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PROGRESS REPORT FOR ATOMIC AND NUCLEAR RESEARCH WITH ACCELERATORS

Since 1 October 1973, the accelerator research program at Kansas State University has been an active and productive endeavor. During this time, the research programs in Atomic Physics and Nuclear Physics have investigated a very large number of interesting physics problems with many exciting results.

During the twelve month period from 1 October 1973 to 1 October 1974 the accelerator dome was charged for a total of 5,080 hours in the course of experiments. In addition, the accelerator was out of operation for preventive and routine maintenance or repair of a fault for a total of 545 hours. Of the experimental acceleration time, only 16 percent was devoted to accelerating protons and the rest was devoted to accelerating heavy ions for use in experiments. These heavy ions included, ^{11}B , ^{12}C , ^{13}C , ^{14}N , ^{16}O , ^{19}F , ^{28}Si , ^{32}S , ^{35}Cl , ^{37}Cl , and I .

PRINCIPAL INVESTIGATOR

James C. Legg was Principal Investigator during the full period being reported on. The Principal Investigator devoted 40 per cent of his time to the project during the academic year and full time during the summer months of 1974. He will continue to devote 40 percent of his time to the project through the remainder of 1974.

ATOMIC PHYSICS PROGRAM

The atomic physics program has continued to be the most active program. This program has included experiments on a wide range of topics, with many important and exciting results.

I. Impact Parameter Dependence of K-Shell Ionization C. L. Cocke and co-workers

During the past year a short path length gas target was constructed to enable us to extend our coincidence measurements of the impact parameter dependence of inner-shell ionization probabilities to gas targets and to allow charge pure projectiles. To date, charge pure beams of carbon and fluorine have been used to produce K-shell vacancies in Argon targets, and the complete impact parameter dependences for collision angles down to 10^{-3} radians have been made for F^{+5} , F^{+9} , and C^{+4} , C^{+6} at 1.58 MeV/amu.^{1,2} These data, when coupled with earlier results from the ionization of Cu by p^3 and oxygen⁴ projectiles reveal clearly the inadequacy of the Coulomb ionization theories to describe colliding systems whose projectile/target nuclear charge ratio exceeds about .3. They further show that the description of charge exchange contributions to the K-vacancy production in terms of the simplest Born-approximation formulations is not possible. This point is made much more forcefully by the shape of the impact parameter dependence than it is by total cross section measurements.

II. Electron Spectrometer[†] C. L. Cocke and co-workers

A cylindrical-mirror electron spectrometer suitable for analyzing electrons both from gas-beam collisions and from foil excited beams has been constructed and installed on the tandem accelerator during the past year. An unusual feature of the spectrometer is a side beam-entrance geometry which allows detection of electrons emitted at large angles to the beam while maintaining the large efficiency of the cylindrical geometry. The spectrometer has been used to measure argon K-Auger electron cross sections for fluorine and chlorine projectiles. The fluorine cross sections as a function of projectile charge state follow the X-ray cross sections measured previously by Winters et. al.⁵, showing no dependence of the Ar-fluorescence yield on projectile charge state. This result is complementary to the data of Refs. 1 and 2.

III. Metastable X-Ray Emitters[†]

A. Lifetime of the 2^3S_1 State in Heliumlike Sulphur and Chlorine⁶ C. L. Cocke and co-workers

Beam-foil measurements of the lifetimes of the 2^3S_1 state in heliumlike sulphur and chlorine have been made. A Doppler-tuned x-ray spectrometer was used to detect the x rays emitted from the $1^1S_0 + 2^3S_1$ transition. Time-of-flight techniques were used to trace the decay profile of the emitted x rays for 38 - 55 MeV sulphur and chlorine beams over flight paths

of 56 - 861 cm. For foil-to-detector flight times greater than one half the theoretical lifetimes of 698 nsec (sulphur) and 374 nsec (chlorine), the respective experimental lifetimes of 706 ± 86 nsec and 354 ± 24 nsec are in agreement with theory. For shorter flight times, the experimental decay profiles are not single exponentials. This experimental effect is the source of the previously reported discrepancy between experimental and theoretical lifetimes of the 2^3S_1 state in heliumlike chlorine.⁷ A paper on this result has been submitted to Phys. Rev. A.

B. Metastable X-Ray Emitters in Highly Ionized Iodine⁸
C. L. Cocke, P. Richard, and co-workers

X-ray spectra of foil excited 40 - 62 MeV iodine beams have been taken using a bent-crystal x-ray spectrometer. The quite complex prompt spectrum is found to simplify considerably downstream. Relatively clean lines from metastable iodine systems are seen at x-ray energies of 533, 543, 553, and 565 eV. Decay profiles for the last two are nearly single exponentials with lifetimes of 4.3 and 2.5 nsec respectively. These transitions have not been previously observed and their identification remains incomplete. Their excitation function and transition energies suggest that the emitting systems belong to charge states $22^+ - 24^+$, and that they result from $4s - 3d$ electric quadrupole transitions.

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[†] Similar work is presently partially supported by O.N.R. under contract N00014-67-A-0403-0002.

IV. The Capture of Electrons from Specific Atomic Shells
 J. R. Macdonald and C. L. Cocke in Collaboration with W. W. Eidson
 of Drexel University.

Cross sections that have been measured in numerous experiments for the production of inner-shell vacancies in target atoms by energetic protons are found to be in good agreement with theoretical results calculated using direct ionization processes.¹ However, it is clear that the transfer to the projectile of target inner-shell electrons in atomic collisions is an additional process that contributes to the vacancy production cross section

determined experimentally. In fact, for higher Z projectiles, elementary considerations² indicate that the two processes may be comparable in magnitude and that the latter process may account for charge dependent trends recently observed in heavy-ion vacancy production cross sections.³ In work that we have recently published a measurement of the cross section for capture of electrons from a specific shell of a heavy target is reported. Using coincidence techniques, the cross section (σ_{CK}) for electron capture of argon K-shell electrons has been determined for 2.5 to 12 MeV protons. This cross section for argon K-shell ionization by electron capture makes a small contribution to the total argon K-shell ionization cross section and the contribution decreases monotonically with energy from 0.4% at 2.5 MeV to 0.06% at 12 MeV.

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V. Electron Capture and Loss Cross Sections Measured in Heavy-Ion Collisions
J. R. Macdonald and co-workers

In continuing our experimental program to determine electron transfer cross sections in heavy-ion collisions with gas targets, we have completed measurements of cross sections for C, N, O, and F ions in various gases over the energy range from 10 to 30 MeV. This work makes up the Ph.D. thesis of Tang Chiao and is being prepared for publication. Calculations have been made in a Brinkman-Kramers approximation to establish a technique to normalize these heavy-ion cross sections in a systematic way. This work makes up the M.S. thesis of James Guffey and is being prepared for publication.

In an extension of this work cross sections in argon have been measured for chlorine ions at energies from 15 to 40 MeV. These cross sections have been used to establish criteria for thin target conditions in atomic collision studies and the data is being prepared for publication.

VI. K X-Ray Production in Single Collisions of Chlorine and Sulphur Ions:
Molecular Promotion Processes
J. R. Macdonald and co-workers

In symmetric ion-atom collisions, molecular promotion processes have been studied at intermediate velocities and the results have been accepted for publication.¹ Cl K x-ray-production cross sections have been measured in single collisions of 0.1 - 1.5 MeV/amu Cl ions with gas targets of He, N₂, Ne, SiH₄, H₂S, HCl, Ar, Kr, and Xe. Cross sections for Ne K, Si K,

S K, Ar K, Kr L, and Xe L x-ray-production and yields for Xe M x rays were also obtained. Similar measurements for both Cl and S ions were made at one velocity as a function of projectile charge state, q , for $5 \leq q \leq 11$. Except at the highest energies, projectile K x-ray-production cross sections are nonmonotonic as a function of target atomic number, Z_2 . Anomalously high target and projectile cross sections occur in the symmetric region: $Z_2 = 17$. For all x-ray lines, the cross sections show an increase with increasing q at constant projectile velocity, with the rate of increase being greatest in the symmetric region. The experimental results indicate the importance of one-step molecular processes suggested by Meyerhof in producing K vacancies. The $2p\sigma - 2p\pi$ transition may be of importance when initial 2p vacancies are carried into K-vacancy-producing collisions. The large cross sections for both target and projectile in nearly symmetric collisions gives evidence for K-vacancy transfer between collision partners.

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VI. Charge Dependence of K X-Ray Production in Symmetric Collisions at High Energy
J. R. Macdonald and co-workers in collaboration with I. A. Sellin and co-workers from the University of Tennessee.

In an experiment at Brookhaven National Lab, we have studied the charge dependence of K x-ray production in symmetric collisions of chlorine and

sulphur ions at ~ 4 MeV/amu. At this energy, molecular promotion effects are not evident, however, the trends in the cross sections are strongly influenced by electron capture processes. The results of this experiment are in preparation for submission to Phys. Rev. A.

VII. Inner-Shell Vacancy Production by Heavy Ions J. R. Macdonald and co-workers

In continuing our work on inner-shell vacancy production studied by x-ray cross section analysis in heavy-ion collisions, we have established the systematic trends with energy, charge state, and projectile atomic number of argon ionization.¹ Although complete excitation functions have not been measured from these cross sections, sufficient data has been published to make comparisons with Coulomb ionization predictions. The importance of electron capture processes to the ionization has not yet been conclusively demonstrated but we speculate that this important process must contribute whenever the projectile enters the collision with a K-shell vacancy.

We have pursued understanding of the ionization process further by examining the decrease in the importance of projectile charge state on inner-shell ionization of heavier target atoms. In preliminary work we have observed that krypton K-shell vacancy production varies by less than 20% as a function of charge state for fluorine ions at 36 and 48 MeV. This work has been submitted for publication in Phys. Rev. A and has motivated us to continue the systematic study of these cross sections.

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VIII. Angular Distribution and Polarization of X Rays from Heavy-Ion Collisions J. R. Macdonald and co-workers

Encouraging preliminary results have been obtained for the polarization of x-radiation following electron capture to excited states in heavy-ion collisions. Polarization of $\sim 23\%$ has been observed for projectile x rays while negligible polarization has been found for target radiation following excitation of inner shells by heavy ions. The results of this work have been submitted to Phys. Rev. Letters and an apparatus to permit more extensive measurements has been designed and is being constructed.

IX. K X-Ray Emission from 20 to 36 MeV Fluorine Projectiles Following Electron Capture to Excited States J. R. Macdonald and co-workers

In continuing our study of electron capture processes by heavy ions, we have published¹ the results of a preliminary experiment to measure

the fraction of capture events to excited states containing K-shell vacancies. The projectile K x-ray emission cross sections for fluorine ions were measured under single collision conditions for charge states ranging from +4 to +9 in a thin argon target. The dependence of these cross sections upon the energy and the initial charge state of the projectile was determined for fluorine ions with energies between 20 and 36 MeV. Over the entire energy range, the K x-ray-production cross section for F^{+9} ions was about 70% of the total electron capture cross section determined in a separate experiment. The K x-ray-production cross section for these fully-stripped ions is attributed to electron capture to excited states of the projectile. Calculations of electron capture cross sections within the Brinkman-Kramers approximation for these heavy-ion collisions are consistent with the observation of large cross sections for capture to excited states.

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- X. Ion Source Development
J. R. Macdonald and co-workers

During the contract year a Negative Ion Sputter Source was delivered to KSU by Extrion Corporation and required beam line development was completed

by September 1974. The emittance of this source permits less than 5% beam transmission through the EN tandem accelerator and design and development work to improve the beam quality is in progress. However, with the present conditions (Oct., 1974) beams of ${}^7\text{Li}$, ${}^{11}\text{B}$, ${}^{12}\text{C}$, ${}^{16}\text{O}$, ${}^{27}\text{Al}$, ${}^{56}\text{Fe}$, ${}^{63}\text{Cu}$, and ${}^{208}\text{Pb}$ have been accelerated from the UNIS source, and experiments using the former three beams have already begun.

Development of a lithium vapor He^+ exchange source has also continued during the contract year and successful acceleration of small helium beams has been accomplished. The development of this source has used the same beam line as the UNIS source and the development of the latter has taken precedence over the optimization of the former. However, the addition of these two sources to our successfully operating diode source gives KSU a state-of-the-art capability to accelerate all heavy ions that can be prepared in the negative charge state.

XI. High Resolution Study of the Charge Dependence of Neon X-Ray Production

by Heavy Ions

J. R. Macdonald, P. Richard and co-workers in collaboration with I. A. Sellin and co-workers of the University of Tennessee.

To examine the distribution of states of neon produced by energetic heavy ions of different charge states, crystal spectra have been obtained in which the neon K-x-ray transitions have been resolved into several components. Analysis of these spectra has been published¹ with the conclusion that the vacancy production cross section, rather than the change in fluorescence

yield dominates the charge dependence of the x-ray yields. Recent results by Burch et. al.² support a contradictory conclusion and these results are an indication of the inadequacy of configuration averaged fluorescence yields in interpreting x-ray data.

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XII. The Study of Atomic Ionization P. Richard and co-workers

The study of multiple ionization in solid targets by high energy heavy ions has been extended to the case of Br projectiles on targets of Al, Sc, and Ti. An experiment was performed at Brookhaven in which 105 MeV O and S beams were used to excite Al, Si, and Ca. Lifetimes of the 3P_2 and $^4P_{5/2}$ states of both Cl and S were also measured. These measurements were made in collaboration with Professor C. F. Moore of the University of Texas. The study of ionization in Ne has been one of the major efforts this year. High resolution x-ray spectra of Ne produced by C, N, O, F, Cl and Ar have been measured. The Ar-Ne and Cl-Ne experiments were performed in collaboration with Professor Macdonald of Kansas State University and Dr. I. A. Sellin of

Oak Ridge. The Ar-Ne experiment was performed at Oak Ridge on the ORIC. The study of projectile x rays from gas targets have also been extended and the results published. The study of Ne Auger electron cross sections has been initiated and some first results for O-Ne and F-Ne have been obtained. A brief description of each of these experiments is given below in addition to other satellite studies.

XIII. Restudy of Cl-Ne Spectra

P. Richard, C. W. Woods, S. J. Czuchlewski, K. A. Jamison, R. L. Kauffman

The experiment discussed above has been repeated with higher energy resolution and better statistics in order to make a re-evaluation of the effective fluorescence yields of Ne in light of discrepancies of high resolution experiments, low resolution experiments, and calculated fluorescence yields. In addition the effects of multiplet splittings are included in the analysis. The results of this experiment and the analysis are being prepared for publication.

XIV. Br + Al, Sc, Ti K α Target X Rays

K. A. Jamison, C. W. Woods, R. L. Kauffman, and P. Richard

A high resolution study of K α x rays from Al, Sc, Ti following 7+ 31-MeV bromine-ion bombardment has been done. This beam was focused onto targets

of Al, Sc, and Ti in a chamber adjacent to a 4" curved crystal spectrometer. K α x rays were then studied using the on-line PDP-15 computer to step the angular setting of the crystal through the desired energy range of the target x rays. Structure due to varying numbers of L-shell ionization was resolved and by off-line analysis on the PDP-15, energies and selective intensities were determined. These values were compared to extensive Hartree-Fock calculations performed on the IBM-370. The comparison was used to determine the average amount of M-shell ionization for each KLⁿ configuration at the time of x-ray emission. These results have been compiled and written up in the form of a paper to Phys. Rev. A. An abstract of this work has been submitted to the 1974 Chicago meeting of the DEAP of the American Physical Society. This work will also be the subject of the M.S. thesis of K. A. Jamison.

- XV. X-Ray Production by 105-MeV Cl and S Beams
P. Richard; C. F. Moore and D. L. Matthews, University of Texas;
and F. Hopkins, Stony Brook.

Target and beam x rays produced by 105-MeV Cl and S beams from the Brookhaven emperor tandem were analyzed with a 4" curved crystal spectrometer. Many new few electron states of Cl and S produced in thin carbon foils were studied and the lifetimes of the 3P_2 (1s2p) He-like states and the $^4P_{5/2}$ (1s2s2p) Li-like states were measured for both Cl and S. The target K x rays from Al, Si and Ca are also investigated. A very pronounced enhancement of double

K-shell ionization is observed which gives a measure of the probability for K-shell ionization. In addition $K\alpha$ and $K\beta$ satellites, and plasmon oscillation peaks are observed in Al, Si, and Ca. The satellite structures do not follow a binomial distribution.

XVI. Multiple Ionization Cross Sections of Ne Produced by Heavy Ions in the 1 MeV/amu Range

R. L. Kauffman, C. W. Woods, K. A. Jamison, and P. Richard

High resolution spectra of Ne K x rays produced by projectiles of $C^{+3,+4,+5,+6}$, $N^{+4,+6,+7}$, $O^{+4,+5,+6,+7,+8}$, and F^{+9} having energies of 1-2 MeV/amu are measured. Previous measurements of $Cl^{+7,+11,+13}$ at 40 MeV and $Ar^{+6,+14}$ at 80 MeV are also analyzed so that a large spread of incident projectiles are examined. The $K\alpha$ x rays are resolved into a number of peaks labeled KL^i , $i = 0, \dots, 7$ corresponding to one initial K-shell hole and i initial L-shell holes. Sufficient resolution is obtained to partially resolve the $1P-3P$ splitting in the KL^7 (He-like) peak. To correct for overlap of peaks, 81% of the KL^6 intensity must be subtracted from the KL^5 peak. Semi-empirical fluorescence yields are applied to obtain relative multiple ionization cross sections. These relative cross sections are fit to a binomial distribution to obtain the probability for L-shell ionization at zero impact parameter, P_L . Good fits to the binomial distribution, predicted by Coulomb ionization theories are obtained to all sets of data except for the F^{+9} induced spectra. The P_L 's cannot be compared directly with theory because for these cases the

existing theories predict the unphysical result, $P_L > 1$. The data does exhibit the same energy dependence predicted by the theory. A paper is being written on this study and will also be the subject of the Ph.D. thesis of R. L. Kauffman.

XVII. Neon K α /K β Satellite Structure Induced by 80-MeV Argon-Ion Impact
J. R. Mowat, R. Laubert, I. A. Sellin, R. L. Kauffman, M. D. Brown,
J. R. Macdonald, and P. Richard

Measurements have been made of the high resolution neon K x-ray structure produced by 80-MeV Ar⁺⁶ and Ar⁺¹⁴ projectiles from the Oak Ridge Isochronous Cyclotron. For the Ar⁺⁶ case transitions from the carbon-like neon system are the transitions having the least amount of multiple ionization which are observed. In the Ar⁺¹⁴ spectra the smallest amount of multiple ionization for which there is evidence is the beryllium-like system. The x-ray intensities are used in conjunction with previously performed poor resolution Si(Li) detector measurements to obtain vacancy production cross sections. The high resolution data aids in providing a more accurate efficiency correction which is a rapidly changing function of energy in the region of interest. The high resolution data is also used to obtain an estimate of the neon fluorescence yield. Thus the ionization cross section, σ_I , can be obtained from the x-ray cross sections. The values obtained are $\sigma_I(80 \text{ MeV Ar}^{+6}) = 1.7 \text{ Mb}$ and $\sigma_I(80 \text{ MeV Ar}^{+14}) = 14 \text{ Mb}$. The absolute uncertainty is estimated as a factor of ~ 2 . A paper on these results has been submitted to the Physical Review.

XVIII. Role of Screening in Multiple Ionization

R. L. Kauffman, C. W. Woods, K. A. Jamison, and P. Richard

High resolution spectra of neon K x-rays produced by heavy-ion projectiles having the same ionic charge but different nuclear charge are studied. For the cases of O^{+6} , N^{+6} , and C^{+6} and for O^{+7} and N^{+7} similar amounts of multiple ionization are produced. This implies that the mechanism creating the ionization scales approximately as the ionic charge of the projectile. This is in disagreement with existing theories of ionization which predict that ionization scales with the nuclear charge of the projectile. This ionic scaling could explain partly some of the charge state effects observed in previous experiments. When the projectile contains L-shell electrons the ionization produced does not scale in the same manner. The results of this work are published in a Journal of Physics B article.

XIX. Multiplet Effects in High Resolution Ne K α Structure

R. L. Kauffman, C. W. Woods, K. A. Jamison, and P. Richard

The decay of all of the states of all possible configurations of neon are examined. In the calculations Russel-Saunders coupling is assumed and a single configuration Hartree-Fock calculation is used to predict the energies of the various levels. Only allowed electric-dipole transitions are considered and line strengths are estimated in the semi-classical radiation approximation. The results show that transitions from a specific ionization state of neon may have a large energy distribution but that the transition strengths are grouped

about a central energy. These energies correspond to the measured centroids of the various peaks observed in high resolution x-ray spectra of neon. Also most of the transitions are contained within the full width at half maximum of the measured peak. This gives good support to the interpretation that the peaks belong to a single ionization state of neon. High ionization states where only a few transitions are possible are the notable exception. These cases need to be examined more thoroughly. A paper on this subject has been submitted to Physics Letters.

- XX. Production of Oxygen and Fluorine Projectile K X Rays in Thin Gas Targets
F. Hopkins, Stony Brook; R. L. Kauffman, C. W. Woods, and P. Richard,
Kansas State University

Hydrogen-like and helium-like K x-ray transitions in oxygen and fluorine projectiles following collisions in various gas targets have been observed in high resolution. Oxygen beams of individual charge states 6^+ , 7^+ , 8^+ incident on neon and argon and fluorine beams of charge states 7^+ , 8^+ , 9^+ incident on helium and neon at ~ 2 MeV/amu energy were used in the experiment. Relative x-ray intensities corrected for detector efficiency have been obtained. The data for electron capture by fully stripped projectiles are compared to the predictions of a simple Brinkman-Kramers model. Additional processes contributing to the x-ray yield for the one- and two-electron projectiles include excitation, electron exchange, and ionization simultaneous with excitation. The results of these studies are published in The Physical Review A 9, 2413 (1974).

XXI. Ne K-Shell Auger Electron Production

C. W. Woods, K. A. Jamison, R. L. Kauffman, C. L. Cocke, and P. Richard

In the past few months we have been engaged in measuring Ne K-shell Auger electron production cross sections, σ_A , from bombardment of Ne by various beams from the tandem Van de Graaff. These experiments were designed to gain more insight into collisions previously studied with high resolution x-ray measurements and were thus aimed at measuring the charge state and nuclear charge dependence of σ_A - at a projectile energy of 1.5 MeV/amu. To date measurements have been performed with H^+ , oxygen in charge states 4^+ to 8^+ , and fluorine in charge states 5^+ to 9^+ . Beams of carbon and nitrogen have been attempted with inconclusive results. The results for protons, oxygen and fluorine are submitted for publication.

The electrons from the Auger decay of K-shell vacancies produced by bombarding a gaseous target of neon with these various beams are analyzed in the cylindrical mirror analyzer with an acceptance cone of 42° designed and constructed here at Kansas State University. The unique feature of this analyzer which makes it ideal for these measurements is the ability to rotate the axis of the analyzer 132° with respect to the beam axis and thus view electrons ejected at 90° to about 175° with respect to the beam direction. This minimizes the background related to collisionally produced electrons and beam Auger electrons. The various projectile charge states are obtained by changing the voltage of the tandem Van de Graaff and extracting a primary beam at the desired energy where possible (i.e. F^{5+} and F^{6+}) or by accelerating the primary beam with the greatest intensity and post stripping with a $20 \mu g/cm^2$ carbon coil (i.e. F^{+7} , F^{+8} , and F^{+9}) and then magnetically analyzing the resultant beam with the switching magnet.

In the future we hope to extend these studies to nuclear species

obtainable only since the installation of the new source, such as beryllium and aluminum. It is also hoped that the new source will be able to supply carbon at high enough currents to make the charge state dependence feasible. Aluminum is an especially good projectile to use since it is close in nuclear charge to neon, as are oxygen and fluorine, but has a greater nuclear charge than neon. Aluminum produced cross sections should be able to answer the question as to whether or not molecular orbital effects are important at these high ion velocities.

XXII. The 3 to 35 MeV Excitation Function of F-Ne

C. W. Woods, K. A. Jamison, R. L. Kauffman, and P. Richard

The near symmetric fluorine induced neon K-shell Auger electron production cross section, σ_A , is being measured for various charge states of the fluorine projectile over the energy range of 3 MeV to 35 MeV. The lower charge states (3+ to 5+) show little variation in cross section at similar energies. The higher charge states (6+ to 9+) have cross sections which increase with increasing projectile charge state. Where it is feasible to run 8+ (energies greater than 15 MeV) fluorine σ_A is nearly equal to the ionization cross section predicted by Coulomb ionization. Charge states lower than 8+ are consistently below this prediction and 9+ is consistently above. Charge exchange to the projectile K-shell is expected to be important for fluorine projectiles with K-shell holes. The energy dependence for all the charge states is similar to the Coulomb ionization prediction. These cross sections can be qualitatively compared to the neon on neon cross sections measured

by Stolterfoht et. al. at low velocity (energy less than 1 MeV). At these low velocities the cross sections are much greater than the Coulomb ionization predictions. This increase is attributed to molecular orbital effects. In the future we hope to extend the measurements with fluorine to lower energy to gain insight into the transition region where both Coulomb and molecular orbital processes contribute to ionization.

XXIII. Charge State Dependence of the Ne K Fluorescence Yield Deduced from

High Resolution Emission Spectra

N. Stolterfoht, D. Schneider, Hahn-Meitner-Institut; P. Richard
and R. L. Kauffman, Kansas State University

Semi-empirical Ne K fluorescence yields for the vacancy configurations KL^i were deduced for $i = 1$ to 7 by comparing satellite intensities in 30-MeV $O^{5+} + Ne$ and 35-MeV $O^{8+} + Ne$ X-ray and Auger spectra measured recently with high resolution. For some cases the semi-empirical fluorescence yields are found to be significantly larger than theoretical values and differ with previous semi-empirical values for the higher degrees of multiple ionization. The values obtained are $\omega_0 = 0.018$, $\omega_1 = 0.021$, $\omega_2 = 0.021$, $\omega_3 = 0.022$, $\omega_4 = 0.045$, $\omega_5 = 0.051$, $\omega_6 = 0.378$, $\omega_7 = 0.551$. These results have been submitted for publication.

XXIV. Observation of Stark Beats in the H-like K X Rays of Oxygen and Fluorine
P. Richard, C. L. Cocke, S. J. Czuchlewski, K. A. Jamison, R. L. Kauffman,
and C. W. Woods

K x rays of highly ionized oxygen and fluorine ions have been shown to exhibit intensity oscillations as a function of an electric field parallel to the beam. The nearly periodic behavior of the oscillations and the linear variation of the beat frequency with projectile velocity suggest a Stark beating between high n hydrogen-like states. Beams of 30-, 25-, and 20-MeV oxygen and fluorine were sent through a thin exciter foil followed at a distance Y by a high transmission Cu mesh elevated to some voltage V with respect to the exciter foil. At a distance X downstream from the grid the K X rays emitted by the beam were observed by a flow proportional counter. The detector was at 90° with respect to the beam and the proportional counter collimated by means of 5° soller slits. The voltage on the Cu grid was varied between -1000 volt and +1000 volt, and the data was obtained by multiscaling the proportional counter as a function of the grid voltage. Most spectra of yield versus grid voltage were taken with $Y = 1/16$ inch, $X = 4.3$ inch, and a $40 \mu\text{g}/\text{cm}^2$ C exciter foil. The effects of changing Y and X were individually tested by setting $Y = 1/8$ inch, and $X = 18$ inch. In addition a thin Cu exciter foil was used in place of C. Some important features of the data are (1) a nearly periodic behavior of the x-ray intensity at both positive and negative voltages, (2) an approximate symmetry about zero volts, (3) a maximum at zero volts, and (4) three oscillations between -1000 volt and zero volt at 30-MeV compared with four oscillation at 20-MeV. If the Stark splitting ΔE is linear with the applied electric field, then the quantity $\Delta E_T = h$ for the experimental geometry used here is proportional to the applied voltage V divided by the beam velocity, v . The voltages for the first maxima for 30-MeV, 25-MeV, and 20-MeV fluorine occur at 200 V, 182 V, and 163 V respectively. The ratio V/v is a constant for these three cases.

XXV. Energy Loss of Low-Energy Calcium Ions in Carbon
K. C. Shane, H. Laumer, and G. G. Seaman

The Doppler shift of gamma rays from the 3.75-MeV 3^- state in ^{40}Ca excited by inelastic proton scattering has been measured to determine the velocity of the recoiling calcium ions. Coincidence measurements between the scattered protons and the gamma rays for calcium ions recoiling into vacuum or through a carbon foil yield gamma ray spectra that reflect the energy loss in the carbon foil and the amount of multiple scattering. The data has been analyzed with the Monte Carlo code of Currie,¹ and give results that indicate that both electronic and nuclear stopping are substantially less than predicted by the Lindhard theory.² This work has been completed and is being written up for publication.

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NUCLEAR PHYSICS PROGRAM

The nuclear physics program has continued to investigate heavy-ion nuclear scattering and reactions at energies near the Coulomb barrier. These studies have been concerned with the mechanisms of heavy-ion interactions and the study of nuclear properties using the unique characteristics of heavy-ion reactions.

I. The Geometrical Dependence of the Deformation Parameters as Determined by Heavy Projectile Scattering
D. O. Elliott, J. S. Eck, and W. J. Thompson

In order to properly understand the dynamics of the interaction of heavy nuclei, it is necessary that all effects which depend only on geometrical or kinematical considerations be stripped from the data. Toward this end we have measured the deformation of ^{24}Mg and ^{28}Si by the elastic and inelastic scattering of protons, deuterons, alpha particles, ^{12}C , ^{14}N , ^{16}O , and ^{18}O . The measured deformations show a systematic trend as a function of projectile radius which can be accounted for by geometrical considerations as proposed by Hendrie.¹ In general the measured deformations show the same dependence on atomic number as predicted by Hendrie but the absolute deformation is too large.

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II. Elastic Scattering of $^{14}\text{N} + ^{12}\text{C}$ Near the Coulomb Barrier
J. H. Johnson, D. O. Elliott, W. J. Thompson, and J. S. Eck

The elastic scattering excitation functions of $^{14}\text{N} + ^{12}\text{C}$ have been measured as a function of energy at six C.O.M. angles between 55° and 120° at ^{14}N bombarding energies between 15.0 and 25.0 MeV. Four angular distributions in the C.O.M. angular range from 20° to 135° at ^{14}N energies of 15.0, 20.0, 21.5, and 23.5 were also taken.

The main results of the present work were threefold:

1. There is no evidence for any non-statistical structures in the excitation functions similar to those observed for $^{13}\text{C} + ^{12}\text{C}$ ¹ and $^{12}\text{C} + ^{16}\text{O}$.²

2. Although many of the heavy particle emission channels for the $^{14}\text{N} + ^{12}\text{C}$ reaction have been shown to proceed almost entirely by the compound nucleus³ the compound contribution to the elastic scattering is negligible and the $^{14}\text{N} + ^{12}\text{C}$ elastic scattering cross section is due almost entirely to shape elastic scattering.

3. The optical model is capable of describing the measured elastic scattering cross sections without the addition of a deuteron exchange interaction as proposed by Von Oertzen.⁴ Furthermore, no auxiliary assumptions such as ℓ -dependent absorption as proposed by Robson⁵ to describe the $^{14}\text{N} + ^{12}\text{C}$ scattering are needed to adequately describe the cross sections.

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III. Direct Extraction of a $^{12}\text{C}^-$ Beam from a Diode Ion Source
J. S. Eck and D. O. Elliott

In order to obtain a high energy ^{12}C beam, it is necessary to extract directly a $^{12}\text{C}^-$ beam from the ion source rather than the conventional CN^- ion. We have successfully extracted 450-600 nA of C^- ions from our Diode Ion Source by introducing CO gas into the intense H_2 arc. The particular reasons for the success of obtaining a C^- beam from CO while only a miniscule C^- beam can be obtained using the conventional methane and W_2 mixture, can be explained in terms of the molecular structure of CO.¹

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IV. Systematics of Backward-Angle Elastic Alpha Scattering
J. S. Eck and W. J. Thompson

Backward angle ($\theta > 90^\circ$) alpha elastic scattering cross sections for target nuclei $32 \leq A \leq 100$ in the bombarding energy range 15 to 40 MeV are systematically investigated using all available data. A simple quantitative prescription for estimating the degree of backward enhancement has been formulated. Strong correlations of the backward enhancement with (α, n) (α, α') Q values and with compound-nucleus level densities have been found. This correlation has been related to the flux removal from high angular momentum (l) entrance channels via l -dependent absorption potentials and compound elastic scattering.

V. Resonances in the $^{12}\text{C} + ^{13}\text{C}$ System
J. C. Legg and D. J. Crozier

Excitation curves for the elastic scattering of ^{13}C from ^{12}C , the $^{12}\text{C}(^{13}\text{C},\alpha)^{21}\text{Ne}$ reaction, and the $^{12}\text{C}(^{13}\text{C},p)^{24}\text{Na}$ reaction have established the existence of a number of heavy-ion resonances in the $^{12}\text{C} + ^{13}\text{C}$ system.^{1,2} Two of these resonances have been analyzed for the elastic-channel ℓ -value, and all of the results to date are consistent with the mechanism of a grazing ℓ -value resonance acting as a doorway state. The discovery of these resonances make less likely any explanation of heavy-ion resonances in terms of alpha-particle structure.

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VI. Resonances in the $^{16}\text{O} + ^{13}\text{C}$ System
J. C. Legg, R. R. Phillips, and D. J. Crozier

Excitation functions for the elastic scattering of ^{13}C from ^{16}O and the gamma rays resulting from the $^{16}\text{O}(^{13}\text{C},pn)^{27}\text{Al}$ reaction have been measured. Preliminary analysis shows the existence of several resonances, some of which are sub-Coulomb carrier resonances. These resonances are now undergoing analysis and a letter will be submitted soon discussing these results.

VII. Lifetimes of Nuclear States in ^{21}Ne

G. G. Seaman, D. J. Crozier, J. C. Legg, and K. C. Shane

The lifetimes of states up to 5 MeV in excitation in ^{21}Ne have been measured by the Doppler shift attenuation method. These lifetimes have been measured previously, but almost entirely with the $^{18}\text{O}(\alpha, n)^{21}\text{Ne}$ reaction, and there are large discrepancies among several measurements. Here, the heavy-ion reaction $^{12}\text{C}(^{13}\text{C}, \alpha)^{21}\text{Ne}$ was used, with gamma rays measured in coincidence with alpha particles at 0° . The much larger recoil energy produced in this reaction gives more reliable centroid shifts, and has the additional advantage that there is less uncertainty in the stopping power since very little nuclear stopping is involved. The lifetimes obtained are very short (of the order of 50 fsec or less), which indicates the need for the larger stopping power at higher recoil energies available in heavy-ion reactions. This work is being written up for publication.

APPLIED PHYSICS PROGRAM

The program on x-ray analysis of trace elements has come to a successful conclusion. The utility of the method has been established, and the KSU Agriculture Experiment Station has funded an ongoing analysis program.

I. Detection of Trace Elements in Flour Samples
G. G. Seaman

Studies carried out on trace amounts of Zn and Br in flour samples have demonstrated to the Grain Science Department at Kansas State University that such methods are reliable and useful. However, since accelerator time is costly per sample analyzed, the KSU Agriculture Experiment Station has funded the purchase of equipment for analysis with X-ray sources. These sources and related electronics are completely independent of the accelerator project. Future use of the accelerator for proton-induced X-ray fluorescence will be limited to occasional testing or corroboration of other measurements.

CONTRACT PUBLICATIONS

from

1 October 1973 to 1 October 1974

Articles

1. Non-Monotonic Target Dependence of C_K X-Ray-Production Cross Sections in Single Heavy-Ion-Atom Collisions, Loren Winters, James R. Macdonald, Matt D. Brown, Tang Chiao, Louis D. Ellsworth, and E. W. Pettus, Phys. Rev. Letters 31, 1344 (1973).
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13. Observation of K X Rays from Highly Ionized States of Neon Produced by 40-MeV Cl^{+7} , Cl^{+11} , and Cl^{+13} Beams, M. D. Brown, J. R. Macdonald, P. Richard, J. R. Mowat, and I. A. Sellin, Phys. Rev. A 9, 1470 (1974).
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29. K α Satellite X-Rays in Al, Sc, and Ti Following Bromine-Ion Bombardment, K. A. Jamison, C. W. Woods, R. L. Kauffman, and P. Richard, submitted to Phys. Rev. A.
30. On the Anomalies of Backangle Alpha Scattering: Inelastic Scattering from the Calcium Isotopes, W. Trombik, J. S. Eck, and K. A. Eberhard, submitted for publication to Phys. Rev. C.
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Invited Papers Presented at Meetings

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2. Experimental Evidence for Molecular Promotion in Heavy-Ion Collisions, M. D. Brown, November, 1973 Meeting of the Southeast Section of the American Physical Society at Winston-Salem, North Carolina.
3. Metastable X-Ray Emitters, C. L. Cocke, 1974 Washington D. C. Meeting of the American Physical Society, Bull. Amer. Phys. Soc. 19, 586 (1974).
4. Ion-Atom Collisions at High Energies, Patrick Richard, 1974 International Conference on X-Ray Processes in Matter at Otaniemi, Finland, July 28-August 1, 1974. Physica Fennica 9, 3 (1974).
5. Generation of X Rays by MeV/amu Heavy Ions, James R. Macdonald, Gordon Conference entitled Particle-Solid Interactions, July 29-August 2, 1974.

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1. Elastic and Inelastic Scattering of ^{12}C on ^{28}Si Near the Coulomb Barrier, D. O. Elliott, J. S. Eck, P. Richard, and F. Hopkins, Bull. Amer. Phys. Soc. 18, 1387 (1973).
2. α -Particle Elastic and Inelastic Scattering from the Ni Isotopes, W. Trombik, K. A. Eberhard, and J. S. Eck, Bull. Amer. Phys. Soc. 18, 1426 (1973).
3. A Systematic Investigation of Back-Angle Enhancement for Elastic α -Particle Scattering, J. S. Eck, K. A. Eberhard, and J. Schiele, Bull. Amer. Phys. Soc. 18, 1427 (1973).
4. Projectile Charge Dependence of the Krypton K-Shell Vacancy Production Cross Section at Energies from 1 to 2 MeV/amu, J. R. Macdonald, S. Czuchlewski, and L. D. Ellsworth, Bull. Amer. Phys. Soc. 19, 89 (1974).
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