P. Giese, and E. C. Montenego
49. "Impact-Parameter Dependent L-K Vacancy-Transfer in Collisions of Ni$^{25+}$ with Ge Solid Targets"
50. "Generalized Ramsauer-Townsend Minima in Heavy-Ion Induced Electron Continua"
51. "An Ion-Ion Collisions System at KSU"

52. "State-Selective Single Electron Capture Cross Sections in He$^{2+}$ + Li(2s) and Li$^{+}$(2p) Collisions"
   R. Shingal, C. P. Bhalla, and S. R. Grabbe

53. "Velocity Dependence of Ionization and Excitation of Hydrogen Molecules by Fast Proton Impact"

54. "Decay Rate Measurements and Calculations of Long Lived HeNe$^{2+}$"  

55. "The Mean Lifetimes of the 2p$\sigma$ Lowest Bound State of HeH$^{2+}$ and its Isotopes"

56. "Mean Lifetime Measurements of He$^{4}$He$^{2+}$"  

57. "Transition from q""2 Scaling to an Inverted q-Scaling for 0 Degrees Binary Encounter Electron Emission"

58. "Ionization of He by Highly Charged Ions at Low Velocity"
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59. "CDW-EIS Calculation of Longitudinal Momentum Distribution in Single Ionization of Helium by Ni$^{24+}$ Ions"
   V. D. Rodriguez, Y. D. Wang, and C. D. Lin

60. "Kinematical Threshold of Recoil-Ion Longitudinal Momentum Distribution in Single Ionization of Helium by Protons and Alpha Particles"
   V. D. Rodriguez, Y. D. Wang, and C. D. Lin

Texas Section of the American Physical Society, Lubbock, Texas (October 27, 1995)

61. "Micro Channel Plate Gains for 1.5 to 150 keV/q Ar with Charge States q = 3+ to 16+"
   D. Fry and M. P. Stockli
FINANCIAL REPORT

It is anticipated there will be no unexpended funds for the current funding period February 15, 1995 - February 14, 1996 (FY-95).