Progress Report

for

Grant No: DE-FG02-86ER13491

Reporting Period: FY 1989-91

Submitted to

U.S. Department of Energy

Title: "Atomic Physics with Highly Charged Ions"

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August 1991

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1. Foreword

This report presents a review of the research performed by the personnel of the J.R. Macdonald Laboratory and of the technical assessments of the laboratory over the three year period of this Department of Energy grant. The report is prepared for the Atomic Physics Program of the Fundamental Interactions Branch of the Division of Chemical Sciences, Office of Energy Research.

Two very significant milestones were reached in the laboratory during this three year grant period. The CRYEBIS and the LINAC facilities were both completed during this period. The first beam of bare Ar ions was extracted from CRYEBIS in the first half of 1989. Since then many experiments have been undertaken using the CRYEBIS facility. First acceleration beam tests were run on the LINAC in September and October of 1990. No experiments have been performed to date using the LINAC beams, but the system is winding up for experiments in the near future. In addition to these two events the tandem Van de Graaff accelerator was successfully upgraded to 7.5 MV operation. Experiments have been run with 7.23 MV on terminal. Both CRYEBIS and the tandem run essentially seven days per week.

This grant period was also one with a very productive research program in which 96 papers were published in refereed journals, an additional 17 papers have been accepted for publication, and 114 papers were given at conferences or meetings. Twenty-three of the latter papers were invited talks.

The XXIV S.N.E.A.P. Conference for accelerator personnel was hosted by KSU October 22-25, 1990 and co-chaired by Tracy Tipping and Robert Krause (Proceedings published by World Scientific Publishing Co., Singapore, 1991), and the XI I.S.I.A.C. Conference was also hosted by KSU August 3-4, 1989 and co-chaired by Lew Cocke and Jim McGuire.

Due to the large scope of the JRM Laboratory and the size of the physical plant two associate lab director positions have been created. Professor Tom J. Gray was appointed to Associate Director for Accelerator Operations and Professor Lew Cocke was appointed to Associate Director for Research Planning. In addition the position of Laboratory Safety Officer was established and Tracy Tipping was appointed to that position. Assistant Professor John Giese has recently joined the JRM Laboratory and Professor Jim McGuire left KSU in July 1991. In the interim, Dr. Rajiv Shingal has been appointed visiting Assistant Professor and Dr. Zheng Chen has been appointed Research Associate in theoretical atomic physics. The remainder of the faculty and staff positions were unchanged during this three year period.

*P. Richard
Laboratory Director
August 14, 1991*

2. JRM Laboratory Schematic

J.R. MACDONALD LABORATORY
MANHATTAN, KANSAS

3. Introduction

The study of inelastic collision phenomena with highly charged projectile ions and the interpretation of spectral features resulting from these collisions remain as the major focal points in the atomic physics research at the J. R. Macdonald Laboratory, Kansas State University, Manhattan, Kansas. The title of the research project "Atomic Physics with Highly Charged Ions" speaks to these points. The experimental work in the past few years has divided into collisions at high velocity using the primary beams from the accelerator and collisions at low velocity using the CRYEBIS facility and secondary beams (recoil ions produced in a high velocity collision) in a so-called SIRS (Secondary Ion Recoil Source) geometry. Theoretical calculations have been performed to accurately describe inelastic scattering processes of the one-electron and many-electron type, and to accurately predict atomic transition energies and intensities for x rays and Auger electrons.

The list of laboratory personnel involved in this project is given in Section 4 and brief summaries of the research performed during this reporting period are presented in Section 5 of this report. Each summary writeup refers to the publications that have resulted from the research. They are referred to by the publication number, as given in Section 7 of the report, List of Publications. A report on the laboratory operations is given in Section 6.

4. J.R. Macdonald Laboratory Personnel

Faculty

Itzhak Ben-Itzhak, Assistant Professor
Chander P. Bhalla, Professor
Kevin Carnes, Assistant Research Professor
C. Lewis Cocke, Professor and Associate Director for Research Planning
Basil Curnutte, Emeritus Professor
Brett DePaola, Assistant Professor
John P. Giese, Assistant Professor
Tom J. Gray, Professor and Associate Director for Accelerator Operations
Siegbert Hagmann, Associate Professor
James C. Legg, Professor and Department Head
Chii-Dong Lin, Distinguished Professor
James H. McGuire,⁺ Professor
Patrick Richard, Distinguished Professor and Laboratory Director
Martin P. Stöckli, Assistant Research Professor

⁺Joined faculty of Tulane University, New Orleans, Louisiana, July, 1991.

Research Associates

Zheng Chen, Research Associate
Emanuel Kamber, Research Associate
 Present address: Western Michigan University
K.R. Karim, Research Associate
 Present address: Illinois State University
Mark Raphaelian, Research Associate
Harald Schöne, Research Associate
Michael Schulz, Research Associate
 Present address: University of Missouri, Rolla
Rajiv Shingal, Research Associate
Jack Straton, Research Associate
 Present address: California State University, Fresno
Theodoros Zouros, Research Associate
 Present address: University of Crete, Heraklion, Greece

Technical Staff

Chrysostomos Hadjistamoulou, Assistant Scientist
Vince Needham, Assistant Scientist
Carol Regehr, Assistant Scientist
Christoph von Arx-Flury, Research Assistant
 Present address: Switzerland
Tracy Tipping, Assistant Scientist

Visitors

John Anthony, U. S. Naval Academy, Annapolis, Maryland
Rudiger Brenn, University of Freiburg, Germany
J. P. Briand, University of Pierre and Marie Curie, Paris, France
Alejandro González, Universidad Nacional de Rosario,
Argentina, South America
Ottmar Jagu.zki, University of Frankfurt, Germany
Y. Kanai, Institute of Physical and Chemical Research, RIKEN,
Saitama, Japan
Bertold M. Krässig, University of Freiburg, Germany
Ch. Kelbch, Visiting Scientist, University of Frankfurt
R. Koch, Visiting Scientist, University of Frankfurt
T. Mukoyama, Kyoto University, Kyoto, Japan
Roberto Rivarola, Universidad Nacional de Rosario,
Argentina, South America
Teresita Quinteros, Universidad Nacional de Rosario,
Argentina, South America
H. Schmidt-Böcking, University of Frankfurt, Germany
Alexander Skutlartz, East Carolina University, Greenville, North Carolina
S.L. Varghese, University of South Alabama, Mobile, Alabama
Theodoros Zouros, University of Crete, Heraklion, Greece

Laboratory Staff

Megan Maskill, Draftswoman
Dave Hill,¹ Machine Shop Foreman
Steve Kelly, Electronics Technician
Chris Koci, Secretary
Robert Krause, Accelerator Engineer
Richard Murphy,² Machinist
Al Rankin, Research Technician
Dea Richard, Administrative Assistant
Mark Ross,¹ Electronics Shop Foreman
Daphne Sand, Secretary
Mike Wells, Cryogenics Engineer

Graduate Research Assistants and Advanced Degrees Awarded

Rami Ali
Chun-Yen Chen
Song Cheng, Ph.D. August, 1991
Present address: Argonne National Laboratory
Vickie Frohne
Stuart Ginther
Hisham Hidmi
Roger Key
Present address: Kansas State University

Do-Hyung Lee, Ph.D. August, 1990

Present address: Brookhaven National Laboratory

Chunlei Liao

Suzanne Maleki

Nabil Malhi, Ph.D. August, 1991

R. Parameswaran

Justin Sanders

Jefferson Shinpaugh, Ph.D. May, 1990

Fulbright Scholar at University of Frankfurt, Germany

William Waggoner, Ph.D. May, 1990

Present address: Hastings College, Hastings, Nebraska

Yudong Wang

Present address: Tulane University, New Orleans, Louisiana

Bernhard Walch

Wuchun Wu

Undergraduate Research Assistants

Wally Axmann**

Troy Brockway**

Andrea Canelos**

John Dayton**

Kent Dieball**

Paul Gibson**

Shone Grabbe

Jim Joyal**

William Kent

Dan Kysar

Allen Landers

David Lee

John Lyle**

Richard Mack

Mark Morrison**

Stephen Muehleisen

Ted Pope

P.D. Shah**

Brian Stutheit**

Mark Whitfield

Mike Wiley

Kirk Wolleson

Steve Worm**

*Part-time

**Left JRM Laboratory

¹Supported by Kansas State University

5. Research Summaries

5.1 One Electron Outer Shell Processes in Fast Ion-Atom Collisions

5.1.1 Binary-Encounter Electrons Observed at Zero Degrees in the Laboratory

P. Richard, D.H. Lee, T.J.M. Zouros, J.M. Sanders, J.L. Shinpaugh, and H. Hidmi

The energy distributions of binary encounter electrons (BEE) produced in high velocity collisions of projectile ions with H_2 and He gas targets have been investigated. The binary encounter electrons are produced in hard collisions between the projectile and a target electron. A typical electron spectrum at zero degrees in the laboratory frame is shown in Fig. 5.1.1.1 for the case of $1 \text{ MeV/u } F^{9+} + H_2$. The cusp electrons occur at the velocity v of the projectile and an energy t whereas the binary encounter electrons labeled BEE in Fig. 5.1.1.1 occur at a velocity of approximately two v (velocity of the projectile) or four t (cusp energy). The binary encounter electrons can be considered to be produced in a process analogous to 180° Rutherford elastic scattering of a free electron from a highly charged ion. The energy distribution of the binary encounter electrons comes from the distribution of electron energies of the bound electron which can be simulated by the Compton profile of the bound electron.

Figure 5.1.1.1: Electron spectrum for $19 \text{ MeV } F^{9+} + H_2$ observed at zero degrees in the laboratory frame. The Cusp electrons occur at an energy t , corresponding to electrons moving with the projectile velocity (capture to the continuum for the case of bare ion projectiles). The binary encounter peak occurs at approximately $4t$, corresponding to electrons moving with twice the projectile velocity (hard collisions between the projectile and a target electron).

The investigation of BEe was initiated in order to establish a normalization procedure for Auger electron measurements and in particular for RTE Auger electron measurements since the peak in the BEe spectrum occurs at approximately the same energy as the RTE Auger electrons. Another motivation for this study is that the RTEA and the BE electrons are coherent and thus the resonances should show a Fano profile. An investigation of RTE as a coherent scattering with elastically scattered electrons (BEe) should enhance our understanding of the similarities and differences between resonance transfer and excitation in ion atom collisions and the analogous dielectronic recombination in free electron-ion scattering.

Impulse approximation: The double differential cross section for binary encounter electron production was calculated by an impulse approximation (IA) treatment (see Publication # 68). The basic idea is that the Rutherford scattering cross section is integrated over the Compton profile of the bound electrons in order to get the single differential cross section. The integrand gives the double differential electron cross section in the projectile frame and is given by

$$[d^2\sigma/d\Omega dE]_{\text{BEe}} = J(p_z(E)) [d\sigma/d\Omega(E, 180^\circ)]_{\text{Ruth}} / ((s + p_z)/m). \quad (1)$$

where J is the Compton profile, s is the cusp momentum, m is the electron mass, and p_z is the z -component of the bound target electron. We have assumed in this model that

$$E = (s^2 + 2sp_z + p_z^2)/2m - E_I \quad (2)$$

where E_I is the ionization potential of the target atom (molecule).

BEe Peak Position and Shape: (see Publication # 68). Using two body collision dynamics for heavy-ion impact on a free electron, the energy of the recoiling electron can be shown to equal $4t\cos\theta_{\text{lab}}$ where the cusp energy $t = (m/M_p)E_p$, m/M_p is the electron to projectile mass ratio, E_p is the projectile energy and θ_{lab} is the laboratory electron observation angle with respect to the beam direction. Thus for zero-degree measurements ($\theta_{\text{lab}} = 0^\circ$) the peak energy should be at $4t$. The observed peak position does not occur at $4t$ as can be seen in Fig. 5.1.1.1. It was found that the peak occurs at an energy of approximately 92 eV below the value of $4t$ in the laboratory frame for all the heavy ions ($Z_p = 6$ through 9) on H_2 studied here, but occurs at an energy of approximately 30 eV below $4t$ for the case of H^+ incident ions.

The reason for this difference between energy shifts in H^+ and the heavy bare projectiles is not completely understood at the present time but does point to the inadequacy of the assumptions inherent in the IA model. The variation of the peak position with projectile Z indicates the possible need for inclusion of two-center effects. Fig 5.1.1.2 shows the IA calculations compared to the data for 19.0 MeV $F^{9+} + H_2$ and He. The PWBA model as well as the IA model described above were found to fit the shape and the electron energy dependence of BE electrons very well for the high Z projectiles.

Figure 5.1.1.2: Comparison between experiment and theory for BEe production. IA is solid line, IA without binding term is dotted line, PWBA is dashed line, and Compton profile centered on 4t is dot-dashed line.

Z Dependence of BEe Cross Sections: (see Publication # 68). The BEe double differential cross sections (DDCS) at zero degrees in the laboratory frame obtained from the spectra was found to scale as Z^2 for bare projectiles in the projectile range $Z=1$ to $Z=9$ of the present study.

Enhanced Q Dependence of BEe Cross Sections: (see Publication # 67). The BEe DDCS was found, however, to increase as the charge state of a particular ion species was reduced. Fig. 5.1.1.3 demonstrates this for the case of F projectiles. The 7+ data are 1.27 times the 9+ data and the 5+ data are 1.4 that of the 9+ data. Other studies at non-zero degrees indicated that the cross section decreased with decreasing

charge state due to screening. At first thought one might expect at best that the cross section would be independent of q at zero degrees in the lab (i.e. in 180° electron scattering). Several authors have discussed this effect and easily demonstrated that the enhancement is due to the potential scattering from a non-bare nucleus (see Section 5.1.2 of this report).

The results of the work performed to date on this subject are contained in Publications # 67 and # 68.

Figure 5.1.13: Q dependence of BEE production for 28.5 MeV $F^{q+} + H_2$ at zero degrees in the laboratory frame for $q = 5+, 7+$ and $9+$ ions. The factor in parenthesis is the observed enhancement above the theoretical prediction for bare projectiles.

5.1.2 Charge-State Dependence of Elastic Scattering Cross Sections at Large Angles between Electrons and Multiply Charged Ions

R. Shingal, Z. Chen, K.R. Karim, C.D. Lin, and C.P. Bhalla

The differential elastic scattering cross sections of electrons from F^{q+} are calculated using a potential scattering model where each fluorine ion is represented by a static potential (Hartree-Fock). The ratio of the cross section for each charge state q to the Rutherford differential cross section for charge $q=9$ is larger than unity

for large angles, in particular, for $\theta = 180^\circ$ (see Fig. 5.1.2.1). The present results are in qualitative agreement with the experimental results of Richard *et al.* (see Publication # 67 and Section 5.1.1). This work was reported in Publication # 61.

Figure 5.1.2.1: Variation of the calculated ratio of differential cross sections for $e^- + F^{q+}$ ($q=3,5,7$) collisions with that for $e^- + F^{9+}$ collisions with scattering angles.

5.1.3 Strong Dependence of Zero Degree Binary Encounter Electron Production on the Initial and Final Charge State

S. Hagmann, O. Jagutzki, A. González, T. Quinteros, A. Skutlartz, D.H. Lee, P. Richard, C. Kelbch, S.L. Varghese, and H. Schmidt-Böcking

Doubly differential cross sections $d^2\sigma/dE_e d\Omega_e$ and fractional probabilities for Binary Encounter (BE) electron emission at 0° electron emission angle as a function of initial (q_i) and final (q_f) projectile charge state have been measured for 0.53 MeV/u F^{q_i} on H_2 and 0.53 MeV/u Cu^{q_i} on He. We show by coincident electron projectile detection that for F^{q_i} -projectiles the pure ionization channel $q_i = q_f$ strongly dominates the differential cross section at $\theta_e = 0^\circ$ and projectile capture and loss channels are of negligible importance. However, for Cu^{q_i} projectiles very strong contributions due to capture and loss are found. (See Figs. 5.1.3.1 and 5.1.3.2.)

In view of a recent calculation by Reinhold *et al.*¹ we conclude from our data the 0° -BE electron emission depends strongly on the shape of the screened projectile potential varying with q_i . For Cu we also find that the q^2 scaling of electron

production is valid only for low electron energies and deviations of up to a factor of 100 are found at high energies. This work is described in Publication # 82 and Accepted for Publication # 17.

Figure 5.1.3.1: Measured relative δ -electron emission cross section for $q_i = q_f = 5+$, $15+$ (pure ionization channels). The curves are drawn to guide the eye.

Figure 5.1.3.2: Measured relative δ -electron emission cross section of pure ionization ($q_i = 5+$) and loss channel ($q_i = 6+$) for incoming Cu^{5+} . The lines are drawn to guide the eye.

Reference for Section 5.1.3

1. C. Reinhold, D. Schultz, R. Olson, C. Kelbch, R. Koch, and H. Schmidt-Böcking, Phys. Rev. Lett 66, 1842 (1991).

5.1.4 Single Electron Capture in Collisions of High Velocity Bare Ions with Atomic and Molecular Hydrogen

P. Richard, J.M. Sanders, H. Schöne, and J.P. Giese

The goal of this experiment is to measure the ratio of cross sections for single electron capture from molecular and atomic hydrogen targets. This ratio of capture from the molecule to that from the atom varies with projectile energy, but it is expected to reach a high-energy limit value of four. From measurement of this ratio we may investigate the role played by quantum interferences between the two centers in the hydrogen molecule. While some measurements have been made with protons and helium projectiles, no measurement of this ratio has been made with highly charged ions in the velocity range of 1-2 MeV/amu.

To measure the desired cross section ratio, the projectile ions are measured in coincidence with recoils of H or H₂. The source of atomic hydrogen is a DC discharge tube (Wood's tube). Primary efforts in the last year have been in the construction and testing of apparatus: the Wood's tube, the gas cell and recoil detector, and a 2-dimensional position-sensitive projectile detector. All these pieces of apparatus have been completed and assembled.

Cross sections for single capture by 1-2 MeV/amu F⁹⁺, F⁸⁺, O⁸⁺, and O⁷⁺ from H₂ have now been measured, and the results are published in Nuclear Instruments and Methods **B56/57**, 104 (1991) (see Publication # 86). It was found that the cross sections followed a simple scaling law¹ in energy and charge which allows the cross sections for other projectiles to be easily estimated. Fig. 5.1.4.1 shows the data together with the scaling from Ref. 1 (labeled Eq. 5), and the scaling given by Schlachter *et al.*²

Figure 5.1.4.1: Total single electron capture for bare and one-electron fluorine and oxygen projectiles colliding with molecular hydrogen. The cross sections and energies have been scaled as in Ref. 1.

References for Section 5.1.4

1. H. Knudsen, H.K. Haugen, and P. Hvelplund, Phys. Rev. A 23, 597 (1981).
2. A.S. Schlacter *et al.*, 15th ICPEAC, Brighton, U.K., 1987 (eds. J. Geddes *et al.* Queen's University, Belfast, 1987) p. 505.

5.2 Role of Electron-Electron Interaction in Two-Electron Processes

5.2.1 Effect of Electron-Electron Interaction on Projectile $1s \rightarrow 2p$ Excitation in Collisions of O^{5+} , F^{6+} , and F^{7+} Ions with H_2 and He Targets

P. Richard, T.J.M. Zouros, J.M. Sanders, and D.H. Lee

Evidence was presented of an excitation process in ion-atom collisions analogous to electron-impact excitation in free-electron-ion collisions. The production of $1s2s2p\ ^4P$ projectile states excited in collisions of $(1s^22s)\ O^{5+}$ and F^{6+} with He and H_2 targets was found to increase with projectile energy above ~ 0.75 MeV/u, in agreement with an impulse-approximation treatment of $1s \rightarrow 2p$ electron-impact excitation of ions in collisions with "quasifree" target electrons. The data and calculations are given in Fig. 5.2.1.1. Such ion-atom excitations could provide presently unavailable information about inner-shell electron-impact excitation.

Figure 5.2.1.1: Data: Cross sections for the production of $1s2s2p\ ^4P$ states by $1s \rightarrow 2p$ projectile excitation in collisions of F^{6+} ($1s^22s$) projectiles with He and H_2 targets vs projectile energy. Only statistical errors are shown. Total absolute error is $\sim 30\%$. Calculation: Electron-electron excitation cross sections using $1s2s2p\ ^4P$ theoretical electron-impact excitation cross sections folded by the Compton profile of the target. Dashed lines, calculated eeE for H_2 targets; dash-dotted lines calculated for He targets. Arrows (at 16.3 and 25.0 MeV), the projectile energy corresponding to the threshold for $1s \rightarrow 2p$ electron-impact excitation.

This work is reported in a Phys. Rev. Letter (see Publication # 37) and in Publications # 54 and # 90.

5.2.2 Effect of Electron-Electron Interaction on Projectile K-Shell Ionization

P. Richard, T.J.M. Zouros, D.H. Lee, and J.M. Sanders

Cross sections for 1s ionization of the ground state of $O^{4+}(1s^2 2s^2)$ were obtained in 10-30 MeV collisions of O^{4+} with H_2 and He targets. High resolution Auger electron spectroscopy was used to detect at 0° with respect to the beam direction, the electrons emitted from the Auger decay of $O^{5+}(1s 2s^2) \rightarrow O^{6+}(1s^2) + e^-$ following 1s ionization of the O^{4+} ions. The electron-nucleus (σ_{enI}) and electron-electron (σ_{eel}) ionization cross sections, due to ionization of the projectile electron either by the target nucleus or the target electrons, respectively, were independently computed. σ_{enI} was calculated within a PWBA treatment, while σ_{eel} was computed within an impulse approximation (IA) treatment of electron impact ionization of O^{4+} . The incoherent sum $\sigma_{enI} + \sigma_{eel}$ was found to be in good agreement with the data. K-shell ionization of the metastable $O^{4+}(1s^2 2s 2p \ ^3P)$ component of the beam was also observed. Fig. 5.2.2.1 contains the data for both H_2 and He targets. This work is given in Publication # 92 and in a Phys. Rev. paper to be published.

Figure 5.2.2.1: Electron-electron ionization (eel) experiment. Data: K-shell projectile ionization cross sections for $O^{4+}(1s^2 2s^2) + H_2$ and He collisions. Calculation: Narrow dashed lines are PWBA calculation for 1s electron-nucleus ionization (enI) using Eq. (1), while the dot-dashed line corresponds to an impulse approximation calculation for 1s eel.

5.2.3 Theory of Angular Distribution in Resonant Transfer and Excitation

C.P. Bhalla

We have shown that angular distributions of Auger electrons and x-rays from deexcitation of doubly excited states produced in the resonant transfer and excitation (RTE) of projectiles in collisions with light targets are, in general, not isotropic. The doubly excited states produced are collisionally aligned. The Auger electron emission to the ground state shows nonisotropic behavior due to the alignment, and the interference with the elastic scattering channel [see Publication # 69]. As an example, we consider 20 MeV $F^{8+} + H_2$ collisions where the doubly excited state $2p^2 \ ^4D$ is formed in RTE. In order to provide realistic plots a Lorentzian profile of width 1.5 eV is folded in the cross section. Fig. 5.2.3.1(a) contains the doubly differential electron production cross sections at several angles $\theta = 180^\circ, 160^\circ, 140^\circ, 35^\circ$ and 25° in the projectile frame of reference. The contributions arising from the resonance is illustrated in Fig. 5.2.3.1(b) by plotting $d^2\sigma/d\Omega d\epsilon - d^2\sigma(BE)/d\Omega d\epsilon$. Several features are noteworthy. The Auger line profile is no longer Lorentzian, and this feature is more dramatically illustrated at $\theta = 35^\circ$ and 25° in Fig. 5.2.3.1(b). The corresponding plots at these angles in Fig. 5.2.3.1(a) show a "dip" (rather than a peak) in the doubly differential cross sections. The solid line in Fig. 5.2.3.2 is a plot of the differential cross section minus the contribution of binary encounter electrons versus angle in the projectile frame. Strongly peaked angular distribution at large - θ values (small laboratory angles) is evident. Recently, Benhenni *et al.*¹ reported their results on the angular distribution of the Auger transition $1s2s2p^2 \ ^3D \rightarrow 1s^2 \ 2s \ ^2S$ in $O^{5+} + He$ collisions at 13 MeV projectile energy. These experimental results are in excellent agreement with our calculations.

Calculations were also performed for collision systems investigated at Kansas State University (see Publications # 70 and 83, and Sections 5.2.4 and 5.2.5). We have shown that in general the differential RTE cross section, where many doubly excited states contribute but are not resolved in experiment, is given by

$$\frac{d\sigma(RTEX)}{d\Omega} = \sum_d \sum_f \sigma_{RTEX}(g \rightarrow d \rightarrow f) W_{d-f}(\theta),$$

where $W_{d-f}(\theta)$ is characteristic x-ray angular distribution from the aligned doubly excited state $|\alpha_d\rangle$ to a final state $|\alpha_f\rangle$.

Figure 5.2.3.1: (a) Doubly differential cross sections versus electron energy and different scattering angles θ_p in the projectile frame for $F^{8+} + H_2$ collisions at 20 MeV projectile energy. (b) The corresponding differences between the doubly differential cross sections and the contributions of the binary electrons are plotted versus electron energy and scattering angles in the projectile frame.

Figure 5.2.3.2: Differential cross section versus angle in the projectile frame for $F^{8+} + H_2$ collisions at 20 MeV projectile energy. The solid line represents the differential cross section minus the contribution of binary encounter electrons background.

References for Section 5.2.3

1. M. Benhenni *et al.*, Phys Rev. Lett. **65**, 1849 (1990).

5.2.4 A Simple RTE Theory Containing Impact Parameter Dependence

B.D. DePaola and O.L. Weaver

Using time dependent first order perturbation theory, we have developed an RTE (resonant transfer with excitation) model which contains impact parameter dependence. Integration over impact parameter yields the standard impulse approximation result. The model is quite easy to use, requiring only the target wave function (in numerical or analytic form) and the radiationless capture rate for the intermediate doubly excited state. The actual calculation involves a simple one-dimensional integration which generally converges rapidly. In the case of atomic hydrogen targets having hydrogenic wavefunctions, the result is analytic. The use of first order perturbation theory, together with other approximations limits the use of the model to high velocity, asymmetric collision systems. Nevertheless, results from these calculations were compared (see Fig. 5.2.4.1) with those of coupled channel calculations for the $\text{He}^+ + \text{H}$ collision system.¹ (This system is currently the only one for which coupled channel calculations exist.) The result of this work has been submitted for publication (# 1).

Figure 5.2.4.1: Weighted impact parameter dependence of the RTE cross section for the $\text{He}^+ + \text{H}$ collision system, with $\text{He}[(2p^2)^1\text{D}]$ as the intermediate state. The solid line with circles is the result of the coupled channel calculation for the TE cross section of Ref. 1. The dashed line with triangles is the RTE assessment in the coupled channel calculation of Ref. 1. The solid line with no symbols is the result of this work.

References for Section 5.2.4

1. W. Fritsch and C.D. Lin, Phys. Rev. Lett. 61, 690 (1988).

5.2.5 Resonant Transfer with Excitation Experiments

Introduction

Resonant transfer with excitation (RTE) is an ion-atom collisions process in which a target electron excites a projectile electron, and is also captured to an excited state of the projectile. This results in a doubly excited, one less charged projectile, which can decay radiatively (RTEX) or through Auger emission (RTEA). The process is the ion-atom analog to dielectronic capture in ion-electron collisions. Our major interest in RTE is due to its being a correlated two electron process. As such it is a convenient testing ground for comparing experiment to "few body" theories. All the RTE work done in the J.R. Macdonald Laboratory has made use of zero degree projectile Auger spectroscopy. Due to the high resolution achieved this technique has the advantage of being state selective. The results of several experiments are reported in the subsections below.

5.2.6 High-Resolution State-Selective Study of RTE in the $F^{8+} + H_2$ System

B.D. DePaola, R. Parameswaran, and W.J. Axmann

In a recent publication¹ some evidence was found for the 2eTE process. In this non-resonant three-electron process a projectile ion is excited by a target electron, while capturing a second target electron to an excited state. We performed an experiment using $F^{8+} + H_2$, with sufficiently high electron energy resolution (1.6 eV, $dE/E = 0.07\%$) to resolve all the lines in the KLL manifold. Because RTE is theoretically known to populate almost exclusively the $(2p^2)^1D$ line for this system (a prediction verified by this experiment), observation of other lines, especially near the 2eTE threshold, provided the means for a very sensitive measurement of 2eTE. As one can see in Fig. 5.2.6.1(a), there is no evidence of any KLL Auger transition, save the $(2p^2)^1D$. This puts a severe upper limit on the 2eTE cross section for populating the KLL manifold in this system. In Fig. 5.2.6.1(b) our measurement of the dependence of the RTE cross section on projectile energy is compared to theory and the results of Ref. 1. The results of the experiment were as follows: (1) no evidence for 2eTE was found either in the Auger spectra directly [Fig. 5.2.6.1(a)], nor in the cross sections [Fig. 5.2.6.1(b)]; (2) the assertion that only the $(2p^2)^1D$ level is appreciably populated in RTE was verified; (3) the extremely good resolution allowed for the first time a careful comparison between theory and experiment of the Fano lineshape of the Auger line, as seen in Fig. 5.2.6.1(a). This helped confirm a

model in which interference between RTEA and binary encounter electrons was considered. The results of this work are contained in Publication # 72.

Figure 5.2.6.1: (a) Doubly differential projectile electron spectra for selected energies of $F^{8+} + H_2$. The spectra have been transformed to the rest frame of the projectile. (b) Differential TE cross sections, measured at 0 degrees (solid circles) and multiplied by 4π to facilitate comparisons with other reported TE measurements. The solid curve is the theoretically predicted result, scaled to experiment. The open circles connected by the dashed line represent the data of Schulz *et al.*, scaled to the results of this work.

Reference for Section 5.2.6

1. M. Schulz *et al.*, Phys. Rev. Lett. 62, 1738 (1989).

5.2.7 KLL, KLM, KLN, and KLO RTEA Cross Sections

B.D. DePaola, R. Parameswaran, C.P. Bhalla, and B.P. Walch

Auger electrons emitted from doubly excited states of C^{4+} ($2\ell 2\ell'$, $2\ell 3\ell'$, $2\ell 4\ell'$, $2\ell 5\ell'$) formed by transfer excitation in collisions of C^{5+} (4-10 MeV) with H_2 and He were studied using high resolution zero-degree Auger electron spectroscopy. The KLL, KLM, KLN, and KLO resonant transfer excitation cross sections were measured. The impulse approximation theory with alignment and interference effects taken into consideration was found to be in reasonable agreement with the experimental data. The theory was normalized by a typical factor of 0.65 to obtain the best fits to the data. The RTEA resonance strengths were evaluated to investigate the n dependence ($n=2,3,4,5$) of RTEA. As seen in Fig. 5.2.7.1, the relative agreement with theory is very good. However, there is a consistent 35% disagreement with theory in the absolute cross section for each of the cases measured. The analysis of this discrepancy is discussed in the next section. The results of this work are contained in Publication # 83.

Figure 5.2.7.1: The RTEA resonance strengths generated by integrating under the theory and experimental points in cross section vs. projectile energy measurements. The theory points have been uniformly multiplied by 0.65.

5.2.8 Analysis of the Discrepancy Between Theory and Experiment of RTEA Cross Sections

B.D. DePaola, C.P. Bhalla, and R. Parameswaran

Although impulse approximation models for RTE are in excellent qualitative agreement with experiment, there is a persistent discrepancy in the absolute cross section for low Z projectiles. In order to test whether this discrepancy was due to our instrument normalization, we compared theory to experiment for the ratio of RTE-produced Auger emission to binary electron production for the $C^{5+} + H_2/He$ collision system. Because we used a ratio, normalization errors were eliminated. It was found that the discrepancy between the ratios was the same as for the Auger emission alone. All evidence point to a gradual breakdown in impulse approximation RTE theories for projectile $Z < \sim 30$.

5.2.9 RTEA Cross Sections Using a Ground State Lithium Vapor Target

B.D. DePaola and R. Parameswaran

Lithium vapor is being used as the target in an RTEA experiment. The projectile is C^{3+} . Cross sections are being measured as a function of projectile energy (4-10 MeV). The study is nearly complete, the preliminary results being in good agreement with impulse approximation theory. As a side benefit from these studies, we also measure the cross section for the production of binary encounter electrons. For both of these measurements, lithium vapor is an especially interesting target since there are precisely two shells having very different binding energies and consequently different Compton profiles. This allows one to test the predictions of impulse approximation theory concerning both the shape and position of the resonance peak.

5.2.10 State-Selective Observation of Resonant Transfer Excitation in Collisions of F^{6+} with He and H_2 Targets

T.J.M. Zouros, D.H. Lee, P. Richard, J.M. Sanders, J.L. Shinpaugh
S.L. Varghese, K.R. Karim, and C.P. Bhalla

The $F^{5+}(1s2s2p^2)^3D$ and 1D states formed by transfer excitation (TE) in 4.75-33.25 MeV collisions of Li-like $F^{6+}(1s^22s)$ with He and H_2 targets were studied using 0° Auger-electron spectroscopy. The TE cross sections for these states showed resonances around 20 MeV with an energy dependence well described by the resonant TE impulse approximation. The H_2 data were practically free of NTE contributions thus allowing direct extraction of resonance-excitation (RE) cross sections permitting a more stringent, quantitative test of the IA model to be made. Measured RE cross sections (assumed here to be 4π times the measured differential cross section) were found to be about 2.2 to 3.2 times larger than theoretical values calculated in the impulse approximation assuming a statistical population of autoionizing states. Fig. 5.2.10.1 (next page) shows the comparison of experiment and theory under these assumptions. A comparison of our high resolution electron data with the results of recent low-resolution RTE studies of the same $F^{6+} + H_2$ collision system¹ offers the unique possibility of providing complementary information about the x-ray and the Auger decay channels thus giving a more complete account of the RTE process.

Doubly excited Be-like $(F^{5+})^{**}$ projectile states are formed by TE in the collision,

The results of this work are reported in Publication # 39. The next section is a continuation of this work.

Reference for Section 5.2.10

1. M. Schulz, R. Schuch, S. Datz, E.J.B. Justiniano, P.D. Miller, and H. Schöne, Phys. Rev. A 38, 5454 (1988).

Figure 5.2.10.1: Data: Absolute electron production cross sections for $(1s2s2p^2)^{3,1}D$ states produced by TE in $F^{6+}(1s^22s) + He$ and H_2 collisions vs projectile energy. Only relative errors are shown. Continuous line, scaled sum of $\sigma_{TE} = a_R\sigma_{RTEA} + a_N\sigma_{NTE}$. Dashed line, RTEA impulse approximation. Dash-dotted line, NTEA calculation. The values of the scaling coefficient a_R are shown in parentheses.

5.2.11 Effects of Alignment and Interference in Resonant Transfer and Excitation for F^{6+} and O^{5+} Collisions with H_2 in 0° Auger Measurements

T.J.M. Zouros, C.P. Bhalla, D.H. Lee, and P. Richard

We have renormalized our previously reported 0° cross sections, discussed in the previous section, for resonant transfer excitation followed by Auger decay (RTEA), $d\sigma_{RTEA}(0^\circ)/d\Omega$ obtained in 0.25-2 Mev/u collisions of F^{6+} and O^{5+} ions with H_2 by normalizing to calculated binary encounter electron yields rather than the usual Ne K-Auger yields. The renormalized data are found to be in good agreement with recent angular dependent impulse approximation calculations of RTE (see Publication # 89 and Section 5.2.3 by C.P. Bhalla), showing the importance of alignment and the small influence of interference between RTEA and elastic electron

scattering for 0° observation.

The angular distribution of the Auger electrons, due purely to the autoionization resonance arises from a nonstatistical population of the magnetic substates. The amplitude for the formation of the state (i.e., 3D and 1D) is nonzero only for $M_{\ell_d} = 0$, when the axis of quantization is defined along the collision direction, and therefore the doubly excited state is collisionally aligned.

In summary, we have modified the values of our previously measured zero-degree SSDCS for RTEA, $d\sigma_{\text{RTEA}}(0^\circ)/d\Omega$, obtained in F^{6+} and O^{5+} collisions with H_2 , in accordance with reevaluated electron detection efficiencies obtained by using the IA treatment of binary-encounter electron production as an absolute normalization standard. This renormalization was found to increase the measured SSDCS by about 35-55%, depending on the laboratory electron energy. The modified SSDCS were compared to calculated values of $d\sigma_{\text{RTEA}}(0^\circ)/d\Omega$ obtained within the angular-dependent impulse-approximation treatment of RTE which considers explicitly the alignment of the doubly excited states and interference effects between RTEA and elastic electron scattering. The calculated interference between elastic electron scattering and RTEA for the collision systems investigated was too small to be observable at *zero* degrees. Extracted radiationless capture strengths Ω_{RC} were found to be in agreement with theory in the case of the 1D states and about 30% smaller than theory for the 3D states, but probably within the overall theoretical and experimental uncertainty (see Fig. 5.2.11.1). The experimental ratio of $\Omega_{\text{RC}}(^3D)/\Omega_{\text{RC}}(^1D)$ was found to be equal to 2.1 ± 0.14 and 2.2 ± 0.13 for O^{5+} and F^{6+} , respectively, as compared to 3, the expected theoretical ratio. Table 5.2.11.1 shows the comparison.

Table 5.2.11.1: Calculated and experimental radiationless capture (Refs. 2, 17, and 29) strengths (Ω_{RC} in units of $10^{-19} \text{ cm}^2 \text{ eV}$) for the production of $O^{4+}(1s2s2p^2)$ and $F^{5+}(1s2s2p^2)$ intermediate states. The initial and final state are assumed to be pure $1s^22s$ states. ϵ_A and ξ are the Auger energies (eV) and yields of the $(1s2s2p^2)^{3,1}D \rightarrow (1s^22s)^2S$ transition, respectively.

Ion	State	$\epsilon_A(\text{eV})$	ξ^a	Ω_{RC}^a	$\Omega_{\text{RC}}^{\text{exp}}(H_2)^b$
O^{5+}	$1s2s(^3S)2p^2 \ ^3D$	448.0	0.899	36.3	25.4 ± 0.8
O^{5+}	$1s2s(^1S)2p^2 \ ^1D$	453.0	0.409	12.1	12.0 ± 0.7
F^{6+}	$1s2s(^3S)2p^2 \ ^3D$	567.84	0.89	35.8	25.1 ± 0.8
F^{6+}	$1s2s(^1S)2p^2 \ ^1D$	576.24	0.50	11.7	11.7 ± 0.6

^aCalculation uncertainty $\sim 15\%$.

^bQuoted experimental errors are the relative errors. Total uncertainty (including uncertainty in calculation of ξ) $\sim 20\%$.

Figure 5.2.11.1: Data: Absolute Auger electron SSDCS, $d\sigma_{RTEA}(0^\circ)/d\Omega$, for $(1s2s2p^2)^3,1D$ states produced in F^{6+} and $O^{5+}(1s^22s) + H_2$ collisions vs projectile energy. The Auger electrons result from transitions back to the ground state. Only relative errors are shown. Solid line, sum of $a_R(d\sigma_{RTEA}/d\Omega) + a_N(d\sigma_{NTEA}/d\Omega)$. Dashed line, a_R times RTEA (resonance term only). Dash-dotted line, a_N times NTEA calculation. Dotted line, a_R times RTEA (interference term only).

5.3 Multi-Electron Processes at Low Energy

C.L. Cocke and M. Stockli

Over the past three years we have brought the EBIS into full time operation capable of delivering beams of highly stripped ions up to Ar^{18+} and Xe^{44+} , for example, and have outfitted the electron beam control system to facilitate use of the source as an ion trap as well as source of external ions. Our low energy program now is focussed on this source. The following projects have been carried out.

5.3.1 Dielectronic Recombination on and Electron Impact Excitation of Helium-like Argon

R. Ali, C.P. Bhalla, C.L. Cocke, M. Schulz, and M. Stockli

The EBIS has proved to be profitably operable as an ion trap from which the ions can be periodically expelled to sample the ion inventory. At the time this work was initiated, this was the only such trap capable of ion extraction, although the EBIT at LLNL¹ now has a similar capability. We have used both this feature and a direct viewing of X rays from within the trap to measure cross sections for dielectronic recombination and electron impact ionization on a heliumlike Ar target.

The dielectronic recombination cross sections were measured by sampling the equilibrium charge state distribution of ions as a function of the electron beam energy in the EBIS. The EBIS is in effect an electronically monoenergetic plasma and comes to a charge state equilibrium which is dependent on the relative cross sections for recombination and ionization. Fig. 5.3.1.1 shows the ratio of lithiumlike to heliumlike charge states expelled from the EBIS after charge state equilibrium balance is reached. The large enhancements of the lithiumlike yields are due to dielectronic recombination onto the Ar^{16+} core through doubly excited lithiumlike states. A simple analysis which requires nothing more than the assumption of no further time evolution of the charge state distribution was used to extract from the data the cross sections for dielectronic recombination, normalizing to the cross section for electron impact ionization of lithiumlike Ar.² The resulting cross sections are in excellent agreement with theoretical calculations carried out by Bhalla.

Additional information on the resonant capture process was obtained by observing the K X rays emitted from these same resonances with a Si[Li] detector. Appropriate grating and sweeping of the electron energy was carried out so that the X rays represent essentially the result of intense electron bombardment of a pure

heliumlike argon target. The X rays were resolved into $K\alpha$, $K\beta$, and K higher groups, and the yields of each group were compared separately to theoretical calculations. Such measurements yield not only relative resonant strengths, but branching ratios as well and are a more detailed test of theory than the charge state information alone. The results are shown in Fig. 5.3.1.2, where excellent agreement with the calculations of Bhalla were found.

Figure 5.3.1.1: a.) Yields of He- and Li-like Ar ions from the EBIS as a function of electron beam energy. b.) The ratio of Li-like to He-like ions as a function of electron energy.

Figure 5.3.1.2: Ar-K-x-ray yields from the EBIS versus electron energy. The solid line is theory from Bhalla for DR resonances, and Bhalla, Zhang and Sampson for the $n=1$ to 2 excitation.

The X ray data yield also cross sections for electron impact excitation of the ground state of heliumlike argon. While it might be expected that the series of DR resonances near threshold should produce a yield which goes smoothly into the excitation yield, the data show a sharp rise in x ray yield in this region. This effect is interpreted as due to the importance of non E1 decays above threshold. The corresponding core decays do not contribute appreciably to the DR yield. The details of the evolution from DR to excitation are still under theoretical investigation (see Bhalla). The measured cross sections for electron excitation are in good agreement with the DWBA calculations of Zhang and Sampson.³

The yields of Ne^{8+} and Ne^{7+} ions from the EBIS have been measured as a function of electron energy. From these data we have extracted the ratio of the cross section for ionization of lithiumlike Ne to that for DR on heliumlike Ne in a way similar to the analysis of the Ar data.

The above work is described in Publications # 2 and # 5.

References for Section 5.3.1

1. D.A. Knapp *et al.*, Phys. Rev. Lett. **62**, 2104 (1989).
2. S. Younger, J. Quant. Spectrosc. Radiat. Transfer **2**, 329 (1981).
3. H.L. Zhang and D.H. Sampson, private communication (1990).

5.3.2 K X Ray Emission from Ar^{17+} Projectiles Interacting with a Ge Surface

M. Schulz, C.L. Cocke, M. Stockli, and S. Hagmann

We have measured K x ray yields in collisions of Ar^{17+} with a single crystal Ge target as a function of the projectile velocity component perpendicular to the Ge surface. Hydrogen-like argon ions with an energy of 51 keV were obtained from the KSU EBIS, and variation of the perpendicular velocity was made by varying the angle of incidence of the ions onto the single crystal surface between 3 and 60 degrees, corresponding to vertical energies between 0.14 and 38 keV. The Si[Li] detector x ray spectra shift to higher angles as the angle of incidence is decreased, and the x ray yield increases (see Fig. 5.3.2.1). A model based on the decomposition of the spectrum into emission above the surface and inside the surface has been constructed which gives an adequate account of the data, and from which we extract a characteristic time for the in-flight filling of the K vacancy of 10^{-12} sec. This time

is much longer than any expected Auger or radiative rate filling the K shell from the L or M shell, and is clear evidence that the major factor governing the K vacancy filling rate for such an ion approaching a surface is the rate at which electrons captured into very highly lying states on the projectile can cascade down to lower levels before they can emit K x rays. A short account of this work will be published in the proceedings of HCI V, Giessen, 1990, and a longer paper has been accepted by Phys. Rev. A (see AFP # 2 and # 11).

Figure 5.3.2.1: Ar-K-x-ray spectra from Ar^{17+} on a Ge crystal.

5.3.3 Ar^q+ on Ar

R. Ali and C.L. Cocke

External EBIS beams of Ar^{6+} to Ar^{17+} are being used to investigate multiple transfer in collisions of highly charged Ar on Ar targets. The charge states of both projectile and recoil are measured, as well as the angular distributions of both products. The results show that the statistical model proposed by Müller¹ for more modestly charged projectiles does not work when such large amounts of electronic potential energy as characterize these ions are brought into the collision. In particular, Ar^{17+} produces a recoil charge state spectrum very similar to that for Ar^{16+} , although the electronic energy carried by the Ar^{17+} is very much higher than that for the heliumlike ion. The results show that between one and two electrons are

typically lost from the collision system, but these are thought to be lost via autoionization of the projectile following, not accompanying, capture. Up to quadruple capture by the projectile is measured, with recoils up to 8+ created.

These data are taken with a cool gas jet, and allow the measurement of all three components of the momentum transfer to the recoil. The longitudinal component of this momentum transfer is a direct measure of the Q value for the reaction. Differences in Q values for single, double, triple and capture (indicated by recoil charge) of 10 to 30 eV have been observed. The resolution is presently limited by the thermal spread in the jet, but the technique promises to be a very useful one for Q value measurements. These experiments are discussed further in the proposal.

Reference for Section 5.3.3

1. A. Müller *et al.*, Phys. Rev. Lett. 51, 107 (1983).

5.3.4 Low Energy, Non-EBIS: Ar⁶⁺ on He

W. Waggoner, E.Y. Kamber, and C.L. Cocke

Angular distributions for single capture of electrons from He by low energy (296-1275 eV) Ar⁶⁺ ions have been measured, the data analyzed and the theoretical analysis completed. A Coulomb deflection function treatment of the collision system reproduced the major features of the distributions, but gave poor quantitative agreement with the data. This work was the thesis project of W. Waggoner, now completed.

5.4 Multi-Electron Processes at High Energy

5.4.1 Electron Capture and Target Ionization in Collisions of Bare Projectile Ions Incident on Helium

J.L. Shinpaugh, J.M. Sanders, J.M. Hall, D.H. Lee, H. Schmidt-Böcking, T.N. Tipping, T.J.M. Zouros, and P. Richard

Absolute cross sections for the processes of single capture, transfer ionization, and single and double ionization were experimentally determined for C^{6+} , N^{7+} , O^{8+} , and F^{9+} projectiles incident on a helium target in the projectile velocity range of 0.25 to 2.0 MeV/amu. The cross sections were determined by measuring projectile ion final charge states in coincidence with target recoil ion final charge states. The single capture and transfer ionization cross sections were corrected for ionization from impurity charge states in the beam and for double collision processes in the target gas cell. These corrections, which are necessary for the relative as well as the absolute cross sections, were found to be as large as fifty percent of the cross section.

The measured cross sections were compared to the multi-state, coupled-channel calculations of Shingal and Lin. It was found that the experiment and calculations agreed well for single and double ionization, but the two did not agree as well for single capture and transfer ionization. The ratio of transfer ionization to single capture was found to scale as Z^2 for the range of nuclear charges studied here.

Fig. 5.4.1.1 shows the ratio of TI to SC as a function of projectile energy for $F^{9+} + He$ and Fig. 5.4.1.2 shows the cross sections for single and double ionization of He by F^{9+} .

Figure 5.4.1.1.

Figure 5.4.1.2.

The ratio of TI to SC peaks at an energy of about 0.6 MeV/amu whereas the calculation of Shingal and Lin (see Publication # 79) peaks at a lower energy (solid line).

First results from this experiment are presented in Publication # 46. The final paper on this work is Submitted for Publication # 8.

5.4.2 Differential Cross Sections for Multiple Ionization of Ne and Ar by Fast Protons

E.Y. Kamber, C.L. Cocke, S. Cheng, and S.L. Varghese

We have recently reported¹⁻³ on the ionization of light (He, D₂) targets by fast protons in collisions which scatter the proton by a "large" angle, where "large" means that the momentum transfer to the proton is many atomic units. Such scatterings are dominated by hard collisions between the proton and quasi-free electrons in the target, and the multiple ionization may be attributed to shakeoff, although the exact mechanism is still under debate. For a multielectron target with more than one shell, multiple ionization has additional contributions from inner shell ionization followed by Auger and Coster-Kronig transitions. We have measured differential cross sections for single and multiple ionization of Ne and Ar by 3 and 6 MeV protons for scattering angles between 0.1 and 0.9 mrad. The data show that the relative probability for multiple ionization grows substantially with scattering angle in this range, in contrast to the single shell target results. A model which takes into account ionization with large angle scattering by both proton-nucleus and proton-electron collisions was constructed, and gives some agreement with the data. In most cases, the conclusion is that hard electron-proton collisions dominate the ionization process. This work is reported in Publications # 3, # 49, and # 62.

5.4.3 One- and Two-Electron Processes in Collisions of O^{8+} with D_2

E.Y. Kamber, C.L. Cocke, S. Cheng, V. Frohne, and S.L. Varghese

This project is directed at understanding one and two electron ionization and capture processes which occur in the collision of bare oxygen nuclei with molecular deuterium targets. The experiment has two phases.

(1.) Total cross sections: we have measured cross sections for six separate reaction channels for this collision system and oxygen energies between 8 and 20 MeV. The channels are single and double electron ionization, ionization-excitation, single capture, capture ionization and capture excitation. The experiments were performed by detecting the charge analyzed projectiles in coincidence with the recoil fragments collected by a known electric field. Separation of ionization and excitation channels was performed by measuring, with a time-of-flight method, the energies of the d^+ ions produced by excited and ionized D_2 molecules. The results show that ionization and excitation processes are of comparable importance and that transfer ionization is larger than capture over this projectile velocity range. Some theoretical model calculations based on the independent electron model are available, and are in qualitative agreement with the results. (See Publication # 9.)

(2.) Molecular orientation dependence of two electron processes from D_2 targets: the dependence on the angle between the beam axis and the molecular target axis of the probability for ionization accompanied by additional excitation/ionization or capture accompanied by additional excitation/ionization of the remaining electron is under study. Recent theoretical calculations (see Publications # 6 and # 23) predict that amplitudes from the two charge centers in the molecule interfere in such a way that the total capture amplitude exhibits a dependence on the orientation of the molecule, and the total cross sections for capture from the molecule can be quite different from the sum of cross sections from two separated atoms. Our experiments measure the dependence of the capture/ionization-excitation probability on the orientation angle. They do this by projecting the recoil d^+ fragments from the collision onto the surface of a position-sensitive detector using a transverse electric field, and by using a combination of the position at which the d^+ strikes and its flight time to reconstruct the velocity space distribution of the primary exploding fragments.

Results have been obtained for bombarding energies between 2 and 16 MeV for O^{8+} capturing from D_2 . The angular dependences go from nearly isotropic at the lowest energy to very marked at 10 MeV, thereafter becoming slightly less marked for higher energies. At 10 MeV the orientation of the molecule perpendicular to the beam is favored by a factor of three over orientation along the beam. This result is in fairly good agreement with calculations by Wang and McGuire (see Fig. 5.4.3.1). (See also Section 5.7.5 in this report.) This work is reported in Publications # 29, # 30, and # 73.

Figure 5.4.3.1: $d\sigma/d(\cos\theta)$ for electron capture accompanied by excitation or ionization of d_2 by O^{8+} at 10 MeV. θ is the angle between the beam and the molecular axis. The solid line is theory (Wang and McGuire).

References for Sections 5.4.2 and 5.4.3

1. E.Y. Kamber, C.L. Cocke, S. Cheng, and S.L. Varghese, Phys. Rev. Lett. 60, 2026 (1988).
2. E.Y. Kamber, C.L. Cocke, S. Cheng, J.H. McGuire, and S.L. Varghese, J. Phys. B 21, L455 (1988).
3. E.Y. Kamber, C.L. Cocke, S. Cheng, and S.L. Varghese, Phys. Rev. A, 41, 150 (1990).

5.4.4 Recoil Ion Momentum Spectroscopy

V. Frohne, S. Cheng, C.L. Cocke, and R. Ali

Recent CTMC calculations by Olson, *et al.*¹ show that during an atomic collision, the electrons from the target atom carry away a significant amount of the momentum in the collision. One prediction arising from the calculations is that the recoil is frequently scattered backwards. No experimental data which show the entire velocity space distribution of the recoil after the collision are available, and the purpose of this experiment is to provide this information. The technique used is to project the ions at right angles to the beam onto the face of a position sensitive detector using a very weak extraction field, and to use this position and the time of flight of the recoils to reconstruct the entire velocity space distribution of the recoils. For 1 MeV/amu F^{9+} on Ne, the results show that for capture of two or more electrons, the net momentum carried away by the electrons from the collision is small, but that this is not the case for softer collisions for which one or fewer electrons are captured. The recoil velocity distributions are disk-shaped about the beam axis for the harder collisions, becoming more spherical in appearance for softer collisions. For the harder collisions, there is no evidence for out-of-plane electron momentum structure as reported by Gonzles *et al.*, (see Publication # 76) and indeed, for double electron capture, very little net momentum is found to be carried away by the continuum electrons. The longitudinal momentum transfer is found to be zero within the resolution of the apparatus, limited by the thermal spread of the target. This means that the recoils exit at 90 degrees within experimental uncertainty. This uncertainty presently corresponds to 6 a.u., which is large enough that for the low charge state recoils, where CTMC calculations predict significant departures from 90 degree recoil production, the experiment cannot yet challenge the theory. For the higher charge states, the CTMC seems to predict somewhat higher longitudinal momenta transfers than seen experimentally. This is the first experiment which has addressed the longitudinal momentum transfer to the recoil, and development of a colder target is discussed further in the proposal. Preliminary reports of this work were given in Publication # 94 and AFP # 17.

Reference for Section 5.4.4

1. R.E. Olson, J. Ullrich, and H. Schmidt-Bcking, Phys. Rev. A 39, 5572 (1989).

5.4.5 Charge Exchange Processes in Fast Collisions of Highly Charged Ions and Ar Atoms

I. Ben-Itzhak, P. Richard, J.L. Shinspaugh, and J.M. Sanders

This research was done in collaboration with

Professor R.L. Watson's group at Texas A&M University

O. Heber, G. Sampoll, B.B. Bandong, R.J. Maurer, E. Moler, and R.L. Watson

Cross sections for the production of Ar recoil ions in collisions with 1 MeV/amu O^{q+} and F^{q+} ($q=2$ to bare nuclei) were measured by the time-of-flight technique. The cross sections for the production, by pure ionization, of recoil ions having charges greater than 6 display an unexpected behavior as a function of q , as can be seen in Fig. 5.4.5.1. They rise at low q , reach a maximum in the vicinity of $q=5-7$, and then decrease at high q . Cross sections calculated using the independent-electron approximation rise continuously in this region and are lower than the experimental cross sections by as much as 4 orders of magnitude for high recoil-ion charge and low q . The observed turnover in the cross sections, as well as the large discrepancies in absolute magnitude between experiment and calculation, are accounted for by vacancy multiplication resulting from L-shell ionization followed by Auger decay.¹ Similar measurements on a Ne target have shown no structure in the pure ionization cross sections. This is expected for a Ne target as K-shell ionization and K-K transfer are negligible at this collision velocity. Thus, no charge multiplication is expected. Information about single and double electron capture and loss in the same collision system acquired in the same experiment is being used to study the dependence of these processes on the projectile charge state and the validity of the scaling laws. This work is reported in Publication # 31.

Figure 5.4.5.1: Experimental cross sections for Ar recoil-ion production by pure ionization as a function of the projectile charge; (a) oxygen projectiles; (b) fluorine projectiles. The numbers along the right-hand side label the recoil-ion charge.

Reference for Section 5.4.5

1. O. Heber, G. Sampoll, B.B. Bandong, R.J. Maurer, E. Moler, R.L. Watson, I. Ben-Itzhak, J.L. Shinpaugh, J.M. Sanders, L. Hefner, and P. Richard, Phys. Rev. A 39, 4898 (1989).

5.4.6 Ionization of Helium by Fast, Highly Charged Projectiles

I. Ben-Itzhak and J.H. McGuire

Both single and double ionization of helium by projectiles of charge q ranging up to 50 were considered at collision velocities corresponding to 1.4 MeV/amu within the independent electron approximation. A simple calculation using a unitarized semiclassical Coulomb approximation probability was sufficient to provide agreement with the charge dependence of the observed total cross sections as can be seen in Fig. 5.4.6.1. Our simple results¹ do not diminish the need for better calculations, like the ones done by Salin,² to give a deeper understanding of single and multiple ionization in ion-atom collisions. Furthermore, the success of the simple model indicates that differential cross section measurements may be needed in order to probe the approximations used in the theory. This work is reported in Publication # 19.

Figure 5.4.6.1: Total cross sections for single and double ionization as a function of the projectile charge q . Data: σ^+ , single ionization; Δ , Ref. 3; $\blacktriangle$, Ref. 4. σ^{2+} , double ionization; $\diamond$, Ref. 3; $\blacklozenge$, Ref. 4. Theory: our model (—); MEDOC, Ref. 2 (---); scaled proton cross sections (---).

5.4.7 Impact Parameter Dependence of Classical Capture Probability by Fast Bare Projectiles from any Initial State

I. Ben-Itzhak and O. L. Weaver

In collaboration with Ashok Jain at Florida A&M University

A model for calculating the single electron capture probability in fast collisions of highly charged ions and atoms was developed. The impact parameter dependence of this single electron capture probability is derived based on the classical Bohr-Lindhard capture model.⁵ In our model the target atom electrons have the spatial distribution of a "frozen" wave function. Using hydrogenic wave functions it is easy to derive the single electron capture probability from any target sub-shell. This single electron capture probability is in good agreement with our AO+ calculations. Using AO+ and OBK calculations it is shown that the final state distribution of the captured electron on the projectile shifts to highly excited states and gets broader as the projectile charge state increases. This justifies the use of a classical approximation for electron capture by highly charged ions in fast collisions. Using this capture probability and SCA ionization probability, cross sections for ionization and charge transfer were calculated within the independent electron approximation. The model calculations are used to study general trends in fast charge exchange collisions for the experiments proposed and performed in J.R. Macdonald Laboratory.

References for Sections 5.4.6 and 5.4.7

1. I. Ben-Itzhak and J.H. McGuire, Phys. Rev. A 38, 6422 (1988).
2. A. Salin, Phys. Rev. A 36, 5471 (1987).
3. J.H. McGuire, A. Müller, B. Schuch, W. Groh, and E. Salzborn, Phys. Rev. A 35, 2479 (1987).
4. H. Knudsen, L.H. Andersen, P. Hvelplund, G. Astner, H. Cederquist, H. Danared, L. Liljeby, and K.G. Rensfelt, J. Phys. B 17, 3545 (1984).
5. N. Bohr and J. Lindhard, K. Dan. Vidensk. Selsk. Mat.-Fys. Medd. 28, no. 7 (1954).

5.4.8 Coincident δ -Electron Spectra in Multi-electron Ionization Events of High Multiplicity

S. Hagmann, B. Krässig, A. González, and T. Quinteros

We have determined the spectral shape of δ -electron spectra in coincidence with the charge state of the emitting recoil ion in 0.53 MeV/u $F^{8+} \rightarrow Ne$ and $Cu^{15-18+} \rightarrow Ne$ collisions.

For low charge states of the Ne recoil ion, which are almost exclusively produced via ionization and no accompanying capture, the shape of the δ -electrons spectra coincides with the shape of the non-coincident spectra, for both projectiles and all charge states of the projectile. The same observation hold for high recoil ion charge states ($q_R = 7+, 8+$) for Cu^{15-19+} projectiles. For projectiles with an open quasi resonant KK charge transfer channel ($F^{8,9+}$) or an open quasi resonant K-L charge transfer channel (Cu^{20+}), the electron energy dependence of the δ -electron spectra coincident with Ne^{6-9+} changes very strongly with increasing recoil charge state q_R the low energy part of the δ -electron spectra with electron energies $E_e \leq 400$ eV is strongly attenuated, the attenuation being more pronounced for higher recoil charge states. This effect is completely counter-intuitive to an argument concerning the available phase space for an increasing number of electrons in the continuum (with increasing recoil charge state q_R). We discussed the results in a simple model of ionization from a bound electron momentum distribution modified through correlated multiple capture. This work is described in Publication # 58.

5.4.9 Observation of Strong Directional Out of Plane Scattering in Two Center Multiple Ionizing Ion-atom Collisions

S. Hagmann, A. González, R. Koch, B. Krässig, T. Quinteros,
A. Skutlartz, and H. Schmidt-Böcking

We have measured the azimuthal and scattering angle distribution of projectiles in coincidence with recoil ions in charge states $3+$ to $8+$ for 0.53 MeV/u $F^{8+} + Ne \rightarrow F^{6+} + Ne^{q+}$. For ionized electron multiplicities between one and six complete scattered particle distributions as functions of the azimuth were obtained. We derive transverse projectile and recoil momenta and find for high multiplicities strong deviations from two body kinematics. It is found that in these cases the

ejected electrons play a significant role in the transverse momentum balance. The ionized electrons are emitted anisotropically and highly directional with respect to the scattering plane such that the electron emission pattern is best imagined as having a jet like feature. This work is described in Publication # 76.

5.4.10 Inclusive Multi-electron Production Probabilities in Charge Transfer Dominated Ion-atom Collisions

S. Hagmann, T. Quinteros, A. González, R. Koch,
B. Krässig and A. Skutlartz

We have measured coincidences between recoiling target ions in charge states q_R defined using time-of-flight techniques and projectiles in selected post collision charge states $4 \leq q_f \leq 9$, scattered by Ne between 0.02 and 3 mrad.

For collision channels with no or only single or double electron capture to the projectile we find that the recoil ion production probabilities $P_{qt}(n, \theta)$ almost always display the monotonic ionization behavior of decreasing probabilities with decreasing scattering angle (i.e. larger impact parameters) and also with increasing multiplicity of target electron loss. However, for higher-multiplicity capture, e.g. quadruple capture, the most probable recoil charge state is 8^+ with high probabilities, even at the smallest scattering angles, and the monotonic behavior gives way to a more complex pattern of $P_{qt}(n, \theta)$.

We find that for low multiplicities, e.g. $m=2$ electrons, pure ionization is the dominant contribution and the channel with simultaneous capture plays a negligible role. The picture changes for a comparison of those channels contributing e.g. to simultaneous emission of $m=6$ electrons into the continuum: here the pure ionization plays no role, and channels with simultaneous electron capture into the projectile during an ionizing collisions contribute dominantly (see Fig. 5.4.10.1, next page), peaking at scattering angles around 0.15 mrad corresponding to roughly twice the radius of the target K shell as impact parameter. This suggests that rearrangement during and after KK charge transfer is a major channel for high multiplicity electron emission. This work is presented in Publication # 58.

Figure 5.4.10.1: Inclusive multielectron emission probability.

5.5 Inner Shell Processes

5.5.1 Investigations of L-Subshell Ionization by Fast Heavy Ions

Tom J. Gray

We have completed a systematic study of LI- and LIII-subshell ionization of solid targets of Yb and Au by fast heavy ions. We have investigated the projectile atomic number and energy per unit mass ($\sim v/\langle v_e \rangle$) dependences of the x-ray production cross sections using incident ions of H, Li, Be, C, N, F, and Si over an energy range from 0.5 Mev/A to 3.0 Mev/A in most cases.

The experimental results have provided systematic data on the $L_{\alpha_{1,2}}$, L_{ℓ} , L_{γ_1} , and $L_{\gamma_{2,3}}$ x-ray production cross sections and the relative anisotropy in the $L_{\alpha_{1,2}}/L_{\ell}$ ratio. Our original goal of providing a data base for spurring additional theoretical interest has been achieved. New coupled channel calculations for LI-subshell ionization by fast heavy ions have come about for comparisons to our data.

Previous theories employed screened hydrogenic 2S wavefunctions to describe the electron participating in the ionization interaction with the incoming heavy ion. Brandt and coworkers introduced modifications to the 2S screened hydrogenic wavefunctions via the perturbed stationary state approach. These modifications resulted in effectively changing the binding energy of the 2S electron matrix element. However, the wavefunctions employed were still basically screened 2s hydrogenic wavefunctions.

Previous work by ourselves and others had shown that there was a projectile energy (velocity) dependent structure in the $L_{\gamma_{2,3}}$ x-ray production cross section related to the 2S character of the LI-subshell electron participating in the ionization process. This feature is shown for incident H ions on Yb in Fig. 5.5.1.1.

By variation of the projectile atomic number we have systematically increased the strength of the ionization interaction at each given projectile incident velocity in going from H ions to Si ions as projectiles. The net effect of the increasing of the strength of the interaction between projectile and target electron is to wash out the structure formerly associated with the 2S character of the LI subshell electrons. By taking the ratio of $L_{\alpha_{1,2}}/L_{\gamma_{2,3}}$ we see that the structure present in the $L_{\gamma_{2,3}}$ cross section shows up as a peak in the ratio $L_{\alpha_{1,2}}/L_{\gamma_{2,3}}$ as shown in Fig. 5.5.1.2. Increasing the interaction strength decreases the structure in the $L_{\alpha_{1,2}}/L_{\gamma_{2,3}}$ ratio as seen in Fig. 5.5.1.2. Hence we believe that we have clearly illustrated a definite case

for the distortion of the electron states through mixing prior to the actual ionization event.

Figure 5.5.1.1: The $L_{\gamma_{2,3}}$ x-ray production cross section for incident H ions.

Figure 5.5.1.2: The ratio of the x-ray production for ions from H to Si incident on Yb.

Shingal has performed coupled channel calculations based upon first principles. Mixing of electronic states in the entrance channel are central to these new calculations. The new coupled channel calculations represent a significant improvement in agreement between theory and the experimental data for heavy ions incident on Yb as shown for N ions incident on Yb in Fig. 5.5.1.3 (next page) and for H ions on Yb as shown in Fig. 5.5.1.1.

One student, Nabil Malhi, finished his Ph.D. dissertation requirements and defended his dissertation on this work during May, 1991. A total of three papers have been written and submitted for publication on this work to date with two papers submitted to Phys. Rev. A and one paper submitted to J. Phys. B.

Figure 5.5.13: The $\sigma_{L_{\gamma_{23}(6)}}$ x-ray production cross section for N + Yb compared to the PWBA, ECPSSR, and the coupled channel calculations of Shingal.

5.6 Molecular Fragmentation Studies

I. Ben-Itzhak, S.G. Ginther, and K.D. Carnes

We have developed a Time-of-Flight (TOF) spectrometer in which all positive fragments produced in a collision with a fast highly charged ion can be measured in coincidence by recording their time of arrival sequentially using multi-hit electronics. A high extraction field in the collision region is used in order to measure the cross section of all breakup channels, given that the time separation between the two fragments is larger than 11 nsec. Under these experimental conditions no ions are lost due to the detector solid angle and fragments lost due to detector efficiency, transmission of the meshes, and collisions with the single exit collimator can be calculated. A low extraction field in the collision region is used to measure the average kinetic energy carried by the fragments, and the distribution around it. We have used the breakup of CH_4^{2+} into $\text{CH}_2^+ + \text{H}_2^+$, which is known to be isotropic, to test the TOF spectrometer for distortions. None were found. Preliminary results of molecular fragmentation studies of diatomic molecules and small polyatomic molecules were presented in the DAMOP meeting.¹ This work is reported in a manuscript submitted for Publication # 9.

5.6.1 Fragmentation of Diatomic Molecules - CO

I. Ben-Itzhak, S.G. Ginther, and K.D. Carnes

In the last few months we have measured the fragmentation process of CO after a collision with a 1 MeV/amu F^{4+} and F^{8+} . The different fragmentation channels can be identified in the spectrum that is presented in Fig. 5.6.1.1. Relative abundances of the main fragmentation channels were evaluated. The fragmentation pattern of the highly ionized CO molecule tends to peak when the two fragments have the same charge, even though the molecule is heteronuclear. The kinetic energy of the fragments increases rapidly from a few eV for $\text{C}^+ + \text{O}^+$ to about 20 eV for $\text{C}^+ + \text{O}^{2+}$ and 44 eV for $\text{C}^+ + \text{O}^{3+}$. The kinetic energy exceeds 100 eV for the highly charged fragments, for example $\text{CO}^{6+} \rightarrow \text{C}^{3+} + \text{O}^{3+}$. The kinetic energy of the different fragmentation channels is in reasonable agreement with a simple Coulomb explosion model. We are in the process of evaluating the distribution of the kinetic energy around its mean for each fragmentation channel by analyzing the time difference ($t_2 - t_1$) spectrum. This spectrum, presented in Fig. 5.6.1.2, is a convolution of the kinetic energy distribution and the response function of the TOF spectrometer. Once the kinetic energy is known and the angular discrimination of

the TOF spectrometer can be evaluated, the relative cross sections for all fragmentation channels will be evaluated.

Figure 5.6.1.1: $F^{4+} + CO \rightarrow CO^{q+} \rightarrow C^{q+} + O^{q'+}$ at 1 MeV/amu. Extraction field 1250 V/cm.

Figure 5.6.1.2: Time difference spectrum of $F^{4+} + CO \rightarrow C^{2+} + O^{+}$ at 1 MeV/amu. Extraction field 156 V/cm.

5.6.2 Fragmentation of Small Polyatomic Molecules - CH₄

I. Ben-Itzhak, S.G. Ginther, and K.D. Carnes

The fragmentation of CH₄ was studied for the same collisions as the CO fragmentation. The different fragmentation channels can be identified in the spectrum that is presented in Fig. 5.6.2.1. The kinetic energy of the CH₄ fragments is relatively small compared to the CO fragments. For example, about 5 eV for CH₃³⁺ + H⁺ and CH₂⁺ + H⁺, in agreement with double photo-ionization measurements.² The lower kinetic energy of the CH₄ fragments is a result of the lower charge states of the hydrogen fragments in comparison to the high charge states of CO fragments. The ratio [CH₂⁺ + H₂⁺] / [CH₃⁺ + H⁺] for F^{q+} impact is approximately the same as the one measured in double photo-ionization² and fast electron impact experiments.^{3,4} On the other hand the ratios [CH⁺ + H⁺] / [CH₃⁺ + H⁺] and [C⁺ + H⁺] / [CH₃⁺ + H⁺] are larger than the same ratios measured in double photo-ionization and fast electron impact. The additional yield in the latter channels may be due to fragmentation of triply (or more) ionized CH₄, assuming that the fragmentation pattern is independent of the ionization mechanism.

Figure 5.6.2.1: F^{q+} + CH₄ → CH₄^{q+} → CH_n^{q+} + H_m⁺ at 1 MeV/amu. Extraction field 1250 V/cm.

The fragmentation of CH_4^{2+} into $\text{CH}^+ + \text{H}_3^+$ was predicted theoretically by Siegbahn⁵ to have a very low threshold energy, thus, a large relative abundance. This fragmentation channel is of interest because it requires a rearrangement of the electron cloud after the ionization and before the breakup takes place. Fournier *et al.*² determined from their null result that the relative abundance of this fragmentation channel is less than 0.5% from the most abundant one. We have measured a relative abundance of about 0.2% for this fragmentation channel. This breakup has the features of a two body fragmentation breakup as can be seen from Fig. 5.6.2.2. The measured abundance is clearly in disagreement with the prediction that it should be a main channel. This may be due to dissociation of most of the H_3^+ formed in the fragmentation of the CH_4^{2+} .

Figure 5.6.2.2: $\text{F}^{4+} + \text{CH}_4 \rightarrow \text{CH}_4^{2+} \rightarrow \text{CH}^+ + \text{H}_3^+$ at 1 MeV/amu. Extraction field 1250 V/cm.

References for Section 5.6.1 and 5.6.2

1. I. Ben-Itzhak, S.G. Ginther, and K.D. Carnes, Bull. Am. Phys. Soc. **36**, 1277 (1991), and submitted to Nucl. Instr. and Meth., Aug. 1991.
2. P.G. Fournier, J. Fournier, F. Salama, P.J. Richardson, and J.H.D. Eland, J. Chem. Phys. **83**, 241 (1985).
3. K.E. McCulloh, T.E. Sharp, and H.M. Rosenstock, J. Chem. Phys. **42**, 3501 (1965).
4. C. Backx and M.J. Van der Weil, J. Phys. B: Atom. and Molec. Phys. **8**, 3020 (1975).
5. E.M. Siegbahn, Chem. Phys. **66**, 443 (1982).

5.6.3 Exotic Negative Ions and Multiply Charged Molecular Ions

I. Ben-Itzhak, I. Gertner, D. Zajfman, and D. Bortman

This research is done in collaboration with the atomic physics group at the Technion, Haifa, Israel

We have continued our search for exotic, stable and metastable, rare gas negative ions and multiply charged molecular ions.¹ Similar research, for example, have been reported by Bae et al.² and Helm et al.³

I. Formation of Doubly Charged Metastable Molecular Ion Ne_2^{2+} in Sub-MeV Stripping Collision $\text{Ne}_2^+ + \text{Ar} \rightarrow \text{Ne}_2^{2+}$

We have performed an experiment in which the long-lived Ne_2^{2+} molecular ion was first observed.⁴ The Ne_2^{2+} was produced by charge stripping of 900 keV Ne_2^+ beam in Ar gas target. The mean lifetime of the Ne_2^{2+} was found to be larger than about 1 μsec . A calculation of the adiabatic potential curves of doubly charged molecular ions done by Penkina and Rebane⁵ predicted that the Ne_2^{2+} is not bound in the electronic ground state since there is no minimum in the adiabatic potential curve. The experimental evidence for its existence even as a metastable suggests that either the detected Ne_2^{2+} was in an excited electronic state or that the theoretical approximation used for the Ne_2^{2+} ground state calculation is not accurate enough. A more detailed calculation of doubly charged rare-gas diatomic molecular ions, including electronically excited states and metastable states is needed. The Ne_2^{2+} molecular ion is the fifth observed doubly charged noble gas diatomic molecular ion. The ones reported before are: NeXe^{2+} , ArXe^{2+} , NeKr^{2+} , and He_2^{2+} . This work is reported in Publication # 71.

II. Negatively Charged Krypton Ions

Recently, Haberland *et al.* reported experimental evidence for the existence of metastable negative Xenon ions.⁶ We have searched for metastable negative krypton ions produced by double electron capture in Ar gas target. The preliminary results indicate that metastable Kr^- might exist, but the results were not conclusive. An improved experiment using ^{86}Kr isotope is underway.

References for Section 5.6.3

1. O. Heber, I. Ben-Itzhak, I. Gertner, A. Mann, and B. Rosner, J. Phys. B: Atom. and Molec. 18, L201 (1985); O. Heber, I. Gertner, I. Ben-Itzhak, and B. Rosner, Phys. Rev. A 38, 4504 (1988); I. Ben-Itzhak, O. Heber, I. Gertner, and B. Rosner, Phys. Rev. A 38, 4870 (1988).
2. Y.K. Bae, J.R. Peterson, H.H. Michels, and R.H. Hobbs, Phys. Rev. A 37, 2778 (1988); Y.K. Bae, M.J. Coggiola, and J.R. Peterson, Phys. Rev. Lett. 52, 747 (1984).
3. H. Helm, K. Stephan, T.D. Mark, and D.L. Huestis, J. Chem. Phys. 74, 3844 (1981); K. Stephan, T.D. Mark, H. Helm, Phys. Rev. A 26, 2981 (1982).
4. I. Ben-Itzhak, I. Gertner, D. Zajfman, and D. Bortman, Phys. Rev. A 41, 6548 (1990).
5. N.N. Penkina and T.K. Rebane, Opt. Spectrosk. 62, 514 (1987); N.N. Penkina and T.K. Rebane, Opt. Spectrosk. 46, 454 (1979).
6. H. Haberland, T. Kolar, and T. Reiners, Phys. Rev. Lett. 63, 1219 (1989).

5.7 Theory

5.7.1 Dielectronic Recombination Process

C.P. Bhalla

I. Total Dielectronic Recombination Rates for He-like Ions

The total DR rate coefficients for heliumlike ions with atomic number $Z = 10, 14, 18, 20, 22, 24, 26$, and 28 were calculated¹ for electron temperature of 0.1 - 10 keV. The total DR rate coefficient is obtained by summing over partial DR rates of a large number of intermediate lithiumlike states from configurations of the type $1s2\ell n\ell'$. Since the complexity of the calculation increases rapidly with n , we have restricted our calculation to $n \leq 8$.

$$\alpha_d(s-f) = \frac{1}{2} (2\pi\hbar^2/mkT_e)^{3/2} F_2^*(s-f) \exp(-E_a/kT_e) \quad (1)$$

T_e is the electron temperature, and $F_2^*(s-f)$ is the satellite intensity factor. In Fig. 5.7.1.1 we plot the DR rate coefficients of heliumlike silicon, argon, titanium, chromium, and nickel as a function of electron temperature. The variation of DR rate coefficients of heliumlike ions with respect to variation in atomic number Z and plasma temperature T_e exhibit the following behavior: (i) for a particular Z the DR rate coefficient increases sharply with temperature, reaches a maximum at about $kT_e = (2/3)E_a$ (E_a is the energy of the lithiumlike autoionizing state $|s\rangle$ with respect to the ground-state energy of the $1s^2$ heliumlike ion) and falls off gradually; (ii) the electron temperature corresponding to the maximum values of DR rate coefficients increases with Z ; (iii) the maximum value of DR rate coefficient decreases with Z ; and (iv) at low electron temperatures DR rate coefficients of lighter elements are larger than the rate coefficients of heavier ions; at very high temperatures this trend is reversed.

These features can be understood as follows: The temperature dependence of DR rate coefficient primarily comes from the terms

$$(kT_e)^{-3/2} \exp(-E_a/kT_e). \quad (2)$$

The effect of the first term of Eq. (2) is a decrease in DR rate coefficient with

temperature which is the same for all elements and for all DR channels. The exponential term lies between 0 and 1 corresponding to $kT_e=0$, and ∞ ; this term increases very rapidly until about $kT_e \approx E_a$ after which the growth becomes extremely slow. The overall variation of DR rate coefficients with T_e is a compromise between these two opposing trends; at low energies the exponential term is responsible for the steep rise in the curves of Fig. 5.7.1.1, at higher energies the $(1/kT_e)^{3/2}$ term falls off at a much faster rate than the increase in the exponential term, the net effect being a gradual decrease in DR rate coefficients as kT_e increases. The rate of growth of the exponential term at low energies is faster if E_a is smaller as is evident from Fig. 5.7.1.1 which shows that the curves rise less steeply as the atomic number Z increases. The values of Auger electron energies E_a for a typical $1s2\ell^2 \rightarrow 1s^2\epsilon\ell$ transition are approximately 0.6, 1.4, 2.2, 2.8, 3.3, 4.0, 4.7, and 5.4 keV, respectively, for $Z=10, 14, 18, 20, 22, 24, 26$, and 28.

Figure 5.7.1.1: Total dielectronic recombination (DR) rate coefficients for helium-like ions with $Z=14, 18, 22, 24$, and 28 as a function of electron temperature.

Differentiating Eq. (1) with respect to kT_e , it can easily be seen that for a particular Z DR rate coefficient is maximum at $kT_e = (2/3)E_a$. As E_a increases with Z , the position of the maxima shifts toward higher energy for heavier elements. The reasons for the decrease in DR rate coefficients with Z at temperatures corresponding to the maximum DR rate coefficients are rather involved.

II. Dielectronic Recombination on Heliumlike Argon

We performed calculations of x-ray and Auger rates and transitions energies to obtain the resonance strengths for doubly excited li-like argon.² The details of the experiment (see Publication # 63) performed with KSU-EBIS and the analysis are described in more detail in Section 5.3.1 of this report.

III. Dielectronic Satellite Spectra of Hydrogenlike Iron from Tokamak Fusion Test Reactor (TFTR)

Spectra of hydrogen-like Fe XXVI have been observed from Tokamak Fusion Test Reactor plasmas with a high-resolution crystal spectrometer. The experimental arrangement permits simultaneous observation of the Fe XXVI Ly- α_1 and Ly- α_2 lines and the associated dielectronic satellites, which are due to transitions $1sn\ell-2pn\ell'$ with $n \geq 2$, as well as the heliumlike $1s^2(^1S)-1s4p(^1P_1)$ and both hydrogen-like Ly- β_1 and Ly- β_2 lines from chromium. Relative wavelengths and line intensities can be determined very accurately. The spectral data are in very good agreement with theoretical calculations. The observed spectra have also been used to estimate the total dielectronic recombination rate coefficient of Fe XXVI. It was also found that the MCDF and the Z-expansion calculations with QED are in good agreement with the experimental data.³

References for Section 5.7.1

1. K.R. Karim and C.P. Bhalla, Phys. Rev. A **39**, 3548 (1989); *ibid* **43**, 615 (1991) shows the variation of satellite intensity factors with n for $1s^2\epsilon\ell \rightarrow 1s2pn\ell' \rightarrow 1s^2n\ell'$ dielectronic recombination processes in heliumlike ions; *ibid* **42**, 3555 (1990).
2. R. Ali, C.P. Bhalla, C.L. Cocke, and M. Stockli, Phys. Rev. Lett. **64**, 633 (1990).
3. V. Decaux, M. Bitter, H. Hsuan, S. von Goeler, K.W. Hill, A. Hulse, G. Taylor, H. Park, and C.P. Bhalla, Phys. Rev. A **43**, 228 (1991).

5.7.2 Two-Electron Processes in Ion-Atom Collisions

C.D. Lin

In the past few years a number of experiments were carried out at the J.R. Macdonald Laboratory and at other laboratories where two-electron processes in ion-atom collision were studied. The two-electron processes include double capture, double excitation, double ionization, transfer ionization and transfer excitation, in collisions involving multiply charged ions with helium and other target atoms and over a broad energy range. One of the central issues is the role of electron-electron interaction in ion-atom collisions for such two-electron processes.

We have studied some of these two-electron transitions for collisions between bare ions and helium atoms using the independent electron model. By approximating the electron-electron interaction in terms of a screening potential, the two-electron Schrödinger equation is replaced by two one-electron time-dependent Schrödinger equations which are solved by the close-coupling expansions using atomic orbitals. This independent electron approximation allows the determination of cross sections for all the two-electron processes in a single calculation. This model also provides a consistent check of the independent electron approximation.

Calculations have been carried out for double capture, double ionization and transfer ionization processes for a few MeV/amu bare ions of helium, carbon, oxygen and fluorine with helium atoms and the results were compared with experiments from Richard's group (see Publications # 79 and # 60). Calculations have also been carried out for double capture to doubly excited states in the lower energy region (a few keV/amu) for He^{++} on He (see Publication # 24) and C^{6+} and O^{8+} on He (submitted for publication in J. Phys. B). The latter calculations were compared with experiments carried out using ECR ion sources. We have been able to predict the dominant double capture channels as well as the dominant doubly excited states populated in such collisions.

I. Density Matrices of Collisionally Populated Excited States

A complete quantum mechanical description of a scattering event is the determination of all the density matrix elements of the final states. In recent years such experiments have been carried out at a number of laboratories where the results can be used to provide a critical test of the theoretical description of the collision process. We have carried out a number of calculations where the density matrix elements, or equivalently, the statistical multiples are compared to experiments. In particular, we calculated the density matrix using the close-coupling method for the $\text{H}(n=3)$ manifold in $p + \text{H}(1s) \rightarrow \text{H}(n=3) + p$ collisions in the 30-80 keV region and compared the results with measurements from the North Carolina State group. We illustrated that a relatively large basis set including effect of the ionization channels is needed in order to obtain good agreement with experiments. The results also showed that the electron cloud tends to lag behind the projectile nucleus in such collision events. The most recent results are given in Manuscripts Submitted for Publication # 6. We have also examined the orientation and alignment parameters of 2p states populated in collisions with both positive and negative charged particles. Some simple systematics have been observed as shown in Publication # 60.

II. Ion-Molecule Collisions

In conjunction with the recent interest in the effect of molecular alignment in ion-molecule collisions at the J.R. Macdonald Laboratory, we initiated a theoretical program where such effects can be studied. In order to avoid the complicated calculations that are required for a full solution of such a program, we made a simple theoretical model where the amplitude for ion-molecule collisions is treated as a coherent superposition of amplitudes from ion-atom collisions where the coherence phase factor depends on the equilibrium internuclear separation of the molecule and the alignment angle of the molecule with respect to the beam direction.

The validity of this model has been checked by calculating the total capture cross sections for H^+ and He^{++} collisions with H_2 where the experimental data are available only for collisions where the molecular alignment has been averaged (see Publication # 93). The results indicate that the simple model is quite adequate for the total capture cross sections. It also addressed why it is inappropriate to treat H_2 as two independent H atoms as used in many theoretical models. The model was also applied to interpret for the first time the classic experiment of Everhart carried out in the early 60's. In this experiment, the charge transfer probability at the scattering angle of 3° was measured for $p-H_2$ collisions as a function of scattering energies. The probability for charge transfer showed a damped oscillatory structure where we showed that the damping part was due to the average over the alignment of the H_2 molecule.

III. Other Inelastic Processes

We continue to pursue problems in ion-atom collisions which are of interest to experimentalists or to the fusion community. For example, we carried out a close-coupling study of the ionization and charge transfer processes for $He^{++} + H$ in the 3-50 keV/amu region. The calculation was carried out to show that the weak ionization cross section can still be adequately calculated using the close-coupling method (see Publication # 59). In the meanwhile the fusion community these days are interested in the excitation cross sections in He^{++} on H. The excitation cross sections are quite small in the 1-100 keV/amu region. We performed a careful close-coupling study and obtained excitation cross sections which were shown to be quite sensitive to the basis sets used. The results have been submitted to Phys. Rev. A.

5.7.3 Correlation in Atomic Scattering

J.H. McGuire

We have developed calculations including correlation for two-electron transitions in high velocity atomic collisions. We evaluated cross sections for double excitation in helium in collisions with various high velocity projectiles including protons and antiprotons. Calculations of double excitation have been done using our formulation¹ for scattering of high velocity projectiles from atoms where electron correlation is included.

We have evaluated² transition probabilities and cross sections for double excitation of helium from the ground state into all doubly excited states in the $n=2$ manifold. The exact probability amplitude may be expressed as $a = \langle \phi_o | \exp\{-i \int V_1 dt\} | \phi_f \rangle$, has been truncated for terms past second order in Z/v . CI wavefunctions have been used to describe initial states, final states and intermediate states. No continuum states have, however, yet been explicitly included in our CI wavefunctions.

Cross sections for projectile-impact excitation into the $2s2p(^1P)$ state are shown in Fig. 5.7.3.1. The proton/antiproton ratio is a factor of $3/2$ in the projectile energy region of 0.1 to 0.3 MeV/amu but decreases at 9 MeV/amu where Giese *et al.*³ made their observation (for which the error bars mask a definitive statement about differences due to the sign of the projectile charge). Also shown are the close-coupling calculation of

Fritsch and Lin⁴ at 1.5 MeV/amu and the experimental results of Pedersen and Hvelplund⁵ for excitation into either $2s2p(^1P)$ or $2p^2(^1D)$ at 1.84 MeV/amu. One may see that our result is almost all first-order at 1.5 MeV/amu, so the difference in magnitude from experiment is not due to our use of a closure approximation. Since this result is very sensitive to the $1s2s$ contribution to the ground-state wave function, inclusion of additional bound and continuum states to the wave function may make a difference.

Figure 5.7.3.1.

Fig. 5.7.3.2 shows the cross sections for excitation into the $2p^2(^1D)$ state. Even though the first- and second-order contributions in our calculations are of the equivalent magnitude over the entire energy range in this case, projectile charge differences are of order 10%. Our result is in near agreement with the data of Giese *et al.*³ and lies above the result of Fritsch and Lin⁴ by a factor of 2 or 3 (p^+ or e^-), and slightly above the results of Hino and

Ishihara (not shown). For excitation into $2s^2(^1S)$ (not shown) our results lie a factor of two below Fritsch and Lin and a factor of about 10 above Hino and Ishihara,⁶ who find factor of two differences between cross sections for p^+ and p^- . These differences in studies of double excitation cross sections of helium are at present unresolved.

Figure 5.7.3.2.

References for Section 5.7.3

1. J.H. McGuire, Phys. Rev. A **36**, 1114 (1987).
2. J.H. McGuire and J.C. Straton, Phys. Rev. A **43**, 5184 (1991).
3. J.P. Giese, M. Schulz, J.K. Swensen, H. Schöne, M. Benhenni, S.L. Varghese, C.R. Vane, P.F. Dittner, S.M. Shafroth, and S. Datz, Phys. Rev. A **42**, 1231 (1990).
4. W. Fritsch and C.D. Lin, Phys. Rev. A **41**, 4776 (1990).
5. J.O.P. Pedersen and P. Hvelplund, Phys. Rev. Lett. **62**, 2373 (1989).
6. K. Hino and T. Ishihara, private communication.

5.7.4 Transfer Ionization Calculations

J.H. McGuire

We have studied two new aspects of transfer ionization in electron shakeover and a double ridge in the differential cross section due to a Thomas singularity in transfer ionization.

Shakeoff, shakeup and shakedown correspond to ionization, excitation and deexcitation which occurs when an atomic wavefunction collapses into a new eigenfunction following vacancy production in an atomic collision where electronic screening changes. We suggest in addition the possibility of shakeover where an electron collapses onto the projectile. By using orthogonalized wavefunctions corresponding to asymptotically correct first Born calculations for electron capture, we have evaluated¹ a shake probability that goes to zero when the electron screening, s , remains unchanged during the collision. Our simple shakeover probability varies as $Z_p^5 Z_T^7 / v^8 [Z_p^{-2} - Z_T^{-2}]$. This may be contrasted to the Brinkman Kramers probability for direct capture which varies as $Z_p^5 Z_T^5 / v^{12}$, where Z_p and Z_T are the projectile and target nuclear charges, s is the change in screening and v is the collision velocity. If our simple shakeover predictions are correct, then the ratio of total cross sections for transfer ionization to single capture increase with velocity at sufficiently high velocities.

It is now evident that there are various ways in which transfer ionization can occur. In one mechanism,² the captured electron collides with the ionized electron during the collision. In this case there is a kinematic singularity when the momentum transferred by the projectile is shared by the two electrons. This singularity, sometimes called a second Thomas singularity, appears as a double ridge in the momentum distribution of the ejected electron as shown in Fig. 5.7.4.1. Calculations using some peaking approximations to evaluate matrix elements have been

Figure 5.7.4.1.

completed in collaboration with T. Ishihara.^{3,4} This double ridge Thomas structure has since been observed.⁵

References for Section 5.7.4

1. J.H. McGuire, N.C. Deb, Y. Aktas and N.C. Sil, Phys. Rev A 38, 333 (1988).
2. J.S. Briggs and K. Taulbjerg, J. Phys. B 12, 2565 (1979).
3. T. Ishihara and J.H. McGuire, Phys. Rev. A 38, 3310 (1988).
4. J.H. McGuire, J.C. Straton, W.J. Axmann, T. Ishihara, and E. Petersen, Phys. Rev. Lett. 62, 2933 (1989).
5. J. Palinkas, R. Schuch, H. Cederquist, and G. Gustaston, Phys. Rev. Lett. 22, 2464 (1989).

5.7.5 Electron Capture from Molecules

J.H. McGuire

We have calculated probabilities and total cross sections for electron capture from diatomic molecules at fixed alignment of the molecular axis.

Calculations for $p + H_2 \rightarrow H + H_2^+$ have been completed.¹ At a fixed alignment of the H_2 molecular axis we find oscillations in the $1s-1s$ differential cross section. We evaluated this reaction in impact parameter space where the physical picture is somewhat more clear than in the wave picture.¹

This impact parameter method was used to evaluate transfer-excitation in a simple independent electron approximation model for

Our results are compared to recent observations of Cheng *et al.* as illustrated in Fig. 5.7.5.1 below.

The alignment dependence of the recoil molecules varies by more than a factor of 2 and may be interpreted in terms of interference between amplitudes scattering from the two atomic centers of the H_2 molecule.

Figure 5.7.5.1: Alignment dependence in dissociation of H_2^+ following single electron capture from H_2 by O^{+8} ions at $E=10$ MeV. Dot: preliminary experimental data (yield, N , of all dissociation products as function of alignment angle θ_p) from Cheng *et al.*; solid line: calculated OBK cross section normalized to experiment.

References for Section 5.7.5

1. Y.D. Wang, J.H. McGuire, and R.D. Rivarola, Phys. Rev. A **40**, 3673 (1989).
2. Y.D. Wang and J.H. McGuire, Phys. Rev. A **44**, 367 (1991).
3. S. Cheng, C.L. Cocke, V. Frohne, E. Kamber, and S.L. Varghese, Nucl. Instr. Meth., to be published.

6. JRM Laboratory Operations

6.1 Tandem Operations

R.D. Krause

Through this reporting period the EN Van de Graaff accelerator at Kansas State University has operated very well. The usual and unexpected problems have occurred with the tandem which have required tandem openings, some serious and the others being routine maintenance. Up-grading and modifications to the tandem have also occurred during this reporting period. General routine openings have been needed to repair the terminal gas stripping leak control, to replace stripping foils, replace charging screens, etc. In November of 1988 while loading insulating gas (SF_6) into the tandem the third stage of our SF_6 compressor failed. The third stage heat exchanger ruptured due to corrosion and many years of service. This problem hindered tandem openings for several months but fortunately none were required during that eight and one half month period. Both the second and third stage heat exchangers were replaced. In January of 1990, both low energy and high energy pumping stations were removed from the EN Van de Graaff accelerator. These pumping stations were original equipment installed by High Voltage Engineering Corporation (now Vivirad-High Voltage Corporation) when the EN tandem was installed in the late 1960's. Each of the two pumping stations included one six inch oil diffusion pump, one refrigeration unit for the diffusion pump cold trap and one roughing pump for the diffusion pump foreline. Installed in place of the two pumping stations were two Varian Cryostack 8 cryopumps. Interlocks incorporated in the original equipment were not modified and are currently being used. The upgrade of the tandem vacuum system has certainly helped in the recovery time and base pressures, going from 10^{-6} Torr to 10^{-7} Torr range. In March of 1990 we removed the High Voltage Engineering Corporation aluminum inclined field tubes and replaced them with Dowlish titanium spiral inclined field tubes. The maximum safe operating voltage with the High Voltage Engineering Corporation aluminum tubes was 6 MV on the terminal. With the new titanium tubes we have achieved 7.4 MV on the terminal without beam (conditioning only), and we have run beams for experiments at 7.23 MV terminal voltage. Currently we are satisfied with these results but we expect to be able to push the terminal voltage higher in the future. The tandem charging belt was replaced during this same period. The belt had a total of 6100 hours of operation and showed considerable wear. The charging belt had the usual belt characteristics that all belts have after this many hours of operation, vertical lap marks, and the neoprene separation from the cotton carcass. Through this reporting period the tandem has logged 7713.0 hours of actual beam time operation. Down time during this period has totalled 1786 hours. Of the 1786

hours, 700 were used for the installation of the new charging belt and the new spiral tubes, 480 hours were devoted to the installation of the new heat exchangers in our SF₆ gas compressor and the installation of the new LINAC prebuncher in the low energy end of the tandem, 384 hours were necessary for the vacuum up-grade and 222 hours for routine and unexpected openings.

6.2 Tandem Ion Sources

R.D. Krause

Our EN Van de Graaff accelerator at Kansas State is injected with two different ion sources. First, a Diode Source was used approximately fifty percent of the beamtime during this reporting period. While in operation, the Diode Source was used to produce fluorine (65%), carbon (20%), nitrogen (10%), and hydrogen (5%) beams. The second source, a Revolving Sputter Source (from the proceedings of the Symposium of North Eastern Accelerator Personnel, 1989, p. 145), has been in operation for the remaining fifty percent of the beam time. During its operation, the Revolving Sputter Source has produced oxygen (50%), fluorine (10%), carbon (10%), lithium (5%), beryllium (5%), silicon (5%), copper (3%), and boron (1%) beams. The remaining time was spent on source development work.

6.3 LINAC Operations

Tom J. Gray

During the last year the LINAC was put through preliminary tests. Several system modifications were made to address specific problem areas and a new cryogenic systems computer was installed for continuous monitoring of relevant parameters throughout the cryogenics system.

I. System Modifications

We encountered vibrational problems on both the superbuncher and energy rebuncher systems. These vibrations represent a serious problem because the two

resonators involved in these separate systems could not be phase locked to the LINAC master clock due to the bandwidth of the vibrations being outside of the control bandwidth of the fast frequency control unit's (VCX) on the resonators. The very high Q of the resonators themselves makes them extremely sensitive to sources of mechanical vibration. An intensive search for the source(s) of vibration was undertaken with null results.

Measurements of the vibration bandwidth of the acceleration resonators in the large cryostats showed bandwidths of ~40 Hz compared to 500 Hz or greater for the two buncher systems. The large cryostat resonator mounting system is very weakly coupled to the external laboratory environment. There the resonators are suspended on thin rods with a low compliance interconnecting bellows between the dewar and individual resonator. The dewar is suspended on three cables from the heat shield which is in turn suspended on three cables from the cryostat top lid. The whole system forms a multiple pendulum with the intermediate masses being much smaller than the resonator-dewar mass. Hence external vibrational energy is taken up by the small intermediate mass of the heat shield and not transmitted into the resonators.

The buncher cryostat systems were adopted from ATLAS. There the resonator was rigidly attached to the LHe dewar which was in turn rigidly attached to the cryostat top plate. A redesign of the resonator mounting system was undertaken and modifications of those systems were made. The rigid coupling of the resonator to the dewar was replaced with the three thin rod and low compliance bellow attachment systems used successfully in the large cryostats. Upon completion of these modifications, systems tests were performed. The superbuncher showed a reduction in vibrational bandwidth to an acceptable level of ~160 Hz while the rebuncher vibrational bandwidth increased rather dramatically to ~3000 Hz. We returned to the superbuncher system to find that the vibrational bandwidth had increased to ~800 Hz with no known changes in any of the systems or the laboratory environment. After several days of intensive investigation we found a thermoacoustic oscillation in the resonator drift tube vent lines when they were closed. Upon allowing a small continuous flow of He through the vent lines the vibrational bandwidth decreased to ~50 Hz. An acoustic vibration damper has been designed for the drift tube vent system and will be installed on our next maintenance downtime. We suspect that the energy rebuncher may also have a thermoacoustic vibrational problem but we have not tested for that to date as we do not need the rebuncher currently for further acceleration tests or initial experiments.

We have installed a computer-based monitoring system on the cryogenics systems. We monitor cryogenic liquid levels, temperatures and pressures at relevant points in the cold box and compressor systems, ambient component and

environmental temperatures, expansion engine speeds, system LHe inventory, and vacuum system parameters. This system has greatly enhanced our abilities in the areas of monitoring overall system performance, diagnostics, and record keeping. We are currently upgrading the system to a 486-based system with expanded monitoring capability to include laboratory water chiller parameters, relevant tandem parameters, ion source parameters, and a personnel access monitoring system for radiation safety purposes.

II. LINAC Tests

In September and October, 1990, we began initial acceleration tests with the LINAC. Our efforts were limited in scope due to a limited number of resonators being operational and our lack of the fast timing instrumentation required to measure the time profile of the bunched beam for beam widths of less than 2 ns. We still face limitations because of our lack of instrumentation necessary for measuring the pulsed beam time profile for bunch widths of less than 2 ns. The tests represented our first efforts at running the total system. We injected 35 MeV F ions and achieved 13 MeV of boost from the LINAC thus giving 48 MeV F ions. These shake down tests allowed us to discover systems which were in need of modification and/or repair. Because of budgetary considerations and the need for implementation of the modifications discovered during our initial testing we shut the LINAC down in November.

We remained shut down until March of this year. Upon cooling the LINAC down to LN₂ temperatures we discovered cold leaks had developed in cryostats 1 and 2. We began a series of cyclic tests to isolate the sources of these leaks. This proved to be a tedious, time consuming task. We located the leaks and repaired the systems involved. The use of residual gas analysis proved most valuable in isolating the LN₂ leak sources. The minimum temperature cycle time from 300°K room temperature to 4.2°K and back to 300°K is one week for a large cryostat. We have learned much about patience in the process of chasing cold leaks.

Upon completion of the LINAC radiation shielding enclosure we began conditioning procedures on each of the resonators in the large cryostat modules. This is a tedious process because we are currently limited by having only one test system with which to condition the resonators. The computer-based LINAC rf control system is not capable of burning through multipacting barriers so we must go through that process manually. We have nine of the twelve acceleration resonators conditioned and running currently. The average field level is of order 3 MV/m with five of six operational low β resonators producing measurable radiation indicating

field levels as high as 4 MV/m and two of three high β resonators producing radiation indicating field levels in excess of 3 MV/m. The nine resonators are running in stable modes with no cooling problems. The VCX units may limit their continuous running levels to ~4.5 MV/m due to long term rf power dissipation in the VCX circuitry. Of the three resonators which are currently non-operational, two have problems with the slow tuner systems and one has a jammed rf drive probe.

We are currently moving toward further beam acceleration tests with a goal of producing 90 Mev F ions and 130 Mev Cl ions. The LINAC itself is ready for the tests but we have encountered beam transmission problems with the tandem injector when the tandem is run at or above 6 MV. We have had recent problems with the Cs sputter negative ion source which has caused us to disassemble, clean, and replace some source components. That source was designed and built with little attention to alignment considerations. We are studying the problem and formulating a solution currently.

We must use the Cs sputter source because of pulsed beam time width considerations. The bunched beam from the prebuncher must have a beam width less than 2 ns prior to injection into the superbuncher. The sputter source provides a beam of order 2 ns wide. On the other hand the diode source was found to have sufficient ripple on its high voltage power supply to limit the beam width to 6 ns, thus making it unusable for injection into the LINAC superbuncher. We designed and installed a de-rippier on the primary side of the HV power supply and did improve the time resolution by lowering it to 4 ns, but this is still not acceptable for acceleration by the LINAC.

III. Beam Lines

We have installed a second switching magnet on the LINAC which serves three beam lines which are currently under construction. By use of a second switching magnet we can use one quadrupole lens for the three beams lines. An additional separate beam line has been constructed and is now ready for use.

IV. Cryogenics Systems

During the last year we have encountered no serious downtime related to the LHe plant. We have replaced the Amtek pressure/mechanical controllers on the high and low temperature J-T expansion valves with Moore electronic controllers. This step was taken to upgrade our control capabilities in the face of large and sudden changes in cold return gas flow to the cold box resulting from

superconducting solenoid operational modes and other cryostat-related operational modes. Prior to changing over to the Moore controllers such cold gas flows caused the LHe plant to go into a cold shock condition requiring operator intervention to re-establish stable operating conditions. With the more flexible parameter control of the Moore controllers we have a larger dynamic range of control and we can keep the J-T valves from closing all the way thus allowing better automatic control of head pressures and gas management.

We did replace one bent and scored piston rod and a set of linear bearings on the warm expansion engine prior to its failure. We have had recurring problems with the intake valve actuating cam leading to the shearing of the locating pin on the camshaft. We are planning to replace the shaft to cure the problem.

We run the LHe plant without LN₂ pre-cool and have sufficient LHe cooling to meet our current and anticipated loads. The LHe refrigerator has proven to be very reliable and requires only minimal technical staff support.

We did have a real time test of all LINAC and cryogenics safety systems this last spring. An electrical fire in another campus building caused a three hour and eight minute power outage in the LINAC laboratory. This left us without electrical power for all LINAC systems. Without power we have no way to recover the boiloff He gas nor to control system pressures. The system is equipped with numerous pressure and vacuum protection safety devices. All such systems performed as designed protecting the laboratory equipment and personnel. We lost 250ℓ LHe due to the extended power outage. Once power was restored we were back to running resonators within two hours of power restoration.

V. Radiation Safety

We have totally enclosed the LINAC in a shielding wall and access gate system. The access gate is fitted with an electric lock which is energized by the cryostat radiation monitors. It is set to lock when the measured radiation external to any of the large cryostats exceeds 5mR/hr. An egress button has been installed to allow any personnel within the LINAC shielding enclosure to scram the resonator rf power supplies thus killing the radiation source and opening the access gate.

A neutron shielded beam dump was designed and constructed. It contains a faraday cup surrounded by 30 cm of borated polyethylene for neutron thermalization and absorption. Neutron and γ monitors are an integral part of the beam dump. Interlocks between the beam dump electronics and beam line gate valves will control the beam transport to the various experimental stations. The beam dump must be in place and interlocked before the beam line gate valve can be opened.

All lab access gates have been installed and appropriate signage has been put in place. We have yet to install the moveable concrete block shielding wall between the LINAC target areas and CRYEBIS. We continue to work to assure that lab radiation safety is in compliance with applicable state safety standards in this area (see Section 6.6).

6.4 CRYEBIS Operations

M.P. Stockli and C.L. Cocke

The dramatic start up of the KSU-CRYEBIS and the production of bare Argon beams in the first half of 1989 is described in a paper, which was presented at the ion source conference in 1989 (see Publication # 64). However, the direct observation of the dielectronic resonances during the tuning of the CRYEBIS focussed the attention on the measurement of the dielectronic recombination of helium-like Argon and helium-like Neon. These measurements, later refined and extended to include electron impact excitation, continued until summer, 1990, and are summarized in Section 5.3.1. The installation of a retractable UHV channel electron multiplier, a retractable UHV Faraday cup and UHV 4-jaw slits in early 1990 allowed us to transport the beam into a newly installed target chamber, without disrupting the experiments above. The new experiments, which used for the first time extracted ion beams, focussed on ion-surface interactions and is described in Section 5.3.2. In fall, 1990, all experiments had to be interrupted for the installation of the accelerator columns and the common beam line, which now guide the beam to the switching magnet. The target chamber was moved to beam line E, following the switching magnet. On November 11, 1990, the first beam was brought on to a thin carbon foil in the relocated target chamber to measure energy loss of highly charged Argon ions in a collaboration with the University of Frankfurt. This experiment established a need for higher energies, which was obtained in December, 1990, by applying a high voltage to the CRYEBIS platform for the first time during regular operation. The Frankfurt experiment was followed by investigations of charge transfer and energy gain in Ar-Ar collisions, which is still in progress, as discussed in Section 5.3.3. Two other groups are scheduled to start experiments during summer, 1991, using a similar setup. We are in the process of formally starting a collaboration with Sandia National Laboratory (R. Schmieder) to study the effect and possible applications of treating insulating surfaces with highly charged

ions. In addition, quite a few outside scientists showed interest in the facility as users or as collaborators. Quite a few general descriptions and many details on the KSU-CRYEBIS facility have been published in 15 papers. However, since such publications are rarely up to date, and lack operational details and instructions, we added a computer-based information service to provide interested parties with up-to-date information on the schedule, status, improvements, events and activities of the KSU-CRYEBIS facility. The same system provides outside and in-house users with forms, guidelines, instructions and other useful information on how to plan, initiate and execute an experiment at the KSU-CRYEBIS facility.

Normally the KSU-CRYEBIS produces ions for external experiments 24 hours a day, seven days a week. Brief interruptions or short shutdowns are often used for maintenance and to implement changes. Typically, the changes simplify operations, enhance performance and reliability, or increase the personnel, equipment, and operational safety, and/or reduce the operational costs. Only a few of a very long list of improvements, which have been implemented over the last two years, can be mentioned here. For example, we installed and recently implemented an ultra-high purity He gas recovery system, which reduces the cost for liquid He by 70% by returning the He to the LINAC cryogenic system. We are almost continuously improving the ion optical controls and diagnostics to facilitate tuning of the source and the beam transport, such as the recent installation of dual controls for the ion optical elements in the extraction region. The dual controls allow us to adjust the elements in one location for optimizing the source, or using another set of controls from a location outside of the HV-fence to optimize the beam transport. The equipment safety was substantially improved with a battery-backed automatic safety shutdown system, which can endure long power failures, but positively de-energizes the superconducting solenoid whenever it cannot positively sense sufficient liquid helium, and thus prevents the stressful quenches without sufficient cooling. To reduce the risk of equipment failures and the associated down time, we implemented a maintenance program with a computer-based check list and log, simplifying required scheduling. The same computer account also contains check lists and instructions for other services, tasks and procedures being executed by us and our trained personnel, students and associates. The check lists and instructions normally circumvent the need for extensive experience or all the bulky manuals, and therefore speed up the required tasks and substantially reduce the risk for errors. Typically, a trainee is first briefed on the objective and the basic principles of the task, then he/she is familiarized with the components and finally he/she is guided through the entire task, following the listed precise step-by-step instructions. Experience shows, that most of the time, only the second execution of the task requires supervision, and

from then on, the trained person can repeat the procedures even after long breaks, guided by the concise, step-by step instructions and the labels on all key components. Such instructions exist for essentially all cryogenic operations as well as a few other operations, yet the system manual is far from being complete.

The most difficult problem during this reporting period was the personnel situation. Shortly before the beginning of this period, the only full time technical staff position, which was assigned to the KSU-CRYEBIS project for the preceding construction period, had to be terminated. We were able to continue with the help of several highly experienced and well trained undergraduate students, which had been working with us for several years. At the present time there is only one part time undergraduate student and 50% of one staff member assigned to CRYEBIS. We recently hired one research associate to work on CRYEBIS experiments, and we have a new inexperienced Ph.D. physics student from Poland who will work for one year on CRYEBIS while learning English. This is a small staff to operate, to maintain, and to continue to expand the CRYEBIS facility.

These efforts associated with CRYEBIS have been reported in a total of ten papers published in the three years preceding June 14, 1991, one of which is a Physical Review Letter presenting the new method of measuring dielectronic recombination (see Publication # 63) with a follow up paper (see Publication # 96), the other eight reporting on the CRYEBIS and/or related technologies (see Publications # 10, 11, 27, 38, 40, 53, 64, and 85). By June 14, 1991, an additional seven papers had been accepted for publication, two of which are technical papers (see Manuscripts Accepted for Publication # 9 and # 12), the other five report the results of the basic research investigated with the KSU-CRYEBIS (see Manuscripts Accepted for Publication # 2, 3, 8, 10, and 11).

6.5 Computer Operations

K.D. Carnes

Our data acquisition and analysis system was completed over three years ago and has performed satisfactorily since then. It has been used to collect data for a variety of experiments, ranging in complexity from single-parameter measurements where all analysis is done on line to complex multi-event, multi-parameter acquisition with data stored in list mode on magnetic tape. Following in-house modification to our software, we have also been able to take data from electron spectrometers in a

multi-channel scaling mode. Most experimenters are now able to use the system routinely without any assistance from our computing staff.

The data acquisition portion of our system consists of three identical acquisition stations, each built around a Digital Equipment Corporation (DEC) VAXStation II/GPX. These computers are basically MicroVAX II's with enhanced graphics performance, including graphics co-processors and 19" monochrome monitors. Each system has a 9-track tape drive for list mode data storage and program exchange, a 205 MByte removable hard disk for data storage (each experimental group has it's own disk packs), and two 71 MByte hard drives for the system disk and program storage. The systems are networked together via DECNET, and have network access to three DEC LN03Plus laser printers.

Since the MicroVAX II alone cannot handle the real time demands of a fast data acquisition system, some sort of front end is necessary. We have chosen to use a Microprogrammable Branch Driver (MBD), first developed at Los Alamos and sold commercially by Bi Ra Systems, Inc. This is a simple 16-bit microprocessor that attaches to the MicroVAX Qbus through a Unibus-to-Qbus converter and serves as a CAMAC branch highway driver. In addition to providing the interface between CAMAC electronics and the MicroVAX, it can be programmed to execute a list of CAMAC commands in response to an event signal. Data is buffered and transferred between the MBD and the MicroVAX via DMA channels, thus enabling maximum transfer rates.

Modern data acquisition and analysis software is too complex to be generated in house at a small lab such as ours, and commercial software with the necessary power is unavailable. The standard solution, therefore, is to use software developed over the years at various national labs. We have chosen XSYS, developed first at the Triangle Universities Nuclear Laboratory and then modified at the Indiana University Cyclotron Facility. The software is written mostly in Fortran and VAX Macro. Despite its complexity, it can now be maintained in house. Designed for multi-parameter nuclear physics experiments, XSYS is flexible enough to accommodate the wide range of experiments at the J. R. Macdonald Lab.

In addition to the three data acquisition computers, we have a VAX 8250 configured for data analysis and general purpose computing. Like the other systems, it has a 9-track tape drive, an RA-60 removable disk, and a connection to DECNET. It has a 456 MByte fixed disk that serves as both a system disk and storage for user files. XSYS runs in analysis mode on the 8250 and displays spectra on graphics terminals that emulate TEK4014's and DEC VT220's.

Analysis can be performed on either the 8250 or on an idle MicroVAX system. As the number of experiments increase with the completion of the LINAC,

all of the MicroVAX's will be occupied with data acquisition or set up, placing a heavy analysis load on the 8250. We hope to address this bottleneck in the future by an additional proposal to fund the purchase of several state-of-the-art workstations.

6.6 Laboratory Safety

T.N. Tipping

Since the last progress report in 1988, the Ludlum area radiation monitor system has had all twelve of its monitors installed and has been in continuous operation since early 1989. As progress has been made on the construction of the LINAC and CRYEBIS, new monitoring needs have appeared. Two additional Ludlum monitors will be installed on a portable "beam dump" for monitoring the LINAC experimental area. This beam dump was constructed in-house and may be positioned at the end of any of the LINAC beam lines. The dump will attenuate neutron radiation from the final beam stop by more than a factor of 100. Correct positioning of the dump on a beam line is assured by a special docking port along with the LINAC radiation interlock system. The interlock system will not allow the beam to enter an experimental beam line unless the dump and its associated area monitors are properly positioned and operational.

In addition to the new monitors, the LINAC radiation interlock system has had several new access gates added. These gates are interlocked such that the beam will be stopped before entering the LINAC if the radiation level in one of the LINAC areas is above a preset value and an access gate to that area is opened. These additional gates have required that a new interlock status panel be designed and constructed. This new panel will be operational in the near future.

The LINAC radiation interlock system also has a "scram" button located inside the LINAC cryostat shielding wall. The scram system will remove power from the RF power amplifiers when activated. This will remove RF energy from the resonators, thus eliminating the x-ray radiation produced by the resonators when operating at high field levels. This system was required by local radiation protection regulations due to the enclosed, high radiation area inside the LINAC cryostat shielding wall.

Illuminated "CAUTION - BEAM ON" warning signs are located at the new LINAC access gates. These signs will be on when the beam is directed into the

LINAC. To maintain consistency and facilitate understanding of the warning signs, the access gate warning signs in the tandem facility were changed from simply "RADIATION" to the same wording as the LINAC signs. Also, every alarm and warning light in the laboratory had a sign installed next to it which explains what the device indicates and the appropriate action to take when activated.

Due to the upcoming sabbatical leave of Lew Cocke who has served as the laboratory radiation safety officer for many years, Pat Richard has taken over the responsibilities of the radiation safety officer. We used this transition as an opportunity to "clean house" in our radioactive source inventory. We transferred numerous "dead" sources to our university radiation safety office for disposal. As a result, we have reduced our inventory of radioactive sources substantially.

The approximately twenty-year-old, lead-acid, wet-cell, emergency light units in the tandem facility were replaced in early 1991 with modern, maintenance-free units. This eliminated two hazards. The first was the increasingly poor reliability of the old units and the second is the problem of dealing with heavy, acid filled batteries.

Numerous structured training programs have also been implemented recently. We are fortunate that our university campus safety department makes available to our laboratory personnel, numerous safety workshops and seminars. The campus safety department annually presents a seminar on radiation safety in the research laboratory. In the spring of 1991, the campus safety department hosted a satellite teleconference sponsored by the American Chemical Society entitled, "Complying with the OSHA Lab Standard." Our campus safety department also presented a summer safety seminar in 1991 which covered hazardous spill control, confined space entry, compressed gas cylinder safety, and numerous other topics. In addition to the campus seminars, I also attended the one-day seminar "Laboratory Safety--Principles, Practice, and Compliance" presented in Chicago by the laboratory safety consultant firm of Kaufman and Associates. In addition to training programs sponsored by our campus safety department, we offer in-house safety training which includes written safety material and safety training in the laboratory. This in-house training is documented and kept on file with other personnel files. We also offer an annual CPR training course for laboratory personnel.

In addition to training programs for laboratory personnel, we have implemented training programs by laboratory personnel. In the spring of 1991, we conducted a seminar for our county emergency medical service personnel. This seminar covered special hazards in our laboratory such as cryogenic fluids and high voltage equipment and special medical treatment procedures for these hazards. We are currently conducting similar special hazards seminars for our city fire department.

7. Publications

7. Publications for Grant Period

August 15, 1988 - June 14, 1991

1. "Shakeover Probability for Electron Capture"
J. H. McGuire, N. C. Deb, Y. Aktas, and N. C. Sil
Phys. Rev. A 38, 3333 (1988).
2. "Angular Dependence of Multiple-Electron Capture in 90-keV Ne^{7+} - Ne Collisions"
H. Schmidt-Böcking, M. H. Prior, R. Dörner, H. Berg, J.O.K. Pedersen, C. L. Cocke, M. Stöckli, and A. S. Schlachter
Phys. Rev. A 37, 4640 (1988).
3. "Differential Cross Sections for Single Ionisation of He and D_2 by Fast Protons"
E. Y. Kamber, C. L. Cocke, S. Cheng, J. H. McGuire, and S. L. Varghese
J. Phys. B 21, L455 (1988).
4. "Evaluation of $n\ell m - n'\ell'm'$ Capture Amplitude in the Target Continuum Distorted-Wave Theory"
N. C. Deb
Phys. Rev. A 38, 1202 (1988).
5. "Cusp-Electrons Used for Velocity Measurements of Heavy Ion Projectiles"
R. Mann, S. Hagmann, and L. Weitzel
Nucl. Instrum. and Methods B34, 403 (1988).
6. "Electron Capture from a Hydrogen Molecule at a Fixed Orientation of the Molecular Axis"
N. C. Deb, A. Jain, and J. H. McGuire
Phys. Rev. A 38, 3769 (1988).
7. "Second-Order Singularities in Transfer Ionization"
T. Ishihara and J. H. McGuire
Phys. Rev. A 38, 3310 (1988).
8. "Orientation and Alignment Parameters in e^+ Impact Excitation of Hydrogen-like Positive Ions"
Ashok Jain, N. C. Deb, N. C. Sil, and C. D. Lin
J. Phys. B: 21, 3793 (1988).

9. "Density Matrices of the $n=2$ and 3 Manifolds of H Atoms Produced in p-H Collisions at 1-50 keV Impact Energies"
Ashok Jain, C. D. Lin, and W. Fritsch
J. Phys. B: 21, 1545 (1988).
10. "Magnetic Precision Alignment of a Long Horizontal Ultra-Straight Solenoid"
Martin P. Stöckli, C. L. Cocke, J. A. Good, and P. Wilkins
Proceedings of "International Symposium on
Electron Beam Ion Sources and Their Applications"
ed. by Ady Herscovitch, AIP, New York (1988) p. 281.
11. "The KSU-CRYEBIS Program"
Martin P. Stöckli, C. L. Cocke, and P. Richard
Proceedings of "International Symposium on Electron Beam
Ion Sources and Their Applications"
ed. by Ady Herscovitch, AIP, New York (1988) p. 115.
12. "Auger and Radiative Deexcitation Rates and Energies of $3\ell 3\ell'$ States of Helium-like Argon and Silicon"
K. R. Karim and C. P. Bhalla
Physica Scripta Vol. 38, 795 (1988).
13. "Multiple Ionisation of Rare Gases by High-Energy Uranium Ions"
H. Berg, R. Dorner, C. Kelbch, S. Kelbch, J. Ullrich,
S. Hagmann, P. Richard, H. Schmidt-Böcking, A. S. Schlachter,
M. Prior, H. J. Crawford, J. M. Engelage, I. Flores,
D. H. Lloyd, J. Pedersen, and R. E. Olson
J. Phys. B 21, 3929 (1988).
14. "State-Selective Single- and Double-Electron Capture by Ar^{4+} and Ar^{5+} Ions from Rare-Gas Atoms"
E. Y. Kamber
J. Phys. B 21, 4185 (1988).
15. "Correlated Electron Capture in the Impact Parameter and Final Projectile Charge-State Dependence of ECC Cusp Production in $0.53 \text{ MeV u}^{-1} \text{F}^{8+} + \text{Ne}$ "
A. Skutlartz, S. Hagmann, and H. Schmidt-Böcking
J. Phys. B 21, 3609 (1988).
16. "Non-Franck-Condon Transitions in Two-Electron Capture from D_2 by Low-Energy, Highly Charged Ar Projectiles"
J. P. Giese, C. L. Cocke, W. T. Waggoner, J.O.K. Pedersen,
E. Y. Kamber, and L. N. Tunnell
Phys. Rev. A 38, 4494 (1988).

17. "Multiple-Electron Capture Processes by Multiply Charged Ions from Rare-Gas Atoms at Low Velocities"
E. Y. Kamber, W. G. Hormis, J. B. Hasted, A. G. Brenton, and J. H. Beynon
J. Phys. B 21, 3423 (1988).
18. "Strong Orientation Effects Observed in the δ -Electron Emission Probability in Fast Ion-Atom Collisions"
A. Skutlartz, S. Hagmann, C. Kelbch, and H. Schmidt-Böcking
Physica Scripta T22, 307 (1988).
19. "Ionization of Helium by Fast, Highly-Charged Projectiles"
I. Ben-Itzhak and J. H. McGuire
Phys. Rev. A 38, 6422 (1988).
20. "Electron Capture at High Velocities"
J. H. McGuire
Indian J. Phys. 62B, 261 (1988).
21. "Multiple-Electron Capture in Close Nearly Symmetric Ion-Atom Collisions"
A. S. Schlachter, E. M. Bernstein, M. W. Clark, R. D. DuBois, W. G. Graham, R. H. McFarland, T. J. Morgan, D. W. Mueller, K. R. Stalder, J. W. Stearns, M. P. Stockli, and J. A. Tanis
J. Phys. B 21, L291 (1988).
22. "Enhancement of Radiative Auger Emission in Lithium-like $_{23}\text{V}^{20+}$ Ions"
E. M. Bernstein, M. W. Clark, K. H. Berkner, W. G. Graham, R. H. McFarland, T. J. Morgan, A. S. Schlachter, J. W. Stearns, M. P. Stöckli, and J. A. Tanis
J. Phys. B 21, L509 (1988).
23. "Orientation-Dependent Atomic Model for Electron Transfer in Ion-Molecule Collisions: Applications to $\text{H}^+ + \text{H}_2$ and $\text{He}^{2+} + \text{H}_2$ "
R. Shingal and C. D. Lin
Phys. Rev. A 40, 1302 (1989).
24. "State-Selective Double-Electron Capture in $\text{He}^{2+} + \text{He}$ Collisions at Intermediate Impact Energies"
Ashok Jain, C. D. Lin, and W. Fritsch
Phys. Rev. A 39, 1741 (1989).
25. "Orientation and Alignment of Collisionally Excited Atomic States"
C. D. Lin, R. Shingal, A. Jain, and W. Fritsch
Phys. Rev. A 39, 4455 (1989).

26. "Theoretical Studies of Electron Capture in $H^+ + H_2$ Collisions"
R. Shingal and C. D. Lin
J. Phys. B: 22, L659 (1989).
27. "Adaptation of Dependex Fittings to International Standards Organization Fittings"
Martin P. Stöckli and Dave Hill
J. Vac. Sci. Technol. A 7, 3124 (1989).
28. "A Zero-Degree Tandem Electron Spectrometer and Rydberg Analyzer for Projectile Electron Studies in Ion-Atom Collisions"
D. H. Lee, T.J.M. Zouros, J. M. Sanders, J. L. Shinpaugh, T. N. Tipping, S. L. Varghese, B. D. DePaola and P. Richard
Nucl. Instrum. & Methods B40/41, 1229 (1989).
29. "Coulomb Explosion of D_2 Following Capture and Ionization by Fast O^{8+} Ions"
S. Cheng, E. Y. Kamber, C. L. Cocke, and S. L. Varghese
Nucl. Instrum. & Methods B40/41, 47 (1989).
30. "Investigation of Internuclear Axis Alignment with Projectile Direction in Recoil Ion Production from Ion-Molecule Collisions"
S. L. Varghese, C. L. Cocke, S. Cheng, E. Y. Kamber, and V. Frohne
Nucl. Instrum. & Methods B40/41, 266 (1989).
31. "Charge Multiplication via Auger Decay of L Vacancies in the Production of Highly Charged Ar Ions by Collisions with 1-MeV/amu O^{9+} and F^{9+} "
O. Heber, G. Sampoll, B. B. Bandong, R. J. Maurer, E. Moler, R. L. Watson, I. Ben-Itzhak, J. L. Shinpaugh, J. M. Sanders, L. Hefner, and P. Richard
Phys. Rev. A 39, 4898 (1989).
32. "Resonant Transfer and Excitation in Collisions of Li-like Fe^{6+} and Ca^{17+} with Light Targets"
C. P. Bhalla and K. R. Karim
Phys. Rev. A 39, 6060 (1989).
33. "Lifetimes of Be-like Levels of Argon and Titanium"
C. P. Bhalla, K. R. Karim and M. Wilson
Nucl. Instrum. & Methods B40/41, 369 (1989).
34. "Calculation of Total Dielectronic Recombination Rate Coefficient for Heliumlike Iron"
K. R. Karim and C. P. Bhalla
Nucl. Instrum. & Methods B40/41, 366 (1989).

35. "Dielectronic Recombination Rate Coefficient for some Selected Ions in the Helium Isoelectronic Sequence"
K. R. Karim and C. P. Bhalla
Phys. Rev. A 39, 3548 (1989).
36. "Dynamics of Inclusive Multi-Electron Emission in Charge Transfer Dominated Highly Charged Ion Atom Collisions"
B. Kraessig, A. Gonzalez, R. Koch, T. Quinteros,
A. Skutlartz, and S. Hagmann
Journal De Physique, Colloque C1-50, (1989).
37. "Projectile 1s→2p Excitation Due to Electron-Electron Interaction in Collisions of O^{5+} and F^{6+} Ions with H_2 and He Targets"
T.J.M. Zouros, D. H. Lee, and P. Richard
Phys. Rev. Letters 62, 2261 (1989).
38. "Kansas State University Accelerator Laboratory Upgrade"
P. Richard
Nucl. Instrum. & Methods 3B40/41, 1 (1989).
39. "High Resolution Studies of Electron Capture and Excitation by O^0 Projectile Electron Spectroscopy"
T.J.M. Zouros, D. H. Lee, J. M. Sanders, J. L. Shinpaugh, T. N. Tipping, S. L. Varghese, and P. Richard
Nucl. Instrum. & Methods B40/41, 17 (1989).
40. "The KSU CRYEBIS"
Martin P. Stöckli, J. Arianer, C. L. Cocke and P. Richard
Nucl. Instrum. & Methods B40/41, 1020 (1989).
41. "Angular Distributions for Ionization on He and D_2 by Fast Protons"
E. Y. Kamber, C. L. Cocke, S. Cheng, S. L. Varghese,
and J. H. McGuire
Nucl. Instrum. & Methods B40/41, 92 (1989).
42. "Electron Capture into Excited States by Ar^{5+} Ions from He and Ne"
E. Y. Kamber
Nucl. Instrum. & Methods B40/41, 13 (1989).
43. "Low Divergence Low Energy Recoil Ion Source"
T. J. Gray, I. Ben-Itzhak, N. B. Malhi, V. Needham,
K. Carnes, and J. C. Legg
Nucl. Instrum. & Methods B40/41, 1049 (1989).

44. "Studies of High Charge State Rydberg Ions"
B. D. DePaola, W. J. Axmann, R. Parameswaran, D. H. Lee, T.J.M. Zouros, and P. Richard
Nucl. Instrum. & Methods B40/41, 187 (1989)
45. "RTE with Li Vapor Target"
R. Parmeswaran, W. J. Axmann, T.J.M. Zouros, and B. D. DePaola
Nucl. Instrum. & Methods B40/41, 158 (1989)
46. "Simultaneous Electron Capture and Target Ionization in Bare-Fluorine-Helium Collisions"
J. L. Shinpaugh, J. M. Sanders, T. N. Tipping, D. H. Lee, T.J.M. Zouros, P. Richard, J. M. Hall, and H. Schmidt-Böcking
Nucl. Instrum. & Methods B40/41, 36 (1989).
47. "Simple Correlation in Atomic Collisions"
J. H. McGuire, N. C. Deb, O. L. Weaver, T. Ishihara, L. Kocbach, and T. Mukoyama
Nucl. Instrum. & Methods B40/41, 340 (1989).
48. "Recoil Distribution in Particle Transfer"
J. H. McGuire, J. C. Straton, W. J. Axmann, T. Ishihara, and E. Horsdal
Phys. Rev. Letters 62, 2933 (1989).
49. "Angular Distributions of Fast Protons in Ionizing Collisions with He, D₂, and Ne Targets"
C. L. Cocke, E. Y. Kamber, S. Cheng, and S. L. Varghese
Nucl. Instrum. and Methods B42, 545 (1989).
50. "Angular Differential Cross Sections in Low Energy Charge Exchange Collisions"
C. L. Cocke
Journal De Physique C1, 19 (1989).
51. "Impact-Parameter Treatment of High-Velocity Electron Capture from Diatomic Molecules at Fixed Orientation"
Y. D. Wang, J. H. McGuire, and R. D. Rivarola
Phys. Rev. A 40, 3673 (1989).
52. "State-Selective Observation of Resonant Transfer Excitation in Collisions of F⁶⁺ with He and H₂ Targets"
T.J.M. Zouros, D. H. Lee, P. Richard, J. M. Sanders, J. L. Shinpaugh, S. L. Varghese, K. R. Karim, and C. P. Bhalla
Phys. Rev. A 40, 6246 (1989).

53. "Vacuum Limits of an Economical, O-Ring Sealed, Versatile Motion Feedthrough"
Martin P. Stöckli
J. Vac. Sci. Technol. A 7, 3377 (1989).
54. "Observation of Electron-Electron Interaction in Collisions of O^{5+} Ions with H_2 Targets"
T.J.M. Zouros, D. H. Lee, and P. Richard
XVI ICPEAC, Book of Invited Papers (1989).
55. "Proposed Measurements of Dielectronic Recombination Using the Indiana Cooler Facility"
J. A. Tanis, E. M. Bernstein, S. Chantrenne, M. W. Clark, S. Datz, P. F. Dittner, C. C. Foster, W. G. Graham, W. W. Jacobs, J.B.A. Mitchell, J. R. Mowat, D. Schneider, and M. P. Stöckli
Nucl. Instrum. & Methods B43, 290 (1989).
56. "Test of Predicted $\Delta n \geq 1$ L-Shell Dielectronic-Recombination Cross Sections"
E. M. Bernstein, M. W. Clark, J. A. Tanis, W. T. Woodland, K. H. Berkner, A. S. Schlachter, J. W. Stearns, R. D. DuBois, W. G. Graham, T. J. Morgan, D. W. Mueller, and M. P. Stöckli
Phys. Rev. A 40, 4085 (1989).
57. "Close Encounters of the Multiple-Capture Kind: Ca Ions in Ar"
A. S. Schlachter, J. Stearns, K. H. Berkner, E. M. Bernstein, M. W. Clark, R. D. DuBois, W. G. Graham, T. J. Morgan, D. W. Mueller, M. P. Stöckli, J. A. Tanis, and W. T. Woodland
Nucl. Instrum. & Methods B40/41, 21 (1989).
58. "Dynamics of Inclusive Multi-Electron Emission in Charge Transfer Dominated Highly Charged Ion Atom Collisions"
B. Kraessig, A. Gonzalez, R. Koch, T. Quinteros, A. Skutlartz, and S. Hagmann
Journal De Physique C1, C1-159 (1989).
59. "Ionisation and Electron Transfer in $He^{2+} + H(1s)$ Collisions"
R. Shingal and C. D. Lin
J. Phys. B: 22, L445 (1989).
60. "Two-Electron Processes in $He^{2+} + He$ Collisions at Intermediate Impact Energies"
C. D. Lin, R. Shingal, Ashok Jain, and W. Fritsch
Journal de Physique C1, 93 (1989).

61. "Charge-State Dependence of Elastic Scattering Cross Sections at Large Angles Between Electrons and Multiply Charged Ions"
R. Shingal, Z. Chen, K. R. Karim, C. D. Lin, and C. P. Bhalla
J. Phys. B 23, L637 (1990)
62. "Differential Cross Sections for Multiple Ionization of Ne and Ar in Collisions with Fast Protons"
E. Y. Kamber, C. L. Cocke, S. Cheng, and S. L. Varghese
Phys. Rev. A 41, 150 (1990).
63. "Dielectronic Recombination on Heliumlike Argon"
R. Ali, C. P. Bhalla, C. L. Cocke, and M. Stöckli
Phys. Rev. Letters 64, 633 (1990).
64. "The KSU Cryogenic Electron-Beam Ion Source"
Martin P. Stöckli, C. L. Cocke, and P. Richard
Rev. Sci. Instrum. 61, 242 (1990).
65. "Autoionization Rates for Selected Double-Rydberg States of Barium"
C. P. Bhalla, K. R. Karim, and M. Wilson
Phys. Rev. A 41, 1715 (1990).
66. "High-Velocity Limits for the Ratio of Double to Single Ionisation of Helium by Projectiles with Electrons"
Y. D. Wang, Jack C. Straton, J. H. McGuire, and R. D. DuBois
J. Phys. B 23, L133 (1990).
67. "Anomalous q Dependence of Binary Encounter Electron Production in Energetic Collisions of F^{q+} ($q = 3-9$) with He and H_2 Targets"
P. Richard, D. H. Lee, T.J.M. Zouros, J. M. Sanders, and J. L. Shinspaugh
J. Phys. B 23, L213 (1990).
68. "Binary-Encounter Electrons Observed at 0° in Collisions of 1-2 MeV/amu H^+ , C^{6+} , N^{7+} , O^{8+} , and F^{9+} Ions with H_2 and He Targets"
D. H. Lee, P. Richard, T.J.M. Zouros, J. M. Sanders, J. L. Shinspaugh, and H. Hidmi
Phys. Rev. A 41, 4816 (1990).
69. "Angular Distribution of Auger Electrons and Photons in Resonant Transfer and Excitation in Collisions of Ions with Light Targets"
C. P. Bhalla
Phys. Rev. Letters 64, 1103 (1990).

70. "Effects of Alignment and Interference in Resonant Transfer and Excitation for F^{6+} and O^{5+} Collisions with H_2 in 0° Auger Measurements"
T.J.M. Zouros, C. P. Bhalla, D. H. Lee, and P. Richard
Phys. Rev. A 42, 678 (1990).
71. "Formation of Doubly Charged Molecular Ion Ne_2^{2+} in Sub-MeV Stripping Collision $Ne_2^{2+} + Ar \rightarrow Ne_2^{2+}$ "
I. Ben-Itzhak, I. Gertner, D. Bortman, and D. Zajfman
Phys. Rev. A 41, 6548 (1990).
72. "High-Resolution State-Selective Study of Transfer with Excitation in the $F^{8+} + H_2$ System"
B. D. DePaola, R. Parameswaran, and W. J. Axmann
Phys. Rev. A 41, 6533 (1990).
73. "Measurement of Electron Capture and Ionization Cross Sections for D_2 in Collision with Fast O^{8+} Ions"
S. Cheng, C. L. Cocke, E. Y. Kamber, C. C. Hsu, and S. L. Varghese
Phys. Rev. A 42, 214 (1990).
74. "Excitation and Ionization in Ion-Atom Collisions"
P. Richard
X-Ray and Inner-Shell Processes, AIP Proceedings, ed. T. A. Carlson, M. O. Krause, and S. T. Manson, p. 315 (1990).
75. "Satellite Spectra for High-Lying Resonance States of Heliumlike Chromium and Nickel"
K. R. Karim and C. P. Bhalla
Phys. Rev. A 42, 3555 (1990).
76. "Observation of Strong Directional Out-of-Plane Scattering in Multiple Ionising Ion-Atom Collisions"
A. D. Gonzalez, S. Hagmann, T. B. Quinteros, B. Krassig, R. Koch, A. Skutlartz, and H. Schmidt-Böcking
J. Phys. B 23, L303 (1990).
77. "A Probe for Real-Time Images of Particle Beams and Their Analyses in a Merged-Beams Apparatus"
J. L. Forand, C. Timmer, E. Wahlin, B. D. DePaola, G. H. Dunn, D. R. Swenson, and K. Rinn
Rev. Sci. Instrum. 61, 3372 (1990).
78. "State-Selective Nonresonant Transfer Excitation in 50-400-keV $^3He^+ + H_2$ and He Collisions"
Ashok Jain, R. Shingal, T.J.M. Zouros
Phys. Rev. A 43, 1621 (1991)

79. "Calculations of Two-Electron Transition Cross Sections Between Fully Stripped Ions and Helium Atoms"
R. Shingal and C. D. Lin
J. Phys. B 24, 251 (1991)
80. "Variation of Satellite Intensity Factors with n for $1s^2\epsilon\ell \rightarrow 1s2pn\ell \rightarrow 1s^2n\ell$ Dielectronic-Recombination Processes in Heliumlike Ions"
K. R. Karim and C. P. Bhalla
Phys. Rev. A 43 615 (1991).
81. "Dielectronic Satellite Spectra of Hydrogenlike Iron from the Tokamak Fusion Test Reactor"
V. Decaux, M. Bitter, H. Hsuan, S. von Goeler, K. W. Hill, R. A. Hulse, G. Taylor, H. Park and C. P. Bhalla
Phys. Rev. A 43, 228 (1991).
82. "Strong Dependence of Zero Degree Binary Encounter Electron Production on the Initial and Final Charge State"
T. B. Quinteros, A. D. Gonzalez, O. Jagutzki, A. Skutlartz,
D. H. Lee, S. Hagmann, P. Richard, C. Kelbch, S. L. Varghese,
and H. Schmidt-Böcking
J. Phys. B 24, 1377 (1991).
83. "Resonant Transfer and Excitation in Collisions of C^{5+} with H_2 and He Targets"
R. Parameswaran, C. P. Bhalla, B. P. Walch, and B. D. DePaola
Phys. Rev. A 43, 5929 (1991).
84. "Double Excitation of Helium by Fast Particles of Charge Z "
J. H. McGuire and Jack C. Straton
Phys. Rev. A 43, 5184 (1991).
85. "The Physics of Electron Beam Ion Sources"
Martin P. Stöckli and C. L. Cocke
Nucl. Instruments and Methods B56/57, 239 (1991).
86. "Single Electron Capture by High Velocity Bare and One-Electron Projectiles in Collisions with Molecular Hydrogen"
J. M. Sanders, Tracy N. Tipping, James Hall, J. L. Shinpaugh, D. H. Lee and Patrick Richard
Nucl. Instruments and Methods B56/57, 104 (1991).
87. "Scattering of Molecular Hydrogen at Fixed Orientation"
Y. D. Wang and J. H. McGuire
Nucl. Instruments and Methods B56/57, 300 (1991).

88. "Angular Distribution and Linear Polarization of Photons in Dielectronic Recombination of Heliumlike Ions"
C. P. Bhalla, K. R. Karim, and M. Wilson
Nucl. Instruments and Methods B56/57, 324 (1991).
89. "Theory of Angular Distributions in Resonant Transfer and Excitation"
C. P. Bhalla
Nucl. Instruments and Methods B56/57, 140 (1991).
90. "Electron Capture and Excitation Studied by State-Resolved KLL Auger Measurement in 0.25-2 MeV/u $F^{7+}(1s^2\ ^1S, 1s2s\ ^3S) + H_2/He$ Collisions"
D. H. Lee, P. Richard, J. M. Sanders, T.J.M. Zouros, J. L. Shinpaugh, and S. L. Varghese
Nucl. Instruments and Methods B56/57, 99 (1991).
91. "Dielectronic Recombination in He^+ Ions"
J. A. Tanis, E. M. Bernstein, S. Chantrenne, M. W. Clark, T. Ellison, C. C. Foster, W. G. Graham, W. W. Jacobs, J. R. Mowat, T. Rinckel, A. Ross, D. Schneider, M. P. Stöckli, and N. R. Badnell
Nucl. Instruments and Methods B56/57, 337 (1991).
92. "Effect of Electron-Electron Interaction on Projectile K-Shell Ionization in Energetic Ion-Atom Collisions Studied by 0° Auger Electron Spectroscopy"
T.J.M. Zouros, D. H. Lee, J. M. Sanders, and P. Richard
Nucl. Instruments and Methods B56/57, 107 (1991).
93. "Projectile Electron Loss with a Molecular Hydrogen Target"
W. E. Meyerhof, H.-P. Hülskötter, Qiang Dai, J. H. McGuire, and Y. D. Wang
Phys. Rev. 43, 5907 (1991).
94. "Recoil Ions"
C. L. Cocke and R. E. Olson
Physics Reports 205, No. 4 153 (1991) North-Holland.
95. "Orientation Dependence in Electron Capture to Arbitrary Projectile n States from Molecular Hydrogen"
Y. D. Wang and J. H. McGuire
Phys. Rev. A 44, 367 (1991).
96. "Dielectronic Recombination on and Electron-Impact Excitation of Heliumlike Argon"
R. Ali, C. P. Bhalla, C. L. Cocke, M. Schulz, and M. Stöckli
Phys. Rev. A 44, 223 (1991).

Manuscripts Accepted for Publication

1. "KLL Resonant Transfer Excitation to $F^{6+}(1s2\ell 2\ell')$ Intermediate States"
D. H. Lee, P. Richard, J. M. Sanders, T.J.M. Zouros,
J. L. Shinspaugh, and S. L. Varghese
Accepted for publication in Physical Review A.
2. "X-Ray Emission from Slow Highly Charged Ar Ions Interacting with
a Ge Surface"
M. Schulz, C. L. Cocke, S. Hagmann, M. Stöckli and H.
Schmidt-Böcking
Accepted for publication in Physical Review A.
3. "Recent Experiments on the KSU EBIS"
C. L. Cocke, R. Ali, C. P. Bhalla, M. Stöckli, and M. Schulz
Accepted for publication in Nuclear Instruments and Methods.
4. "Electron-Electron Interactions in Two-Electron Phenomena in
Collisions of Fast Ions with He Atoms"
J. P. Giese and J.O.P. Pedersen
Accepted for publication in Nuclear Instruments and Methods.
5. "RTE Studied in Electron Emission"
B. D. DePaola
Accepted for publication in Nuclear Instruments and Methods.
6. "Contribution of Exchange on Charge-State Dependence of Large Angle
Electron-Ion Elastic Scattering"
C. P. Bhalla and R. Shingal
Accepted for publication in J. Phys. B: Atomic, Molecular
and Optical Physics.
7. "A Simple Apparatus for Demonstration of Gaseous Diffusion"
Roger Key and B. D. DePaola
Accepted for publication in The Physics Teacher.
8. "Recent Experiments on the KSU-CRYEBIS"
M. Schulz, R. Ali, C. L. Cocke, S. Hagmann, M. Stöckli,
and H. Schmidt-Böcking
Accepted for publication in Nuclear Instruments and Methods.

9. "The Status of the Electron Beam Ion Sources"
Martin P. Stöckli
Accepted for publication in Z. Phys. D.
10. "X Rays from Electron Bombardment of Heliumlike Argon"
R. Ali, C. P. Bhalla, C. L. Cocke, M. Schulz, and M. Stöckli
Accepted for publication in Z. Phys. D.
11. "K-X-Ray and Auger Emission from H-like Argon Ions"
M. Schulz, C. L. Cocke, M. Stöckli, S. Hagmann, and H. Schmidt-Böcking
Accepted for publication in Physical Review A.
12. "A Simple, Economical Vacuum Valve Control- and Protection System for a Charged Particle Beam Switching Station"
Martin P. Stöckli and Paul E. Gibson
Accepted for publication in J. Vac. Sci. Technology.
13. "Space and Time Correlation in High Velocity Multiple Electron Transitions"
J. H. McGuire and Jack C. Straton
Accepted for publication in Nuclear Instruments and Methods.
14. "Multiple Electron Excitation Ionization, Transfer in High Velocity Atomic and Molecular Collisions"
J. H. McGuire
Accepted for publication in Advances in Atomic, Molecular and Optical Physics 29, 217 (1991).
15. "Review of Some Aspects of Multiply Ionizing Collisions Involving Heavy Ion Projectiles"
C. L. Cocke
Accepted for publication in Proceedings of Workshop on High-Energy Ion-Atom Collision Processes, Debrecen.
16. "Double Excitation of Helium by Fast Protons and Antiprotons"
Jack C. Straton
Accepted for publication in Nucl. Instruments and Methods.
17. Abnormal Behavior of Zero Degree δ -Electron emission of the Projectile Ion Change State"
O. Jagutzki, S. Hagmann, H. Schmidt-Böcking, R. Olson, D. Schultz, R. Dorner, R. Koch, A. Skutlartz, A. González, T. Quinteros, Ch. Kelbch, P. Richard
Accepted for publication in J. Phys. B 24, 2579 (1991).

Manuscripts Submitted for Publication

1. "A Simple Theory of Resonant Transfer and Excitation Containing Impact Parameter Dependence"
B. D. DePaola and L. Weaver
Submitted to Physical Review Letters, May 1991.
2. "Production of Hydrogen Rydberg States and Quantum Beats in Collisions of Protons with Argon"
B. D. DePaola, C. H. Chang, and C. C. Hsu
Submitted to International Journal of PIXE, May 1991.
3. "Recent Trends in Ion-Atom Collisions"
C. L. Cocke
Submitted to Proceedings of International Conference on the Physics of Electron and Atomic Collisions.
4. "Close-Coupling Study of Electron Excitation in 1-300 keV/u He^{2+} - H Collisions"
W. Fritsch, R. Shingal and C. D. Lin
Submitted to Phys. Rev. A.
5. "State-Selective Double Capture in Collisions of Bare Ions with Helium Atoms at Low Energies: I. Total Cross Sections"
Z. Chen, R. Shingal and C. D. Lin
Submitted to J. Phys. B.
6. " $\text{H}(n=2 \text{ and } 3)$ Density Matrices Produced in Proton - Helium Collision at Intermediate Energies"
R. Shingal and C. D. Lin
Submitted to J. Phys. B.
7. "Measurement of the Ratio of L_{III}/L_I Ionization of Yb by Heavy Ions of Impact Energy 0.5-3 MeV/amu"
N. B. Malhi and T. J. Gray
Submitted to Phys. Rev. A.
8. "Electron Capture and Target Ionization in Collisions of Bare Projectile Ions Incident on Helium"
J. L. Shinpaugh, J. M. Sanders, J. M. Hall, D. H. Lee, H. Schmidt-Böcking, T. N. Tipping, T.J.M. Zouros, and P. Richard
Submitted to Phys. Rev. A.
9. "Coincidence Time-of-Flight Studies of Molecular Fragmentation,"
I. Ben-Itzhak, S. G. Ginther, and K. Carnes
Submitted to Nucl. Instrum. and Methods

Abstracts for Grant Period

August 15, 1988 - June 14, 1991

Tenth International Conference on the Application of Accelerators in Research and Industry, Denton, TX (November 7-9, 1988).

1. "Autoionization Rates for Selected Excited States of Neutral Barium with One Rydberg Electron"
M. Wilson, C. P. Bhalla, and K. R. Karim
2. "Simultaneous Electron-Capture and Target Ionization in Bare Fluorine Plus Helium Collisions"
J. L. Shinpaugh, J. M. Sanders, T. N. Tipping, D. H. Lee, T.J.M. Zouros, P. Richard, J. Hall, and H. Schmidt-Böcking
3. "Multielectron Emission in Charge Transfer Dominated Ion Atom Collisions"
S. Hagmann, A. Gonzalez, R. Kioch, B. Kraessig, T. Quinteros, H. Schmidt-Böcking, and A. Skutlartz
(Invited)
4. "A Zero-Degree Tandem Electron Spectrometer and Rydberg Analyzer for Projectile Electron Studies in Ion-Atom Collisions"
D. H. Lee, T.J.M. Zouros, J. M. Sanders, J. L. Shinpaugh, T. N. Tipping, S. L. Varghese, B. D. DePaola, and P. Richard
5. "High Resolution Studies of Electron Capture and Excitation by Zero Degree Projectile Electron Spectroscopy"
T.J.M. Zouros (Invited)
6. "Kansas State University Accelerator Laboratory Upgrade"
Pat Richard (Invited)
7. "Low Beam Divergence Low Energy Recoil Ion Source"
T. J. Gray, I. Ben-Itzhak, N. B. Malhi, V. Needham, K. Carnes, and J. C. Legg
8. "The KSU CRYEBIS"
Martin P. Stöckli, C. L. Cocke, and P. Richard
9. "Multiply Charged Ions in Collision with Atoms"
C. I. Cocke (Invited)

10. "Angular Distributions for Ionization of He and D₂ by Fast Protons"
E. Y. Kamber (Invited)
11. "Correlation in Atomic Scattering"
J. H. McGuire (Invited)
12. "RTE with Li Vapor Target"
R. Parameswaran (Invited)
13. "Electron Capture into Excited States by Ar⁴⁺ and Ar⁵⁺ Ions from Rare Gas Atoms"
E. Y. Kamber
14. "Studies of High Charge State Rydberg Ions"
B. D. DePaola, W. J. Axmann, C. Parameswaran, D. H. Lee, T. J. Zouros, and P. Richard
15. "Coulomb Explosion of D₂ Following Capture and Ionization by Fast O⁸⁺ Ions"
S. Cheng, E. Y. Kamber, C. L. Cocke, and S. L. Varghese
16. "Investigation of Internuclear Axis Alignment with Projectile Direction in Recoil Ion Production from Ion-Molecule Collision"
S. L. Varghese, C. L. Cocke, S. Cheng, E. Y. Kamber, and V. Frohne
17. "Lifetime of Be-like Levels of Ar⁺¹⁴ and Ti⁺¹⁸"
C. P. Bhalla, K. R. Karim, and C. P. Bhalla
18. "Calculation of Total Dielectronic Recombination Rate Coefficient for Heliumlike Iron"
K. R. Karim and C. P. Bhalla
19. "Single Electron Capture by 0.5-1.5 MeV/u F⁹⁺ and F⁸⁺ on Hydrocarbon Gases"
T. R. Dillingham, B. M. Doughly, J. M. Hall, T. N. Tipping, and J. L. Shinpaugh

Annual Division of Nuclear Chemistry and Technology, American Chemical Society Meeting, Dallas, TX (9-14 April 1989).

20. "Accelerator-Based Recoil Molecular Ion Studies"
Tom J. Gray

21. "Translational Energy Spectroscopy of Low Energy Capture by Multiply-Charged Ions from Atomic and Molecular Targets"
E. Y. Kamber and C. L. Cocke

Annual Meeting of Division of Atomic, Molecular, and Optical Physics, Windsor, Ontario, Canada (17-19 May 1989).

22. "Resonant Transfer and Excitation in Collisions of Li-like F^{6+} and Ca^{17+} with Light Targets"
C. P. Bhalla and K. R. Karim
23. "Energy Non-Conserving Ridges in Particle Transfer"
J. H. McGuire and J. C. Straton
24. "Ionization of He, D_2 , and Ne by Fast Protons Scattered Through Large Angles"
C. L. Cocke (Invited)
25. "An Orientation-Dependent Atomic Model for Electron Transfer in Ion-Molecule Collisions"
R. Shingal and C. D. Lin
26. "The KSU-CRYEBIS Status Report"
M. P. Stöckli, C. L. Cocke, and P. Richard
27. "Binary Encounter Electrons Observed at Zero-Degrees in Collisions of Highly Charged Fast Ions with H_2 and He Targets"
P. Richard, D. H. Lee, T.J.M. Zouros, J. M. Sanders, J. L. Shimpugh, and T. N. Tipping
28. "Observation of Inner-Shell Projectile Electron Excitation by a Target Electron in Energetic Collisions of Li-like Ions with H_2 and He Targets"
T.J.M. Zouros, D. H. Lee, and P. Richard
29. "Electron Capture from Diatomic Molecules at Fixed Orientation"
Y. D. Wang, J. H. McGuire, and R. D. Rivarola

Annual Spring Meeting of the American Physical Society, Baltimore, Maryland (1-4 May 1989).

30. "Theoretical Developments in Collisions of Atoms and Antimatter"
J. H. McGuire (Invited)

International Conference on Ion Sources, Berkeley, California (10-14 July 1989).

31. "The KSU-CRYEBIS"
Martin P. Stöckli, C. L. Cocke, and P. Richard

International Conference on the Physics of Electron and Atomic Collisions, New York York (26 July-1 August 1989).

32. "Scattering Angle Dependence of Kinetic Energy of Recoil Ions in 0.53 MeV/u $F^{8+} + Ne$ "
A. D. Gonzalez, S. Hagmann, R. Koch, B. Kraessig, T. B. Quinteros, and A. Skutlartz
33. "Coincident δ -Electron Spectra in Multi-Electron Ionization Events of High Multiplicity"
B. Kraessig, A. D. Gonzalez, S. Hagmann, and T. B. Quinteros
34. "Inclusive Multi-Electron Production Probabilities in Charge Transfer Dominated Ion-Atom Collisions"
T. Quinteros, A. Gonzalez, S. Hagmann, R. Koch, B. Kraessig, and A. Skutlartz
35. "Differential Cross Sections for Multiply Ionizing Proton-Ne and Ar Collisions"
E. Y. Kamber, C. L. Cocke, S. Cheng, and S. L. Varghese
36. "Measurement of Electron Capture and Ionization Cross Sections of D_2 in Collision with Fast O^{3+} Ions"
S. Cheng, C. L. Cocke, E. Y. Kamber, C. C. Hsu, S. L. Varghese, and R. Shingal
37. "State-Selective Charge Stripping Processes of Ar^{2+} and Kr^{2+} Ions in Collisions with Rare-Gas Atoms"
E. Y. Kamber and A. G. Brenton
38. "Observation of Electron-Electron Interaction in Collisions of O^{5+} Ions with H_2 and He Targets"
T.J.M. Zouros, D. H. Lee, and P. Richard
39. "The KSU-CRYEBIS"
Martin P. Stockli, C. L. Cocke, and P. Richard
40. "Resonant Transfer and Excitation in Collisions of F^{8+} with Light Targets"
C. P. Bhalla

41. "Autoionization Rates for Selected Double-Rydberg States of Barium"
C. P. Bhalla, M. Wilson, and K. R. Karim
42. "Charge Transfer in $H^+ + H_2$ and $He^{++} + H_2$ Collisions Using an Orientation Dependent Atomic Model"
R. Shingal and C. D. Lin
43. "The Correlated Scattering Propagator"
Jack C. Straton and J. H. McGuire

Annual Meeting of Division of Plasma Physics, Anaheim, California (13-17 November 1989).

44. "Dielectronic Satellite Spectra for Li-like Argon"
C. P. Bhalla, K. R. Karim, and M. Wilson

Annual Meeting of Division of Atomic, Molecular, and Optical Physics, Monterey, California (21-23 May 1990).

45. "Angular Distributions for Single Electron Capture by Ar^{6+} and Ar^{8+} Ions from He"
E. Y. Kamber, C. L. Cocke, S. Cheng, W. Waggoner, and V. Frohne
46. "Double Excitation of He by Protons and Antiprotons"
J. C. Straton and J. H. McGuire
47. "Thomas Peak of the Second Kind"
J. H. McGuire, J. C. Straton and W. J. Axmann
48. "Electron-Ion Collisions Inside the KSU EBIS"
C. L. Cocke (Invited)
49. "Compton Profiles for Excited, Aligned Targets"
B. D. DePaola
50. "High Resolution Investigations of RTEA Cross Sections"
R. Parameswaran, W. J. Axmann, B. P. Walch, and B. D. DePaola
51. "Formation of Doubly Charged Metastable Molecular Ion Ne_2^{2+} in Sub-MeV Stripping Collision $Ne_2^+ + Ar \rightarrow Ne_2^{2+}$ "
I. Ben-Itzhak, I. Gertner, D. Zajfman, and D. Bortman

52. "Angular Distribution of Auger Electrons and Photons in Resonant Transfer and Excitation in Collisions of Ions with Light Targets"
C. P. Bhalla
53. "Variation of Satellite Intensity Factors with n for $1s^2\epsilon\ell \rightarrow 1s2pn\ell \rightarrow 1s_{2n}\ell$ Dielectronic Recombination Processes in Heliumlike Ions"
K. R. Karim and C. P. Bhalla
54. "Observation of Strong Directional Out-of-Plans Scattering in Multiple Ionizing Ion Atom Collisions"
A. D. Gonzalez, S. Hagmann, T. B. Quinteros, B. Krassig,
R. Koch, A. Skutlartz, and H. Schmidt-Böcking
55. "Systematic Studies of the Molecular Properties of Intrashell and Intershell Doubly Excited States of C^{4+} and He"
M. Dunn, Z. Chen, and C. D. Lin
56. "State-Selective Double Capture to Doubly Excited States by Bare Ions from Helium Atoms"
Z. Chen, R. Shingal, and C. D. Lin
57. "Study of the Excited $H(n=2 \text{ and } 3)$ Density Matrix Formed in Proton-Helium Collision at Intermediate Energy"
R. Shingal and C. D. Lin
58. "Effects of Alignment and Interference in 0° Auger Resonant Transfer Excitation (RTEA) for $F^{6+,7+}$ and $O^{5+,7+}$ Collisions with H_2 "
T.J.M. Zouros, H. Hidmi, D. H. Lee, B. DePaola,
C. P. Bhalla, J. Sanders, J. Shinpaugh, and P. Richard
59. "Electron Capture and Target Ionization in Collisions of Bare Projectile Ions Incident on Helium"
J. L. Shinpaugh, J. M. Sanders, T. N. Tipping, D. H. Lee,
T.J.M. Zouros, J. M. Hall, and P. Richard

15th International Conference on X-Ray and Inner-Shell Processes, Knoxville, Tennessee (9-13 July 1990).

60. "Inner-Shell Ionization in Ion-Atom Collisions"
P. Richard (Invited)

12th International Conference on Atomic Physics, Ann Arbor, Michigan (29 July - 3 August 1990).

61. "Dielectronic Recombination in Helium-like Heavy Ions"
R Ali, C. P. Bhalla, C. L. Cocke, P. Richard, and M. P. Stöckli

5th International Conference on Physics of Highly-Charged Ions, Giessen, Germany (September 10-14 1990).

62. "Strong Directional Out-of-Plane Scattering in Multiple Ionizing Highly Charged Ion-Atom Collisions"
A. Gonzalez, S. Hagmann, T. Quinteros, B. Krassig, R. Koch, A. Skutlartz, and H. Schmidt-Böcking
63. "The Status of the Electron Beam Ion Sources"
Martin P. Stöckli (Invited)
64. "X-Rays from Electron Bombardment of Heliumlike Argon"
R. Ali, C. P. Bhalla, C. L. Cocke, M. Schulz, and M. Stöckli
65. "K X-Ray Emission from Highly Charged Ar Projectiles Interacting with a Ge Surface"
M. Schulz, C. L. Cocke, M. Stöckli and S. Hagmann

4th Workshop on High-Energy Ion-Atom Collision Processes, Debrecen, Hungary (17-19 September 1990).

66. " Z_p and q -Dependence of 0^+ Binary Encounter Electrons in 1-2 MeV/u Collisions of Ions with H_2 and He Targets"
T.J.M. Zouros, P. Richard, D. H. Lee, J. M. Sanders, J. L. Shimpagh, and H. Hidmi
67. "Review of Some Aspects of Multiply Ionizing Collisions Involving Heavy Ion Projectiles"
C. L. Cocke (Invited)

11th International Conference on the Application of Accelerators in Research and Industry, Denton, Texas (5-8 November 1990).

67. "Electron Capture by O^{8+} from Aligned Molecular Deuterium"
S. Cheng (Invited)

68. "Electron Capture and Excitation Studied by State-Resolved KLL Auger Measurements in 0.25-2 MeV/u $F^{7+}(1s^{21}S, 1s2s^3S) + H_2/He$ Collisions"
D. H. Lee, P. Richard, T.J.M. Zouros, J. M. Sanders,
J. L. Shinpaugh, and S. L. Varghese
69. "Angular Distribution and Linear Polarization in Dielectronic Recombination of Lithiumlike Nickel"
C. P. Bhalla, K. R. Karim, and M. Wilson
70. "Single Electron Capture by High Velocity Bare and One-Electron Projectiles in Collisions with Molecular Hydrogen"
J. M. Sanders, Tracy N. Tipping, James Hall, J. L. Shinpaugh, D. H. Lee, and Patrick Richard
71. "Transition from the Quantum to a Classical Limit on the Atomic Scale"
J. H. McGuire, Jack C. Straton, Y. D. Wang, and L. O. Weaver
72. "Two Electron Capture in Collisions of Fully Stripped Ions with Helium"
Z. Chen, R. Shingal, and C. D. Lin
73. "Scattering of Molecular Hydrogen at Fixed Orientation"
Y. D. Wang and J. H. McGuire
74. " KL_n ($n=2,3,4$) RTEA Cross Sections for $C^{5+} + H_2$ "
R. Parameswaran, B. P. Walch, and B. D. DePaola
75. "Measurement of the Ratio of L_{III}/L_I Ionization by Fast Heavy Projectiles"
Tom J. Gray and Nabil Malhi
76. "One and Two Electron Transitions in Ion Atom Collisions"
Rajiv Shingal (Invited)
77. "Electron-Electron Interactions in Two Electron Phenomena in Collisions of Fast Ions with He Atoms"
John Giese (Invited)
78. "Space and Time Correlation in High Velocity Multiple Electron Transitions"
J. H. McGuire (Invited)
79. "Recent Experiments on the KSU CRYEBIS"
M. Schulz, R. Ali, C. P. Bhalla, C. L. Cocke, S. Hagmann,
H. Schmidt-Böcking, and M. Stöckli (Invited)

80. "Angular Distribution of Auger Electrons and Photons in Resonant Transfer and Excitation in Collisions of Ions with Light Targets"
C. P. Bhalla (Invited)
81. "Effect of Electron-Electron Interaction on Projectile K-Shell Ionization in Energetic Ion-Atom Collisions Studies by Zero Degree Auger Electron Spectroscopy"
T.J.M. Zouros (Invited)
82. "Kansas State Zero Degree RTEA Experiments"
P. Richard (Invited)
83. "The Physics of Electron Beam Ion Sources"
Martin P. Stöckli (Invited)
84. "RTE Studied in Electron Emission"
B. D. DePaola (Invited)
85. "Double Excitation of Helium by Fast Protons and Antiprotons"
Jack C. Straton (Invited)

Annual DOE Contractors' Meeting, Albuquerque, New Mexico (November 15-16 1990).

86. "Theory for Multiply Charged Ions"
Macdonald Laboratory Group
87. "High Energy Collisions Involving Multiply Charged Ions"
Macdonald Laboratory Group
88. "Low Energy Collisions Involving Multiply Charged Ions"
Macdonald Laboratory Group

International Conference on Physics of Electronic and Atomic Collisions, Australia (July 10-16, 1991)

89. "Comparison of Coherence Parameters of Atomic Excited States Obtained from the CTMC and the Quantal Calculations"
N. Toshima and C. D. Lin
90. "Two-Center Interference Effects in Ion-H₂ Collisions"
Y. D. Wang and J. H. McGuire

91. "Ejected Electron Spectra of Doubly Excited States from Double Capture in Collisions of Bare Ions with Helium Atoms"
Z. Chen, R. Shingal, and C. D. Lin
92. "Long Range Interactions in Collisions Between Protons and H_2^+ Targets
Silvia E. Corchs, J. H. McGuire, Roberto D. Rivarola, and Y. D. Wang
93. "Calculations of Cross Sections for Doubly Excitation of Helium by Fast, Charged Particles"
Jack C. Straton and J. H. McGuire
94. "Interrelationships for High Velocity Limit of Ratios of Cross Sections for Double to Single Transitions in Collisions of Atoms with Charged Particles and Photons"
J. H. McGuire (Invited)
95. "Fokker-Planck Equation in Atomic Scattering"
D. E. Neuenschwander, B. N. Turner, and J. H. McGuire
96. "Observations of the Recoil Ion Angular and Momentum Distributions in the 1 MeV/u $F^{9+} + Ne$ Collision System"
V. Frohne, C. L. Cocke, and S. Cheng
97. "Investigations of Binary Encounter Electrons and the Process of Resonant Transfer and Excitation (RTE) with a Li Vapor Target"
R. Parameswaran, S. Maleki, B. P. Walch, and B. D. DePaola
98. "Electron Capture by O^{8+} from Aligned Molecular Deuterium"
S. Cheng, C. L. Cocke, V. Frohne, E. Y. Kamber, and S. L. Varghese
99. "Recent Trends in Ion-Atom Collisions"
C. L. Cocke (Invited)

Annual Meeting of the Division of Atomic, Molecular, and Optical Physics,
Washington, D. C. (22 April 1991).

99. "Electron-Electron Interaction in Projectile $1s \rightarrow 2p$ Excitation for Collisions of O^{5+} , F^{6+} , with H_2 and He"
D. H. Lee, P. Richard, T.J.M. Zouros, and J. M. Sanders

100. "Ionization and Electron Capture by O^{8+} from Aligned Molecular Deuterium"
S. Cheng, C. L. Cocke, V. Frohne, E. Y. Kamber, and
S. L. Varghese
101. "Dissociation of H_2^+ Following Single Electron Capture from H_2 by Heavy Ion Projectiles"
Y. D. Wang and J. H. McGuire
102. "Molecular Fragmentation in Collisions with Fast Highly Charged Ions"
I. Ben-Itzhak, S. G. Ginther, and K. Carnes
103. "A Simple RTE Theory Containing Impact Parameter Dependence"
B. D. DePaola and O. L. Weaver, Jr.
104. "H(n=2) Excitation in Collisions of Alpha Particles with Ground State Hydrogen Atom"
R. Shingal and W. Fritsch
105. "Recoil Ion Velocity-Space Distributions for 1 MeV/amu F^{+9} on Ne"
V. Frohne, R. Ali, S. Cheng, and C. L. Cocke
106. "Double Excitation of Helium by Fast Projectiles of Charge Z"
J. H. McGuire and J. C. Straton
107. "Zero $0^+ \delta$ -Electron Emission Cross Section for Pure Ionization Condition in 0.53 MeV/u Cu^{9+} ($q_1=5+, 15+$) on He Collisions"
O. Jagutzki, S. Hagmann, H. Schmidt-Böcking, R. Dörner, R. Koch, A. Gonzalez, T. Quinteros, Ch. Kelbch, A. Skutlartz, R. Olson, and P. Richard
108. "L-Subshell Ionization of Yb and Au by Fast Heavy Ions"
Nabil B. Malhi and Tom J. Gray
109. "Electron Correlation and Shape of Doubly Excited States of Atoms in External Static Electric Fields"
Z. Chen and C. D. Lin
110. "Double Capture and Angular Distributions of Ejected Electrons in Collisions of C^{5+} and N^{7+} with He"
Z. Chen, R. Shingal, and C. D. Lin
111. "Dielectronic Satellite Spectra of High-Lying Resonance States of Heliumlike Si, Ca, and Ti"
C. P. Bhalla, K. R. Karim, M. Ruesink, and S. Biel

112. "Variation of Dielectronic Satellite Intensity Factors with n for
Selected Hydrogenlike Ions"
K. R. Karim, M. Ruesink, S. Biel, and C. P. Bhalla
113. "A Simple RTE Theory Containing Impact Parameter Dependence"
B. D. DePaola and O. L. Weaver

International Workshop on Auger Spectroscopy and Electronic Structure, Malmö,
Sweden (4-6 September 1991).

114. "Theory of Angular Distribution of Auger Electrons in Resonant
Transfer and Excitation"
C. P. Bhalla

8. Financial Report

It is anticipated that there will be no unexpended funds for the current funding period of February 15, 1991 to February 14, 1992 (FY91).

END

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01/30/92**

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