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PROGRESS REPORT FOR ATOMIC AND NUCLEAR RESEARCH OF ACCELERATORS:

Since 1 October 1972, the accelerator research program at Kansas State University has been an active and increasingly productive endeavor. During this time, the research programs in Atomic Physics and Nuclear Physics have actively investigated a very large number of interesting physics problems with many exciting results.

During the twelve month period from 1 October 1972 to 1 October 1973 the accelerator dome was charged for a total of 5,628 hours in the course of experiments. In addition, the accelerator was out of operation for preventive and routine maintenance a total of 284 hours. Finally, the accelerator was out of operation for repair of a fault five separate times during the year for a total of 151 hours. Of the experimental acceleration time, only 24 percent was devoted to accelerating protons and the rest was devoted to accelerating heavy ions for use in experiments. These heavy ions included ^{12}C , ^{13}C , ^{16}O , ^{18}O , ^{19}F , ^{28}Si , ^{32}S , ^{35}Cl , and ^{37}Cl .

During this period of time, the university sponsored a series of heavy-ion discussions by eight visitors. These visitors were D. Allan Bromley, Eugen Merzbacher, Donald Robson, J. D. Garcia, Ivan Sellin, Frans Saris, Walter Greiner and H. T. Fortune. These visitors provided great stimulation to the already active program of experimentation here at Kansas State.

PRINCIPAL INVESTIGATOR

James C. Legg was Principal Investigator during the full period being reported on. The principal investigator devoted 40 percent of his time to the project during the academic year and full time during the summer months of 1973. He will continue to devote 40 percent of his time to the project through the remainder of 1973.

ATOMIC PHYSICS RESEARCH

The atomic physics research led by Professors Cocke, Macdonald, and Richard has employed a variety of techniques in observing the results of energetic collisions between atoms and ions, and they have discovered during the past year a number of puzzling and exciting phenomena.

X-ray Emission from Foil-Excited Chlorine Beams

C. L. Cocke, B. Gurnutte, J. R. Macdonald, and R. Randall

Metastable K-x-ray emitters produced in foil-excitation of chlorine beams between 23 and 55 MeV have been observed and their production probabilities surveyed over this energy range. Using coincidence techniques we find that the emitters belong primarily to the helium- and lithium-like components in the post-foil beam. A search for x-ray emission from systems with more than three electrons has been made with largely negative results. The major metastable x-ray emitters have been identified as the $(1s2p)^3P_2$ and $(1s\ 2s\ 2p)^4P_{5/2}$ states in helium- and lithium-like chlorine whose radiative decay is magnetic quadrupole. Using both coincidence techniques and a Doppler-tuned x-ray spectrometer we have measured the lifetimes and binding energies of these states. The lifetime of the 2^3P_2 state is in good agreement with theory, while the binding energies show the importance of relativistic contributions in the theory.¹⁻⁴

¹ G. W. F. Drake, Ap. J. 158, 1199 (1969).

² N. T. Doyle, Advances in Atomic and Molecular Physics, Vol. 5, 337, Ac. Press, N. Y. (1969).

³ E. Holein and S. Geltman, Phys. Rev. 153, 81 (1967).

⁴ R. Snyder, J. Phys. 84, 1150 (1971).

X-Ray-Emission from Foil-Excited Sulphur

C. L. Cocke, B. Curnutte and R. Randall

Similar studies on sulphur beams show that the 3P_2 and $^4P_{5/2}$ states are again the major metastable x-ray emitters. Lifetimes and binding energies have been measured and are again in excellent agreement with theory.¹⁻⁴ In addition, high resolution spectra taken at the foil exciter show strong emission from identified helium- and lithium-like lines but only weak emission from lower charge states, even though the latter represent the larger part of the equilibrium charge state fraction. This effect is attributed to the rapid fall of fluorescence yield with increasing electron number and strengthens the general conclusion that k-shell vacancy metastability becomes rare with increasing electron number. These results indicate that the customary discussion of x-ray spectra in terms of "satellites" is at best treacherous for few-electron systems.

¹ G. W. F. Drake, Ap. J. 158, 1199 (1969).

² N. T. Doyle, Advances in Atomic and Molecular Physics, Vol. 5, 337, Ac. Press, N. Y. (1969).

³ E. Holein and S. Geltman, Phys. Rev. 153, 81 (1967).

⁴ R. Snyder, J. Phys. 84, 1150 (1971).

Decay of the 2^3S_1 State in Heliumlike Chlorine
C. L. Cocke, B. Curnutte and R. Randall

The lifetime of a long lived K-x-ray emitter produced in foil-excitation of chlorine beams between 40.3 and 57.5 MeV has been measured to be 280 ± 25 nanoseconds. The measured photon energy of the transition indicates that it arises from the $1^1S_0 \leftarrow 2^3S_1$ decay in heliumlike chlorine. The observed lifetime is shorter than the theoretical M1 lifetime of 381^5 ns predicted for this transition. This M1 decay is allowed only in the relativistic formulation of the problem, being identically zero in a non-relativistic approximation. A similar discrepancy has been noted in argon where the theoretical and experimental numbers are 212 ns and 170 ns,⁶ respectively and suggest that this problem may be serious and that decay of this state is not entirely understood. No explanation of the discrepancy is forthcoming at present.

Impact-Parameter Dependence of the Probability for Copper K-shell

Ionization by Oxygen Projectiles
C. L. Cocke and R. Randall

The experimental impact parameter dependence of the probability for copper K-shell ionization by oxygen projectiles with energies between 25 and 43 MeV is presented. Since the projectile nuclear charge is much less than that of the target, one might hope for an adequate description of the collision as a direct coulomb ionization⁷ by the projectile nuclear charge. The shape of the experimental curve at 43 MeV is encouragingly similar to that calculated in the semiclassical Coulomb approximation.

Impact Parameter Dependence of Chlorine K-X-Ray Production in Violent Cl-Al,
Cl-Ti and Cl-Cu Collisions
C. L. Cocke, R. Randall and B. Curnutte

We have measured experimental probabilities for the production of chlorine K-X-rays in violent Cl-Al, Cl-Ti and Cl-Cu collisions as a function of the impact parameter (B) describing the collision. Over this range in target Z one progresses from a situation in which coulomb ionization is likely to dominate (Cl-Al) to one in which promotion of the chlorine K-electron via rotational coupling of $2p\sigma$ and $2p\pi$ orbital becomes possible (Ti, Cu). We have measured the impact parameter dependence of Cl-K-x-ray production by bombardment of thin Al, Ti and Cu foils using the detection of the Cl-K-X ray in coincidence with 21, 39.8 and 50 MeV chlorine ions scattered at small angles ($\theta < 4^\circ$). From our results we conclude that (1) an enhancement of the probability near matching Z (Ti-Cl) is observed, and (2) the plateau shape of the impact parameter dependence at small B for this collision pair is found. Both points support the interpretation that this enhancement is due to a promotion mechanism.

⁵G. W. F. Drake, Phys. Rev. A, 3, 908 (1971).

⁶H. Gould, R. Marrus and R. W. Schmieder, Phys. Rev. Letters 31, 504 (1973).

⁷J. Bang and J. M. Hansteen, kgl. Dan. Vidensk. Selsk., Mat.-Fys. Medd. 31, 13 (1959).

⁸J. S. Briggs and J. Macek, J. Phys. B, 5, 579 (1972).

Atomic Collision Experiments
J. R. Macdonald and Collaborators

During the year 1973, the atomic collision program of J. R. Macdonald has made very significant progress on a large number of experimental programs. Contributions to the program have been made by M. Brown, L. D. Ellsworth, Tang Chiao, L. Winters, and E. Pettus. Drs. Macdonald and Brown have also undertaken cooperative experiments with Ivan Sellin using the Oak Ridge Cyclotron for Physics experiments.

The measurement of charge exchange cross sections for high velocity heavy ions has continued in the past year. These experiments are now accompanied by complete on-line analysis with the PDP-15 computer and the large amount of data that is necessary to determine systematic trends in cross sections can be handled efficiently. Single- and multiple-electron capture and loss cross sections have been determined for C, N, O and F ions with a full range of incident charge states at velocities from 5 to 15×10^8 cm/sec in various target gases.^{9,10,11} Although the results obtained in these experiments will not be discussed in detail, an important discrepancy has been found between experimentally determined capture cross sections for fully stripped nuclei in different targets and the semiempirical scaling law developed by Nikolaev¹² that was expected to describe these cross sections. For all ions studied, the scaling law is in good agreement with the experimental results in light target gases but is too high by factors 3 and 9 respectively in argon and krypton. These deviations and large multiple electron transfer cross sections which have been observed are not fully understood.

⁹ Tang Chiao, PhD. Thesis, K. S. U., 1973.

¹⁰ T. Chiao, J. R. Macdonald, L. D. Ellsworth, S. M. Ferguson, M. D. Brown, L. M. Winters and S. A. Savoy, B.A.P.S. 18, 661 (1973).

¹¹ S. M. Ferguson, J. R. Macdonald, T. Chiao, L. D. Ellsworth, and S. A. Savoy, to be published, Phys. Rev. A., Nov. 1973.

¹² V. S. Nikolaev, Sov. Phys. Uspekhi 8, 269 (1965).

Inner shell ionization cross sections of argon, krypton, and xenon by 1.5 to 5.0 MeV protons have been measured in single collisions in thin gas targets.^{13,14} These results are in good agreement with the available theoretical treatments. To reduce background and permit the extension of these experiments to proton energies up to 12 MeV, a low mass, high transmission gas cell has been constructed. Preliminary results have been obtained for protons in argon and the data is in agreement with our earlier work^{13,14} at low energy and is in agreement with theory over the entire energy range.

X-ray-production cross sections measured for gas targets bombarded with energetic heavy ions have produced a number of unexpected results in our work in the past year. We have reported a large dependence of x-ray yield in argon, krypton, and xenon upon the charge state of fluorine ions at 35.7 MeV.¹⁵ Further work on this phenomenon for C, N, O, and F ions in argon^{16,17} has shown that this projectile charge dependence is a general result for ions containing K-shell vacancies incident on heavier target atoms.

In collaboration with the group of I. A. Sellin, the projectile charge dependence in the inverse collision system has been studied for heavy projectiles on lighter target atoms.¹⁸ A much stronger dependence of x-ray

¹³ Loren M. Winters, M.Sc. Thesis, K. S. U., 1972.

¹⁴ Loren M. Winters, James R. Macdonald, Matt D. Brown, Louis D. Ellsworth, and Tang Chiao, Phys. Rev. A 7, 1276 (1973).

¹⁵ J. R. Macdonald, Loren Winters, Matt D. Brown, Tang Chiao, and Louis D. Ellsworth, B.A.P.S. 17, 1145 (1972) and James R. Macdonald, L. M. Winters, Matt D. Brown, Tang Chiao, and Louis D. Ellsworth, Phys. Rev. Lett. 29, 1291 (1972).

¹⁶ James R. Macdonald, L. M. Winters, T. Chiao, E. Pettus, M. D. Brown, and L. D. Ellsworth, Proceedings of the VIII ICPEAC, Belgrade, Yugoslavia, 1973, p. 733.

¹⁷ Loren M. Winters, James R. Macdonald, Matt D. Brown, Tang Chiao, Louis D. Ellsworth, and E. W. Pettus, to be published in Phys. Rev. A Oct., 1973.

¹⁸ J. R. Mowat, I. A. Sellin, D. J. Pegg, R. S. Peterson, Matt D. Brown, and James R. Macdonald Phys. Rev. Lett. 30, 1289 (1973).

yields on projectile charge state has been observed for this situation, and preliminary experiments suggest that the increase in x-ray yield results directly from an enhanced collision mechanism and not just from the factor ~ 3 enhancement of the fluorescence yield in the decay mode.

Following the observation of the surprising dependence of inner shell vacancy production on the incident projectile configuration, we have investigated the dependence of inner shell vacancy production on the atomic number of fully stripped nuclear projectiles.^{19,20} A strong deviation from the Z^2 scaling predicted by all available theoretical models of the ionization process was observed for K-shell vacancy production of bare nuclei of C, N, O and F at energies from 1 to 2 MeV/amu.

A further unexpected observation in heavy ion x-ray production in atomic collisions has been made in single collisions of chlorine ions in various gas targets. The non-monotonic target dependence of Cl K x-ray production²¹ in these single heavy-ion-atom collisions is strong evidence for the importance of many-electron processes in these collisions rather than a single electron promotion.

In the past year, the decay of the transient C-C collision system has been studied by the observation of X-rays with energies greater than

¹⁹ J. R. Macdonald, L. M. Winters, M. D. Brown, L. D. Ellsworth, T. Chiao, and E. W. Pettus, Phys. Rev. Letters 7, 251 (1973).

²⁰ M. D. Brown, J. R. Macdonald, L. M. Winters, L. D. Ellsworth, T. Chiao, and E. Pettus, B.A.P.S., 18, 558 (1973).

²¹ Loren M. Winters, J. R. Macdonald, M. Brown, L. D. Ellsworth, T. Chiao, and E. W. Pettus, Proceedings of the VIII ICPEAC, Belgrade, Yugoslavia, 1973, p. 741.

800 eV.²² The interpretation of these X rays as originating in the decay of molecular levels of the collision system has been used to account for the results. Although the experimental results have a large uncertainty because of absorption complications, the results have been used to support theoretical treatments of the collision system which explain the observed x-ray spectrum in terms of collision broadening of the decay of inner shell levels.^{23,24}

²² J. R. Macdonald, M. D. Brown, and Tang Chiao, Phys. Rev. Lett. 30, 471 (1973).

²³ J. Briggs, private communication and paper presented at the ISIAC Seminar, Paris, 1973.

²⁴ W. Lichten, private communication and paper presented at the ISIAC Seminar, Paris, 1973.

High Resolution Measurements of Target and Projectile X Rays from Ion-Atom Collisions

Patrick Richard and Collaborators

During the past year many important discoveries have been made in the study of X-rays from ion-atom collisions by studying the X-ray spectra with a high resolution crystal spectrometer. Members of the group consist of Dr. Forrest Hopkins, D. O. Elliott K. A. Jamison, R. L. Kauffman and C. W. Woods. Two collaborative efforts were undertaken with C. L. Cocke, M. D. Brown, James. R. Macdonald of our lab and Ivan Sellin and Richard Mowat of the University of Tennessee and Oak Ridge National Laboratory. In addition work initiated at the University of Texas was extended and completed in collaboration with C. F. Moore and D. Olsen.

During the past year, a 4" curved crystal vacuum x-ray spectrometer, Model 25600, purchased from Applied Research Laboratories, Sunland, California, has been set up and used in several different types of experiments. A variety of crystals, including LiF, RAP, KAP, ADP, Ge, NaCl, and lead stearate, have been tested and used in the spectrometer.

The spectrometer has been used to measure X rays from thin and thick solid targets in order to study the ionization process. In addition to the work performed with solid targets, several measurements have been performed with a differentially pumped gas cell which has been adapted to the curved crystal spectrometer. A capacitance manometer and controller, servo-driven valve and controller, and a pressure balance unit have been installed as an automatic pressure control system. Metastable x-ray emission has also been investigated by tracking the x-ray intensity in the beam as a function of time after excitation.

A summary of some of the results of this work is given below:

Using high-resolution studies of K α X rays several investigations of inner-shell ionization reactions have been performed. A study of Al K α X rays

produced by reactions with O, F, and Cl beams at energies greater than approximately 1 MeV/amu has been analyzed to yield probabilities for single and multiple L-shell ionization probabilities deduced from the relative intensities of the K α satellite lines. These calculations were further refined to distinguish between probabilities of vacancy formation in the 2s and 2p shells.²⁵

A simple procedure for computing single and multiple ionization cross sections using the binary encounter approximation (BEA) was developed.²⁶ Comparison with experimental results for ionization produced in a variety of targets by protons, alpha particle, and oxygen beams showed that the BEA predictions of the gross features are in good agreement with the proton and alpha data but disagree with the oxygen data.²⁷ However, under close scrutiny several areas of disagreement are found for the multiple inner-shell ionization of aluminum by alpha bombardment.²⁸ The role of Coster-Kronig transitions in multiply-ionized states was investigated and it was found that the absence of these transitions for single K-shell, multiple L-shell vacancy configurations of elements near aluminum has significant effects in the analysis of x-ray data from heavy-ion collisions.²⁹ Finally, it was discovered that there is a peaked Z-dependence for the production of K-shell vacancies. The ratio of the Cl double K-shell vacancy production to the Cl single K-shell vacancy

²⁵ F. Hopkins, D.O. Elliott, C. P. Bhalla, and P. Richard, Phys. Rev. A, to be published.

²⁶ J.H. McGuire and P. Richard, Phys. Rev. A8, 1374 (1973).

²⁷ R.L. Kauffman, J. H. McGuire, P. Richard, and C. F. Moore, Phys. Rev. A8, 1233(1973).

²⁸ P. Richard, R. L. Kauffman, J. H. McGuire, C. F. Moore, and D. K. Olsen, Phys. Rev. A8, 1369 (1973).

²⁹ C.P. Bhalla and P. Richard, Phys. Lett. 45A, 53 (1973).

production was found to be a maximum around a target Z of 20 for a 30-MeV incident chlorine beam.³⁰

Another anomalous effect reported this year was the discovery of x-ray peaks at energies slightly lower than the lowest energy single electron K x-ray transition in both aluminum and silicon.³¹ The mechanism which produces these low-energy x-ray peaks has not been definitely determined yet, although possible mechanisms have been suggested.

High resolution studies have been made of highly-ionized oxygen, fluorine, and neon X rays. These experiments have allowed identification of H-, He-, and Li-like transitions and their production rates in a variety of experimental conditions.³²⁻³⁵ The Ne K α x-ray transitions were measured as a function of oxygen-projectile charge state and an effective fluorescence yield was extracted.³⁶ Finally metastable x-ray transition lifetimes were measured for the $^3P_1(1s)(2p) - ^1S_0(1s)^2$ and the $^4P_{3/2}(1s)(2s)(2p) - ^2S_{1/2}(1s)^2(2s)$ transitions in both oxygen³⁷ and fluorine.³⁸ A $t^{-3/2}$ dependence was found for cascading through the $^1P_1(1s)(2p)$ state of He-like fluorine, in accord with previous measurements in oxygen.³⁹

³⁰ C.W. Woods, F. Hopkins, R. L. Kauffman, D. O. Elliott, K. A. Jamison, and P. Richard, Phys. Rev. Lett. 31, 1 (1973).

³¹ P. Richard, C.F. Moore, and D. K. Olsen, Phys. Lett. 43A, 519 (1973).

³² R.L. Kauffman, C. W. Woods, F. F. Hopkins, D. O. Elliott, K. A. Jamison, and P. Richard, Journ. of Phys., to be published.

³³ J.R. Macdonald, P. Richard, C. L. Cocke, M. Brown, and I. A. Sellin, Phys.Rev.Lett. 31, 684 (1973).

³⁴ F. Hopkins, C. W. Woods, R. L. Kauffman, and P. Richard, Phys. Rev. A, to be published.

³⁵ M. D. Brown, J. R. Macdonald, P. Richard, J. R. Mowat, and I. A. Sellin, Phys. Rev. A, to be published.

³⁶ R. L. Kauffman, F. Hopkins, C. W. Woods, and P. Richard, Phys. Rev. Lett. 31, 621 (1973).

³⁷ P. Richard, R. L. Kauffman, F. Hopkins, C. W. Woods, and K. A. Jamison, Phys. Rev. A, to be published.

³⁸ P. Richard, R. L. Kauffman, F. F. Hopkins, C. W. Woods, and K. A. Jamison, Phys. Rev. Lett. 30, 888 (1973).

³⁹ P. Richard, Phys. Lett. 45A, 13 (1973).

NUCLEAR PHYSICS PROGRESS

The nuclear interaction of heavy ions has expanded the scope of nuclear physics in recent years. The introduction of high angular momentum and high excitation energy through the use of heavy projectiles has shown many new phenomena which cannot be investigated readily using light-ion projectiles.

With the variety of heavy-ion beams available from the K.S.U. accelerator, it is natural that a major portion of the research by Drs. Eck, Richard, Seaman, Legg and collaborators has concentrated on heavy-ion nuclear physics. However, the choice of nuclear physics experiments is made always on the basis of the physical interest rather than the type of ion used.

Particle Emission from High Excitation in the ^{40}Ca System

F. F. Hopkins, J. S. Eck, D. O. Elliott, Patrick Richard, and J. R. White

The nature of systems formed in the mass 40 region by heavy-ion reactions has received little attention experimentally to date. The use of heavy ions adds new dimensions to reactions involving much lighter bombarding projectiles, specifically the introduction of higher values of angular momentum might be expected to play an important role in determining the distribution of types of particles emitted for a mass 40 system. Data for levels of 43-55 MeV excitation in ^{75}Br , formed by $^{12}\text{C} + ^{63}\text{Cu}$ and $^{11}\text{B} + ^{64}\text{Zn}$ reactions, have been

taken.⁴⁰ These data have shown an increase in α emission as compared to proton emission for the heavier ^{12}C projectile. In addition a calculation for fusion using optical model transmission coefficients by Kowalski, Jodogne, and Miller⁴⁰ predicts the cross-section for $^{50}\text{MeV } ^{16}\text{O}$ incident on ^{27}Al . In these calculations only a small range of angular momentum centered at $J = 18$ contributes significantly to the cross-section. The reactions studied in the present work would reach lower but still substantial values of J . Theoretical treatments are sparse, especially in the energy region reported in this paper. A theoretical paper⁴⁰ dealing with compound nucleus formation (fusion) as compared to transfer reaction rates for the $^{16}\text{O} + ^{27}\text{Al}$ reaction at lab bombarding energies above 50 MeV has provided good agreement with data in that higher energy region.

The present work considers two different entrance channels to the ^{40}Ca system, $^{12}\text{C} + ^{28}\text{Si}$ at carbon bombarding energies of 24-26 MeV and $^{16}\text{O} + ^{24}\text{Mg}$ at oxygen bombarding energies of 30 to 40 MeV.

Reaction products from compound nucleus formation via the $^{16}\text{O} + ^{24}\text{Mg}$ and $^{12}\text{C} + ^{28}\text{Si}$ reactions have been identified by means of γ -ray - γ -ray coincidence techniques. For bombarding energies in the ranges $24 \text{ MeV} \leq E_0 \leq 40 \text{ MeV}$, the light particle emission consists largely of the (2p), (pn), and (np) modes. The data also suggest that single proton and single neutron emissions take place. The relative cross-section for certain of the γ -rays associated with the (2p) and (pn) processes imply a steadily increasing fusion cross-section over the 30 - 40 MeV range.

⁴⁰ R.C. Reedy, M. J. Fluss, G. F. Herzog, L. Kowalski and J. M. Miller, Phys.Rev. 188, 1771 (1969) and L. Kowalski, J. C. Jodogne, and J. M. Miller, Phys.Rev. 169, 894 (1968), and H. Guthrod, (private communication).

Study of One and Two-neutron Transfer Reactions on ^{27}Al using ^{18}O and ^{13}C

Beams

J. S. Eck and S. A. Schiller

Total cross sections for the transfer reactions $^{27}\text{Al}(^{18}\text{O}, ^{17}\text{O})^{28}\text{Al}$, ^{27}Al , and $^{27}\text{Al}(^{13}\text{C}, ^{12}\text{C})^{28}\text{Al}$ were measured in the center of mass energy range 11-17.5 MeV for ^{13}C and 12.6-20.5 MeV for the ^{18}O by observing the residual radioactive nuclei ^{28}Al ($\tau_{1/2} = 2.31$ minutes) and ^{29}Al ($\tau_{1/2} = 6.6$ minutes). A thick target (1.0 mil) of ^{27}Al was bombarded under conditions of constant beam current for a period of 20 minutes for each energy setting. The energy was varied in 0.5 MeV steps. The residual activities were determined by switching the beam off and measuring the yield of 1.28 MeV gamma rays from the first excited state in ^{29}Si and 1.78 MeV gamma rays from the first excited state in ^{28}Si . The ^{28}Si and ^{29}Si are produced by the beta decay of ^{28}Al and ^{29}Al respectively.

Cross sections on the order of 10 millibarns for the $^{27}\text{Al}(^{18}\text{O}, ^{17}\text{O})^{28}\text{Al}$ and $^{27}\text{Al}(^{18}\text{O}, ^{16}\text{O})^{29}\text{Al}$ sections, and on the order of 20 millibarns for the $^{27}\text{Al}(^{13}\text{C}, ^{12}\text{C})^{28}\text{Al}$ reactions were obtained. Possible structure effects indicated by variation in the cross section in the $^{27}\text{Al}(^{18}\text{O}, ^{16}\text{O})^{29}\text{Al}$ reaction in the vicinity of 18.5 MeV in the center of mass are currently being studied further. Also the cross section data for the $^{27}\text{Al}(^{18}\text{O}, ^{16}\text{O})^{29}\text{Al}$ reaction are being compared with cross section data from a paper by Y. Eyal et al.,⁴¹ who studied the reaction. $^{26}\text{Mg}(^{18}\text{O}, ^{16}\text{O})^{28}\text{Mg}$. One would expect similar results due to the similarity in neutron shell structure.

⁴¹ I.Y. Eyal, J. Dastrousky and Z. Fraenkel, Nucl. Phys. A180, 545 (1972).

Elastic Scattering of ^{12}C Ions by ^{28}Si Near the Coulomb Barrier
D. O. Elliott, F. F. Hopkins, J. S. Eck, and Patrick Richard.

Heavy ion transfer reactions are in most cases analyzed in terms of the Distorted Wave approach (DWBA) or the Coupled Channels approach (CCBA). In either case, a detailed knowledge of the entrance channel wave functions is a necessary condition for a meaningful analysis. Most such detailed information comes from optical model analyses of elastic scattering.

We have examined the elastic scattering of ^{12}C on ^{28}Si at energies near the Coulomb barrier. Previous work by Siemssen⁴² and Gale and Eck⁴³ has centered on $^{14,15}\text{N} + ^{28}\text{Si}$, and $^{16,18}\text{O} + ^{28}\text{Si}$ respectively, and from these data Cramer⁴⁴ has developed a Global Optical potential. We have analyzed our data with the optical model program OPTICS by Eastgate et al.,⁴⁵ operating in an interactive mode on the PDP-15 in The Nuclear Studies Laboratory. The resulting optical model parameters are in generally good agreement with Cramers proposed parameters.

⁴² R.H. Siemssen, ANL-7837, p. 145 (unpublished).

⁴³ D.S. Gale and J. S. Eck, P. R. C. 5, 1950 (1973).

⁴⁴ P.J. Eastgate, W. J. Thompson, and R. A. Hardckopt, C. P. C. 5, 64 (1973).

⁴⁵ J.G. Cramer, University of Washington, Seattle, private communication.

Stopping Power of Very Low Velocity Ions by Doppler Shift Measurement

K. C. Shane, H. Laumer and G. G. Seaman

The successful application of Doppler shift measurements of recoil ion velocities to the stopping power of 20 MeV ^{20}Ne ions in aluminum⁴⁶ has led to consideration of extending the technique to much lower energies. Very few measurements have been made of slowing down processes at energies where the so-called nuclear stopping is important, so experiments have been initiated to measure the stopping power or difference in range of ^{40}Ca ions at velocities. Coincidence measurements are made of protons inelastically scattered from the 3 - state at 3.75 MeV in ^{40}Ca and the de-excitation gamma rays for a thin Ca target on a carbon foil where (1) the Ca ions recoil through the carbon and where (2) the Ca ions recoil into the vacuum. The lifetime of the state is long enough for the Ca ions to pass through the foil before decaying. The Doppler-shifted gamma ray energy gives a measure of the velocity of the Ca ion, as well as the amount of multiple scattering. Calculations of the expected energy shift are being made with the Monte Carlo code of Currie.⁴⁷

Neutron Transfer Reactions Induced by ^{13}C Beams

G. G. Seaman and H. Laumer

Measurements of the total reaction cross section for the reaction $^{23}\text{Na} (^{13}\text{C}, ^{12}\text{C}) ^{24}\text{Na}$ have been completed for ^{13}C energies of 9 to 24 MeV. Observation of gamma rays from the .473- and 1.35-MeV excited states in ^{24}Na and from the decay of the ground state to 1.369- and 4.123-MeV states in ^{24}Ne yield values of the population of the ground state and two excited states in ^{24}Na . The sub-coulomb data is being analyzed with a semi-classical DWBA calculation of Alder, Marf, Pauli and Trautmann⁴⁸ to attempt to extract spectroscopic factors.

⁴⁶ K.C. Shane and G. G. Seaman, Phys. Rev. B8, 86 (1973).

⁴⁷ W.M. Currie, Nucl. Instr. and Meth. 73, 173 (1969).

⁴⁸ R. Alder, R. Marf, M. Pauli and D. Trautmann, Nucl. Phys. A191, 399 (1972).

$^{11}\text{B}(^{12}\text{C},\alpha)^{19}\text{F}$ Reaction
W. Hartwig and J. C. Legg

Excitation curves for this reaction at 0° reveal broad peaks in the yield for certain individual states. The widths of these maxima are on the order of 1.5 MeV and they are centered at energies where $\Delta l = 2$ is favored by a grazing particle-transfer reaction forming that state. The angular distributions at these energies are suggestive of a direct-reaction process similar to that suggested by Middleton, Garret, and Fortune⁴⁹ as the mechanism for the $^{12}\text{C}(^{12}\text{C},\alpha)^{20}\text{Ne}$ reaction populating quartet states in ^{20}Ne . The states in ^{19}F which are involved in these reactions are the 1.346-MeV $5/2^-$, 1.459-MeV $3/2^-$, and 4.002-MeV $7/2^-$ states. The wave functions for these states have been calculated by Benson and Flowers⁵⁰ on the basis of $p_{1/2}$ and $p_{3/2}$ holes coupled to ^{20}Ne states. The yields to the various states at their maxima are in good agreement with these calculations, under the assumption that the reactions are direct reactions populating the $p_{3/2}^{-1}(\otimes)2^+$ admixtures to the states.

⁴⁹ R. Middleton, J.D. Garret, and H. T. Fortune, Phys. Rev. Lett. 27, 950 (1971).

⁵⁰ R. G. Benson and B.H. Flowers, Nucl. Phys., A126, 305 (1969).

$^{76}\text{Se}(p,p)^{76}\text{Se}$ Analog Resonances
J. C. Legg and J. W. Gray

Proton elastic scattering excitation curves have been obtained in the range of bombarding energies from 2.0 to 4.5 MeV. Several resonances were observed which could be identified as analogs of states in ^{77}Se . Six resonances were observed for which resonance parameters could be extracted. These lie in the bombarding energy range from 3.7 to 4.4 MeV and are identified as isobaric analogs of ^{77}Se states with excitations between 0.53 MeV and 1.27 MeV. Analysis of these results yields spectroscopic factors which are in reasonably good agreement with those from (d,p) experiments except for the strongest s-wave resonances. This discrepancy in spectroscopic factor and a discrepancy in excitation energies, which is also observed are readily explained by a small mixing of the two analog states by the Coulomb interaction.

APPLIED PHYSICS PROGRESS

Detection of Trace Elements in Flour Samples

G. G. Seaman and R. Martin

Studies of trace elements in flour samples at levels of a few parts per million have been carried out in collaboration with the Grain Science Department K and L X-rays from heavy elements were produced by bombarding thick flour samples with 4 MeV protons and detected with a 200-eV resolution Si(Li) detector. All of the twenty-three samples taken from various stages of the milling process showed amounts of Zn and Br. There were correlations between Zn levels and ash content, and between Br concentration and protein content. This work is now being written up for publication. Consideration is being given to the possibility of using an x-ray machine or x-ray source to carry out on-line analysis at a flour mill.

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1. Dependence of X-Ray Yields in Argon, Krypton, and Xenon upon the Charge State of Fluorine Ions at 35.7 MeV, J. R. Macdonald, L. Winters, M. D. Brown, T. Chiao, and L. D. Ellsworth, Phys. Rev. Lett. 29, 1291 (1972).
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10. Can the $\alpha + {}^{16}\text{O}$ Resonance at 29 MeV be Described by the Optical Model with ℓ -Dependent Absorption, K. A. Eberhard, J. S. Eck, and J. Schille, and W. Trombik, contr. to Int. Conf. on Nucl. Phys., Munich, Aug. 27 - Sept. 1, 1973.
11. Back-Angle Scattering of α -Particles from the Even Ni-Isotopes Between 18 and 27 MeV, K. A. Eberhard, J. S. Eck, W. Trombik, G. Hinderer, H. H. Rossner and A. Weidinger, contr. to Int. Conf. on Nucl. Phys. Munich, Aug. 27 - Sept. 1, 1973.
12. Impact Parameter Dependence of Chlorine K-X ray Production in Violent Cl-Al, Cl-Ti and Cl-Cu Collisions, C. L. Cocke, R. Randall and B. Curnutte, contr. to VIII ICPEAC, Belgrade, July 15-21, 1973.
13. The Importance of Excitation Processes in Inner Shell Vacancy Production in Swift Atomic Collisions, J. R. Macdonald, L. Winters, T. Chiao, E. Pettus, M. D. Brown and L. D. Ellsworth, contr. to VIII ICPEAC, Belgrade, July 15-21, 1973.
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15. Exponential Projectile Charge Dependence of Ar K and Ne K X-Ray Production by Fast, Highly-Ionized Argon Beams in Neon Targets, J. R. Mowat, I. A. Sellin, D. J. Pegg, R. S. Peterson, M. D. Brown, and J. R. Macdonald, contr. to VIII ICPEAC, Belgrade, July 15-21, 1973.
16. Elastic and Inelastic Scattering of ${}^{21}\text{C}$ on ${}^{28}\text{Si}$ Near the Coulomb Barrier, D. O. Elliott, J. S. Eck, P. Richard, and F. F. Hopkins, contr. to Bloomington meeting of APS, 1 - 3 November 1973.
17. α -Particle Elastic and Inelastic Scattering from the Ni Isotopes,

W. Trombik, K. A. Eberhard, and J. S. Eck, contr. to Bloomington meeting of APS, 1 - 3 November 1973.

18. A Systematic Investigation of Back-Angle Enhancement for Elastic α -Particle Scattering, J. S. Eck, K. A. Eberhard, and J. Schiele, contr. to Bloomington meeting of APS, 1 - 3 November 1973.