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OREGON STATE UNIVERSITY

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Corvallis, OR 97331

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3
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Table of Contents

	<u>Page</u>
I. <u>Introduction</u>	1
II. <u>Intermediate Energy Heavy Ion Research</u>	
A. Heavy Target Fragmentation in the Projectile Energy Region From 7.4 to 19 MeV/A	2
III. <u>Relativistic Heavy Ion Research</u>	
A. Target Fragment Energies and Momenta in the Reaction of 4.8 GeV ^{12}C and 5.0 GeV ^{20}Ne with ^{238}U	3
B. The Energy Dependence of ^{209}Bi Fragmentation in Relativistic Nuclear Collisions	21
C. Target Residue Recoil Properties in the Interaction of 8.0 GeV ^{20}Ne with ^{181}Ta	26
D. Energy Variation of Product Mass and Charge Distributions in the Interaction of Relativistic Heavy Ions with Ta and U	33
E. Product Mass and Charge Distributions in the Interaction of Relativistic Heavy Ions with the Rare Earths	40
F. Product Mass and Charge Distributions in the Interaction of 28 GeV Protons with U	45
G. Do Nucleon-Nucleon Collisions Dominate Nucleus-Nucleus Interactions?	48
H. Target Fragment Angular Momentum in Relativistic Nuclear Collisions	52
I. Target Fragment Kinematic Properties in the Interaction of 42 GeV ^{20}Ne with ^{238}U	55
IV. <u>Personnel</u>	60
V. <u>Publications</u>	60
VI. <u>Oral Presentations</u>	61
Appendix--Collected Reprints and Preprints	61

I. Introduction

In this report we summarize the highlights of the work done between 1 September, 1979 and 30 August, 1980 that was supported by USDOE Contract No. DE-AM06-76RL02227, Task Agreement No. DE-AT06-76ER70035, Mod. #A002. The work reported herein is the result of a collaborative effort involving G.T. Seaborg and his research group and the nuclear chemists at Oregon State University. Each project discussed was the result of a joint effort of the two groups, interchanging roles in data acquisition and analysis. The individuals contributing to each project are listed at the end of each section with the names of the Oregon State scientists being underlined. Some of the work reported herein is in its preliminary stages and use of the data contained in these preliminary reports should be made only after consultation with the appropriate authors.

The work described herein is part of a project involving the study of low energy (<10 MeV/A), intermediate energy (10-100 MeV/A), and relativistic (>250 MeV/A) heavy ion reactions, with primary emphasis in the last year being in the latter two areas. An exciting new idea of research started in the past year was the experimental characterization of the changes in target fragmentation reaction mechanisms in the energy regime from 10-100 MeV/A. Target fragment yields, energies, momenta, etc. were measured for the $^{16}\text{O} + ^{197}\text{Au}$ reaction for projectile energies from 7.4 to 19.0 MeV/A. There were modest changes in these properties over this energy region. However, preliminary observations of target fragment yields in the $^{20}\text{Ne} + ^{181}\text{Ta}$ reaction at a projectile energy of 40 MeV/A show dramatic differences from lower energy yield distributions and a greater similarity to higher energy distributions. Thus, the

transition between "low energy" and "high energy" heavy ion reaction mechanisms as evidenced in the product yields appears to occur between 19 and 40 MeV/A.

In the area of relativistic heavy ion (RHI) studies, the two major findings of greatest interest were (a) the observation that the target fragment momenta for the reactions of 8 GeV ^{20}Ne with ^{181}Ta and 4.8 GeV ^{12}C with ^{238}U exceeded momenta observed in relativistic proton-nucleus collisions and were not correctly predicted by current models (intranuclear cascade and firestreak) of these interactions (b) the observation of sidewise peaked light fragment angular distributions from the reaction of 42 GeV ^{20}Ne with ^{238}U , in agreement with theoretical predictions of the formation of compressed nuclear matter in these collisions. Work continued on determination of the variation of target fragment yields with projectile energy in the interaction of RHI's with rare earth targets, Ta and U. In the latter cases, the yields were shown to be in basic agreement with predictions of the firestreak and intranuclear cascade models of these reactions. Preliminary estimates of the target fragment angular momenta based upon fragment isomer ratios agreed with calculations using the intranuclear cascade model.

II Intermediate Energy Heavy Ion Research

A. ✓ Heavy Target Fragmentation in the Projectile Energy Region from 7.4 to 19 MeV/A

Low energy (≤ 10 MeV/A) heavy ion reactions are characterized by a lengthy projectile-target interaction leading to reaction mechanisms such as complete fusion, deep inelastic scattering, quasielastic scattering, etc. depending on the impact parameter associated with the

collision. Typical product yield distributions for a reaction such as $^{16}\text{O} + ^{197}\text{Au}$ at $E_{^{16}\text{O}} \leq 10$ MeV/A are characterized by two peaks centered at the mass number of the projectile and target (from quasielastic and deep inelastic scattering) and a large broad bump centered in between the two peaks representing the fission of the compound nucleus and sequential fission of the target-like fragment. High energy (>250 MeV/A) heavy ion reactions are characterized by a short projectile-target interaction involving some nuclear transparency leading to reaction mechanisms such as spallation and fragmentation. The goal of this research is to experimentally characterize the transition between low energy and high energy target fragmentation in heavy ion reactions.

To accomplish this goal, we have studied the $^{16}\text{O} + ^{197}\text{Au}$ reaction at incident projectile energies of 7.4, 12, 17.1, and 19.0 MeV/A and the $^{20}\text{Ne} + ^{181}\text{Ta}$ reaction at a projectile energy of ~ 40 MeV/A. The quantities measured in these studies were the yields of the target fragments ($\sigma(A,Z)$) using radioanalytical methods and the target fragment kinematic properties using thick target-thick catcher recoil techniques.

The data for the target fragment yields for the $^{16}\text{O} + ^{197}\text{Au}$ reaction are shown in Figure II-A-1, along with other data^{1,2} for similar low energy and high energy reactions. As seen in examining Figure II-A-1, the fragment yields are basically similar for the reaction of 8, 12, 19 MeV/A projectiles with ^{197}Au and very dissimilar to the same yields from reactions initiated by 400 MeV/A projectiles. It does appear that there are increased yields of fragments with $60 \leq A \leq 100$ in the 19 MeV/A bombardment compared to the 12 MeV/A bombardment. These fragments most likely represent sequential fission of the target-like

fragment following a deep inelastic collision. A more detailed examination of the yields of near target fragments is shown in Figure II-A-2 wherein one sees a sharp decrease in the ability to transfer mass to the target-like fragment and have it survive as the projectile energy increases from 12 to 19 MeV/A. This is consistently with the previously noted trends in the fission fragment yields. The trend of the most probable Z for a given A for the various projectile energies reflects similar behavior as the fragment isobaric yields.

Preliminary measurements of the fragment yield distribution in the ~ 40 MeV/A $^{20}\text{Ne} + ^{181}\text{Ta}$ reaction reveal dramatically different product distributions with very small yields of fission fragments ($60 \leq A \leq 140$) and large yields of species with $140 \leq A \leq 180$ similar to high energy heavy ion reactions. Comparison of these data with the known systematics^{3,4} of light ion Ta reactions at lower projectile energies shows that large changes in the reaction mechanism(s) governing the product yields in these reactions must take place between projectile energies of 20 and 40 MeV/A. Further experiments to measure the target fragment kinematic properties in the energy range from 20-86 MeV/A are planned using the facilities of the LBL 88" cyclotron, the LBL Bevalac and the CERN SC synchrotron.

Figure II-A-3 shows the longitudinal component of the velocity imparted to the target fragment in the first stage of the projectile-target interaction (in units of c), β_{11} , plotted as a function of fragment mass number A for the reaction of 12, 19 MeV/A ^{16}O and 400 MeV/A ^{12}C (ref 5) with ^{197}Au . One can see that fragments with $120 \leq A \leq 140$ in the 12 MeV/A bombardment have source velocities corresponding to fission of the compound nucleus while the fragments with $60 \leq A \leq 100$

result from the fission of a system moving with a lower velocity, presumably sequential fission of a target-like fragment. In the 19 MeV/A bombardment, the $120 \leq A \leq 140$ fragments result from the fission of a nucleus whose velocity is considerably less than the compound nucleus. Recent work⁶ with the $^{16}\text{O} + ^{238}\text{U}$ reaction would suggest that these nuclei are products of incomplete fusion (or massive transfer) reactions with the "missing momentum" appearing in light particle emission. The data for the two lower energy bombardments shows considerably more momentum transfer in the projectile target interaction than observed in the high energy reaction.

(W. Loveland, P.L. McGaughey, R.M. McFarland, K.J. Moody, R.J. Otto and G.T. Seaborg)

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Fig. II-A-1 Target fragment isobaric yields from the reaction of 12 and 19 MeV $^{16}\text{O} + ^{197}\text{Au}$ (this work, 8 MeV/A $^{20}\text{Ne} + ^{197}\text{Au}$ (Binder¹) and 400 MeV/A ^{20}Ne with ^{197}Au (Morrissey et al.²).

Fig. II-A-2 Target fragment isotopic yields for the
reaction of 12 MeV/A and 19 MeV/A ^{16}O
with ^{197}Au .

Fig. II-A-3 Target fragment longitudinal velocity component $\beta_{||} (=v_{||}/c)$ corresponding to that component of the fragments velocity contributed by the initial projectile target interaction (as given in the two step vector model). Data are shown for the reaction of 12 MeV and 19 MeV/A ^{16}O with ^{197}Au (this work) and the reaction of 400 MeV/A ^{12}C with ^{197}Au (Kaufman, et al.⁵).

III. Relativistic Heavy Ion Research

A. Target Fragment Energies and Momenta in the Reaction of 4.8 GeV ^{12}C and 5.0 GeV ^{20}Ne with ^{238}U

The study of the fragmentation of a ^{238}U target nucleus by relativistic heavy ion (RHI) projectiles has revealed many new and interesting phenomena, particularly in regard to the yields of the survivors of deep spallation processes (with $A_{\text{fragment}} > 150$). To better understand these phenomena, we measured the target fragment energies and momenta for two such reactions ($4.8 \text{ GeV } ^{12}\text{C} + ^{238}\text{U}$ and $5.0 \text{ GeV } ^{20}\text{Ne} + ^{238}\text{U}$) using the thick target-thick catcher recoil technique. Details of the experimental techniques and data analysis have been described previously.¹

A portion of the results of these studies for the reaction of 4.8 GeV $^{12}\text{C} + ^{238}\text{U}$ is shown in Figure III-A-1. Here the fraction of target fragments recoiling forward from the target relative to the fraction recoiling backward (F/B) along with the target fragment energies is shown as a function of the product mass number A and the displacement ($Z - Z_A$) of the fragment atomic number, Z , from the non-integral Z corresponding to the center of the valley of β -stability, Z_A . In this figure one sees evidence for the occurrence of several different processes.

The lightest fragments ($A < 40$) are characterized by high kinetic energies and large values of F/B which is consistent with their production in a "fragmentation" mechanism. The heaviest fragments ($A > 150$) are neutron-deficient, show very large values of F/B and very low fragment kinetic energies. Undoubtedly, these products are the result of deep spallation of ^{238}U nuclei. The intermediate mass products ($80 \leq A \leq 140$) are a complex mixture of fission and deep spallation products. The most n-rich products ($90 \leq A \leq 110$) are mostly fission fragments (F/B ~ 1 , high

kinetic energies). The mass and atomic numbers of these products and their kinetic energies are consistent with their formation in the fission of a species with $A \sim 210$, $Z \sim 85$ with some slight admixture of deep spallation products. Their kinetic energies are too low to be consistent with the fission of uranium-like species, a phenomenon similar to that observed in such high energy induced reactions such as photon-induced fission where fission occurs primarily at the end of the evaporation chains involved in de-excitation of the primary target fragments.

The group of fragments with $40 \leq A \leq 70$ represents an interesting class of events. Their kinetic energies are relatively high and the values of F/B are also larger ($2 \leq F/B \leq 3$). One possible explanation of the origin of these events is that they represent the products of the fission of a species with $A \sim 120-130$. Their kinetic energies are completely consistent with this idea and their F/B ratios would indicate their formation in a non-peripheral collision. The other part of this scenario would be the large group of neutron-deficient products with $120 \leq A \leq 140$ which represent the non-fissioning survivors of the precursors of the $40 \leq A \leq 60$ events.

In Figure III-A-2, we show a comparison between measured and calculated values of the longitudinal velocity $\beta_{||} (=v_{||}/c)$ imparted to the fragment in the first step of the projectile-target interaction for the 4.8 GeV $^{12}\text{C} + ^{238}\text{U}$ reaction. The calculations of $\beta_{||}$ were made using the intra-nuclear cascade model of Yariv and Fraenkel³ and the firestreak model.⁴ The measured values of $\beta_{||}$ selected for use in Figure III-A-2 are for neutron deficient species. This selection was made to emphasize deep spallation reactions and to de-emphasize fission, i.e., to select products from collisions with significant projectile-target overlap. As one

can see from examining Figure III-A-2, the cascade model grossly overestimates the values of $\beta_{||}$ for all fragments with $A < 209$ with the firestreak model predictions also in gross disagreement with the experimental data. This situation may be analogous to the overestimates of the deep spallation product momenta in proton-nucleus collisions by cascade calculations.⁵ Crespo, Cumming, and Alexander⁵ speculated that the primary spallation products might emit fragments such as ^{24}Na thus reducing the spallation product momenta and providing a natural mechanism for producing the high momenta associated with these light fragments. This mechanism is reasonable given the calculated excitation energies (firestreak model) of the precursors of the $A = 160-190$ fragments which range in energy from 595 to 380 MeV, respectively.

(W. Loveland, Cheng Luo, P.L. McGaughey, D.J. Morrissey and G.T. Seaborg)

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Fig. III-A-1 A contour plot of the fragment kinetic energies $\langle E \rangle$ and F/B ratios as a function of the fragment mass number A and the position of the fragment relative to the center of the valley of β -stability, $Z-Z_A$.

Target Fragment Energies

48 GeV $^{12}\text{C} + ^{238}\text{U}$

Fig. III-A-2 A comparison of the calculated and measured
values of $\beta_{||}$ • XBL 808-1743.

B. The Energy Dependence of ^{209}Bi Fragmentation in Relativistic Nuclear Collisions

An ambiguous point in the description of relativistic heavy ion (RHI) reactions is the amount of excitation energy deposited in the spectator fragments by the interaction. Various models of the fast interaction generate primary fragments with varying amounts of excitation energy which after de-excitation reproduce the experimental results for light nuclei. Although direct measurements of this excitation energy are difficult, one can follow the trend of primary fragment excitation through some relatively simple experiments. Excitation energy in a high mass (but relatively non-fissionable) nucleus at low angular momentum is carried off mostly by evaporated neutrons. Thus, if the primary fragment cross section distributions are governed by geometry, then differences in the N/Z ratio of final residues of RHI reactions as a function of bombarding energy (same projectile and high mass target) will represent differences in the excitation energy.

Following this idea, we report the variation of the production of gold isotopes from three RHI reactions with ^{209}Bi . In these experiments bismuth metal foils surrounded with Mylar catchers were irradiated with beams of 4.8 GeV (0.40 GeV/A) ^{12}C , 8.0 GeV (0.40 GeV/A) ^{20}Ne and 25.2 GeV (2.1 GeV/A) ^{12}C ions from the LBL Bevalac facility. The target fragmentation products stopped in the target or catcher foils and the induced radioactivities were measured by direct gamma ray spectroscopy and by gamma ray spectroscopy of a chemically separated gold fraction.¹ The gamma ray emitting nuclei were identified using standard techniques² and the production cross sections were calculated for those activities observed in the unseparated foils.

The measured cumulative yield cross sections (which include contributions from nuclei produced by radioactive decay) were corrected for this decay feeding by an iterative fitting of Gaussian distributions to the decay-corrected (and independent yield) cross sections.² The resulting calculated and measured independent yield cross sections $\sigma(Z,A)$ are shown in Figure III-B-1. The yield of ^{194}Au is depressed relative to the other nuclidic yields in all the reactions for reasons that are not clear.

Cursory inspection of Figure III-B-1 shows that the distributions of Au fragments are very similar for the three reactions studied in this work. A more detailed examination of the data shows that there is a slight (≈ 1 amu) shift of the distribution centroids toward larger A values as the projectile energy increases. Thus, although the incident projectile energy changes by over 20 GeV, the excitation energy imparted to target fragments changes by less than 10 MeV.

We are left with the question of whether this apparent saturation in energy transfer is predicted by current models of fragmentation reactions. One highly developed model of such collisions which makes predictions about the fragmentation products is the intranuclear cascade model of Yariv and Fraenkel.³ The results of the calculations of the position of the centroid of the gold isotopic distributions using this model are in approximate agreement with the results of our study but predict values of the distribution centroids which are systematically more neutron deficient ($\sim 1-2$ amu) than our data. Thus, the experimentally observed limiting fragmentation behavior of high mass nuclei is predicted by this model of relativistic nucleus-nucleus collisions.

What universal feature of RHI reactions is responsible for this behavior? In this case involving very peripheral collisions (impact parameter $b \approx 9 \text{ fm} \geq R_{Bi} \approx 7.0 \text{ fm}$), it is simply a matter that the predicted changes in experimental distributions are very small compared to the sensitivity of the experimental measurement. Unfortunately, selection of events involving more central events suffer from the fact that such events integrate more fully the primary reaction processes through the subsequent de-excitation of the primary fragments. We conclude that the observation of limiting fragmentation behavior in yield distributions can be produced by a variety of effects, none of which are connected to the central issue of transfer of projectile kinetic energy into internal excitation.

(K. Aleklett[†], D.J. Morrissey, W. Loveland, P.L. McGaughey, and G.T. Seaborg)

References

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1. The bismuth metal foils were dissolved in conc. HCl-conc. HNO₃ (1:2) with carriers. After dissolution, excess NO₂ was driven off, the solution was cooled and diluted with water. The Au was extracted twice into ether, washed twice with 1.5 M HCl and plated on Pt. This procedure required approximately 25 minutes.
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Fig. III-B-1 The isotopic production cross sections for gold products from the reaction of 4.8 and 25.2 GeV ^{12}C and 8.0 GeV, ^{20}Ne with ^{209}Bi are shown. The lines represent the best Gaussian fit to each distribution with the arrows showing the distribution centroids.

C. Target Residue Recoil Properties in the Interaction
of 8.0 GeV ^{20}Ne with ^{181}Ta

We report the results of an interlaboratory study of the target fragment momenta and energies from the reaction of 8.0 GeV ^{20}Ne with ^{181}Ta . We found that the fragment kinetic properties are considerably different than those found in the reaction of 25 GeV $^{12}\text{C} + ^{181}\text{Ta}$ and furthermore, the specific product forward momenta observed in the reaction of 8 GeV $^{20}\text{Ne} + ^{181}\text{Ta}$ exceed those in relativistic proton induced reactions with heavy targets.

The experimental technique used to measure the target fragment recoil properties was the thick target-thick catcher technique. Independent foil stacks from each of the participating laboratories were irradiated simultaneously and the product radioactivities assayed by off-line γ -ray spectroscopy. The results of these measurements are presented as the fractions of each radionuclide which recoiled out of a target into the forward and backward directions, F and B, respectively. The forward to backward ratios, F/B, for various target fragments are shown in Figure III-C-1 along with data from similar proton induced reactions. (All data are the weighted averages of the measurements of the different laboratories which, in general, agreed within experimental uncertainty.) The results were transformed into kinematic quantities using the simple two step vector model of high energy nuclear reactions. In this model, each target fragment kinematic property is decomposed into two components, one resulting from an initial fast projectile - target interaction (the "abrasion step" of the abrasion-ablation model) and another resulting from the slow de-excitation of the excited primary fragment (the ablation step).

The general variation of F/B values with product mass shown in Figure III-C-1 is similar to that observed in the interaction of relativistic protons ($1 \leq E_p \leq 300$ GeV) with heavy targets. However, a detailed comparison of the F/B values measured in this work for the reaction of 8 GeV ^{20}Ne with similar values from proton-induced reactions reveals that while the trend of F/B with product mass A is similar for all systems, the product F/B values for the 8 GeV $^{20}\text{Ne} + ^{181}\text{Ta}$ reaction exceed any equivalent values for the other reactions. From these F/B values (and the forward velocity or angular distributions they represent) we can conclude that limiting fragmentation (with respect to kinetic properties) have not been attained in the interaction of 8 GeV ^{20}Ne with ^{181}Ta . This conclusion is based upon the non-equivalence of the F/B values for the reaction of 8 GeV ^{20}Ne with ^{181}Ta (this work), 25 GeV ^{12}C with ^{181}Ta ¹ and 25 GeV ^{12}C with ^{197}Au ².

It is instructive to compare the momenta imparted to selected target fragments in the ablation phase (or second step) of the reaction since variation of this property with changes of projectile type and energy can reveal the extent to which the ablation phase of the reaction mechanism is influenced by the abrasion process which occurs during the initial projectile-target interaction. Figure III-C-2 shows a plot of $\langle P \rangle$, the component of the target fragment momenta due to the ablation phase of the reaction versus A for the spallation of Ta by 8 GeV ^{20}Ne and by protons of 0.45, 0.58, and 19 GeV.

For the 8 GeV ^{20}Ne induced reaction a steady increase in $\langle P \rangle$ is observed as one moves from near-target products to those that have resulted from the removal of ~ 50 nucleons from ^{181}Ta . This increase in

$\langle P \rangle$ goes approximately as $\sqrt{\Delta A}$, and is indicative of sequential, step-wise momentum "kicks" being imparted, in a random walk fashion, to the ablating target fragment. The general pattern based on these results for Ta and those for Au targets is that the ablation phase of reactions leading to products with $\Delta A \lesssim 50$ is essentially energy and projectile invariant.

(W. Loveland, D.J. Morrissey, K. Aleklett**, G.T. Seaborg, S.B. Kaufman***, E.P. Steinberg***, B.D. Wilkins***, J.B. Cumming⁺, P.E. Haustein⁺, and H.C. Hseuh⁺)

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Fig. III-C-1 Comparison of target fragment F/B ratios for various relativistic proton and heavy ion reactions with ^{181}Ta and ^{197}Au .

Fig. 3/

XBL 801-71

Fig. III-C-2 Dependence of fragment momentum on product mass for the interaction of ^{20}Ne ions and protons with Ta. Data points are for: 8 GeV ^{20}Ne , the present work; 0.45 GeV ^1H , o, ref. 7; 0.58 GeV ^1H , ref. 10 and 19 GeV ^1H , +, , also ref. 10. The solid curve through the filled circles for $A > 130$ is given by $P = 5.15 \sqrt{\Delta A}$ where $\Delta A = 181 - A$. The uppermost curve is a parabola through the open circles.

Fig. 83

XBL 805-970

*

D. Energy Variation of Product Mass and Charge Distributions in the Interaction of Relativistic Heavy Ions with Ta and U

The yields of various target fragments of differing A and Z in relativistic nuclear collisions are measures of some details of the projectile-target interaction and the excitation energy transferred to the target nucleus in the interaction. If the velocity of the incident projectile becomes high enough, then the projectile-target nucleus interaction time approaches a constant value and experimental product distributions, such as the yield distribution, do not change with further increases in projectile energy. This behavior, termed "limiting fragmentation" appears to dominate the yield distributions in the interaction of relativistic heavy ions (RHI's) with low mass targets, such as Cu, for projectile energies from ~ 4 GeV on up.⁽¹⁾ Sometime ago, we initiated a program to systematically survey the changes in product yield distributions as a function of projectile energy for the heavy targets Ta and U. The use of heavy targets should allow the occurrence of more collisions in which the central densities of the projectile and target nuclei overlap considerably compared to light nuclei, such as Cu.

To date, we have performed experiments to measure these target fragment yield distributions in the reaction of 3 GeV ^{12}C , 5 GeV ^{20}Ne , 8 GeV ^{20}Ne , 21 GeV ^{20}Ne , 25 GeV ^{12}C , 28 GeV p and 42 GeV ^{20}Ne with ^{181}Ta and 3 GeV ^{12}C , 4.8 GeV ^{12}C , 5.0 GeV ^{20}Ne , 8.0 GeV ^{20}Ne , 12 GeV ^{12}C , 21 GeV ^{20}Ne , 25 GeV ^{12}C , 28 GeV p and 42 GeV ^{20}Ne with ^{238}U . In Figure III-D-1, we show the results of the analysis of these experiments for the reaction of 5 GeV ^{12}C , 8 GeV ^{20}Ne , 21 GeV ^{20}Ne , 25 GeV ^{12}C , with ^{181}Ta . In general, the variation of product yield with mass number A appears similar for these systems, except, perhaps, for some slight

enhancement in the yields in the 21 GeV $^{20}\text{Ne} + ^{181}\text{Ta}$ reaction. The situation for U is quite different as shown in Figure III-D-2. Here one sees a dramatic increase in heavy residue yields as the incident projectile energy increases from 8 to 25 GeV.

We have attempted to compare these experimental product yield distributions with predictions of two current models of relativistic nuclear collisions, the intranuclear cascade model of Yariv and Frankel² and the nuclear firestreak model³. As pointed out in part previously⁴, the experimental target fragment distributions for the interaction of RHI's with Ta are well described by the intranuclear cascade model and more recently, they have been properly described by the firestreak model. The general shape of the distribution of products with $A > 100$ is governed by the geometry of the colliding nuclei (as evidenced by this shape being given correctly by the simple-abrasion ablation model.⁵) For the interactions of RHI's with U, the general shape of the target fragment yield distribution, especially the yields of heavy residues ($A > 160$) is governed primarily by the excitation energy given to the target fragments in the primary projectile-target interaction and the details of the variation of fission barriers with A, etc. It is possible to reproduce the general features of the fragment mass distributions in these systems, i.e., the large yield of fission fragments with $60 \leq A \leq 140$ and the appearance of significant yields of heavy residues which are the non-fissioning survivors of intermediate impact parameter collisions using the nuclear firestreak model and reasonable assumptions about the variation with A, Z, and E^* of Γ_f , Γ_n , Γ_p , etc.

(W. Loveland, P.L. McGaughey, D.J. Morrissey, L.L. Nunnolley, C. Oertel, and G.T. Seaborg)

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Figure III-D-1 Target Fragment yield distributions for the interaction of 5 GeV ^{20}Ne , 8 GeV ^{20}Ne , 21 GeV ^{20}Ne and 25 GeV ^{12}C with ^{181}Ta .

Figure III-D-2 Product mass distributions from the interaction of 25 GeV ^{12}C , 8 GeV ^{20}Ne and 28 GeV p (reference 6) with U.

E. Product Mass and Charge Distributions in the Interaction of Relativistic Heavy Ions with the Rare Earths

The interaction of relativistic heavy ions (RHI's) of varying energies with target nuclei of Cu, Ag, Ta and U has been reported previously.¹ We have felt that the development of a general systematics of the Z, A variation of target fragment yields and kinematic properties will be aided by measurement of these quantities in the interaction of RHI's with rare earth nuclei. Furthermore, the use of rare earth targets known to have widely differing ground state deformations and "softness" should help us to explore the feasibility of using RHI reactions as probes of nuclear ground state correlations, as suggested previously.⁴⁻⁶ Therefore, in the past year we have measured the target fragment yields and kinematic properties in the reaction of 3 GeV ^{12}C , 8 GeV ^{20}Ne , 12 GeV ^{12}C , and 28 GeV p with ^{165}Ho along with the interaction of 12 GeV ^{12}C with ^{144}Sm and ^{152}Sm .

We wish to report the results from the study of the interaction of 8 GeV ^{20}Ne with ^{165}Ho . A ^{165}Ho metal foil target of thickness 114 mg/cm² was enclosed between two mylar catcher foils and irradiated with 3.6×10^{13} ^{20}Ne ions from the LBL Bevalac. Gamma-ray spectrometric measurements of the radioactivity induced in the target and catcher foils began approximately one hour after bombardment and continued for five weeks. Approximately 60 radionuclides were identified in each target on the basis of their γ -ray energy, half-life and radiation abundances. No corrections were made for the contribution to foil activities from secondary induced reactions because previous studies had shown such corrections to be negligible for similar targets and experimental conditions.

Independent and cumulative radionuclide yields were calculated from the radioactivity measurements on the irradiated foils. Using procedures described elsewhere,² independent yield formation cross sections were calculated for all radionuclides, Gaussian charge dispersions [of the form $P(Z,A) = (2\pi\sigma^2)^{-\frac{1}{2}} \exp(-(Z - Z_p)^2/2\sigma^2)$] were fitted to the data, and the charge dispersions were integrated to give the isobaric yields.

Figure III-E-1 shows the measured isobaric yield distributions for the 8 GeV $^{20}\text{Ne} + \text{Ho}$ reaction along with the previously studied 21 GeV $^{20}\text{Ne} + \text{Ho}$ reaction.³ The product yield distributions are in striking agreement, in accord with similar findings for the RHI + Ta reaction. Also, as discussed previously, the general shape of the product yield distributions from these reactions is in accord with predictions of the simple abrasion-ablation model.

We hope to see if the same trends for target fragment kinematic properties and yields (at other projectile energies) are followed for the RHI + Ta and RHI + Ho systems along with attempts to see if the target ground state deformation or softness affect the fragment yields in a measurable way.

(R.H. Kraus, Jr. and W. Loveland)

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Figure III-E-1 Target fragment isobaric yield distributions for the interaction of 8 and 21 GeV ^{20}Ne with ^{165}Ho .

F. Product Mass and Charge Distributions in the Interaction of 28 GeV Protons with U

The study of the fragmentation of a ^{238}U target nucleus induced by relativistic heavy ion (RHI) projectiles from the outset has revealed many new and interesting phenomena. In the first measurements of the yields of target fragments of differing Z and A from the reaction of 25.2 GeV ^{12}C with ^{238}U , Loveland et al.¹ found, in addition to the expected yields of fission fragments, surprisingly large yields of fragments with $160 \leq A \leq 190$. (See Figure III-D-2.) Subsequent measurements by McGaughey et al.² for the reaction of 8.0 GeV ^{20}Ne with ^{238}U showed a smaller enhancement of these heavy product yields (see Figure III-D-2) but the yields of these products still appeared to exceed any such yields observed^{3,4} in the reaction of 28 GeV protons with U.

Because of the paucity of data for fragments with $180 \leq A \leq 200$ in the reaction of 28 GeV protons with ^{238}U , we thought it to be of interest to determine these yields radiochemically as well as to remeasure the product yield distribution for this reaction. A natural uranium foil of thickness 33.5 mg/cm^2 was irradiated for 63 minutes in a beam of 28 GeV protons of intensity 7.8×10^{13} protons/min. from the Brookhaven AGS. (The beam intensity was measured using the $^{27}\text{Al}(p, 3p_n)$ ^{24}Na and $^{27}\text{Al}(p, 3p_n)^{22}\text{Na}$ monitor reactions.) Following shipment to Berkeley, one-half of the target was subjected to direct γ -ray spectroscopy while a chemical separation procedure developed by Kratz et al.⁵ was used on the other half. The unseparated foil and chemical fractions involving the halogens, metals forming volatile bromides, and the heavy metals were counted with a $60 \text{ cm}^3 \text{ Ge(Li)}$ detector for a period of 25 days following the end of bombardment.

Using a data analysis scheme outlined previously⁶, 88 radionuclides were identified in the chemically separated fractions while 85 nuclides were identified in the unseparated foil. Chemical yields were determined using tracers or by normalization to yields in the unseparated foil. For those nuclides measured by both groups the measured nuclidic production cross sections agreed within experimental error with those measured by Friedlander et al.^{3,4} Using techniques described previously⁷, isobaric yields are being computed. Preliminary results, reported previously⁸, indicate isobaric yields of species with $185 \leq A \leq 205$ to be ~ 10 mb, indicating significant survival of these deep spallation products in the proton induced reactions.

(B.V. Jacak, W. Loveland, D.J. Morrissey and G.T. Seaborg).

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G. Do Nucleon-Nucleon Collisions Dominate Nucleus-Nucleus Interactions?

DeVries and Peng have pointed out recently⁽¹⁾ that the total reaction cross section in light projectile-intermediate mass target interactions shows an energy dependence very similar to that of the nucleon-nucleon interaction. From this behavior they infer a significant transparency in composite projectile-nucleus collisions. We thought it would be interesting to examine these effects in the interaction of heavier ions (C, O, Ne) with heavy targets (Ta, Au) where more of the total reaction cross section involves collisions in which there is significant overlap between the central densities of projectile and target.

As our measure of these effects, we have examined the energy dependence of the reaction cross section leading to radioactive products in heavy ion-heavy nucleus collisions. This cross section, determined by summing the isobaric yields of the target fragments with $A > 40$, is certainly a lower limit on the total reaction cross section since it excludes inelastic scattering and multi-particle breakup channels.

In Figure III-G-1, we show the nucleon-nucleon interaction cross section and the $^{20}\text{Ne} + ^{181}\text{Ta}$ "radioactive residue cross section" as a function of energy. In compiling the data for Figure III-G-1, data from several different reactions were combined together to form the $^{20}\text{Ne} + ^{181}\text{Ta}$ data base by scaling the results from the $^{16}\text{O} + ^{181}\text{Ta}$, $^{20}\text{Ne} + ^{197}\text{Au}$, $^{12}\text{C} + ^{181}\text{Ta}$ and $^{16}\text{O} + ^{197}\text{Au}$ reactions by their geometrical cross sections, $\sigma_g = \pi(R+x)^2$. In using this equation, R was set equal to $R_{\text{proj.}} + R_{\text{tgt.}}$ where $R_i = r_0 A_i^{1/3}$; with $r_0 = 1.30$. E is the center-of-mass energy and λ the reduced wave length of the incident projectile.

The results shown in Figure III-G-1 do not offer any evidence for considerable transparency in the $^{20}\text{Ne} + ^{181}\text{Ta}$ reaction, particularly when compared to transparencies seen in composite particle ($d, \alpha, ^3\text{He}$) reactions with light nuclei (^{12}C). Either this transparency is not present in heavy ion-heavy target interactions or it manifests itself in the reaction channels not included in the radioactive residue cross sections or ? Through planned experiments in the projectile energy range from 20-100 MeV/A (see Section II-A), further confirmation of the experimental data will be obtained.

(W. Loveland)

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Figure III-G-1 The $^{20}\text{Ne} + ^{181}\text{Ta}$ reaction cross section leading to products with $A > 40$ and the nucleon-nucleon cross sections as a function of projectile energy.

H. Target Fragment Angular Momentum in Relativistic Nuclear Collisions

One very important dynamical parameter that characterizes any heavy ion induced nuclear reaction is the angular momentum transfer between projectile and target in the interaction. For the interaction of relativistic heavy ions (RHI's) with medium or high mass targets, very little experimental information concerning this transfer is available. From data on relativistic heavy ion induced fission⁽¹⁾, the average value of the transferred angular momentum is $J_{\text{rms}} \leq 13 \hbar$.

Another potential source of information about the transferred angular momentum in collisions of intermediate impact parameter is the yield of states of differing spin in a single target fragment, i.e., the fragment isomer ratio. Several measurements⁽²⁾ exist of the yield of high spin and low spin states of near-target fragments from the interaction of 25.2 GeV ^{12}C with Bi and Pb. In all such cases, there is preferential population of low spin ($J \sim 2$) states compared to high spin states ($J \sim 12$). The problem in quantitatively interpreting these observations has been to relate these isomer ratios to the initial spin populations of their precursors by reconstructing the particle evaporation and γ -ray decay leading from the precursor to the final isomer ratio.

Recently Rudstam has published⁽³⁾ a formalism (along with a convenient computer program) to simulate the particle evaporation- γ -ray decay process following high energy reactions. We have used this formalism, along with a trial and error procedure to calculate the angular momentum transfer in peripheral reactions leading to the production of Ir and Au fragments in the reaction of 25.2 GeV ^{12}C with Pb and Bi, respectively.

We have arrived at a $J_{\text{rms}} \sim 6 \pm 2 \hbar$ for these events, in good agreement with predictions of the intranuclear cascade calculation of Yariv and Fraenkel of $J_{\text{rms}} \sim 6.5 \hbar$ for these events. It will be of interest to see if this agreement between experiment and theory persists for more central collisions such as those producing Ir fragments from ^{238}U or if more sophisticated treatments of the de-excitation of the fragments change these conclusions.

(W. Loveland, P.L. McGaughey and G.T. Seaborg).

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I. Target Fragment Kinematic Properties in the Interaction of 42 GeV ^{20}Ne with ^{238}U

Since the first measurements of the yields of target fragments from the interaction of relativistic heavy ions (RHI's) with U, it has been apparent that many new and interesting phenomena were to be found. Last year, we began a systematic program of study of the kinematic properties of the fragments from the interaction of RHI's with U. The first results of that study (see Section III-A) revealed new phenomena not seen in p-U collisions and phenomena that are not understood in terms of current theoretical models of relativistic nuclear collisions. During the past year we also measured the target fragment energies, momenta and angular distributions in the interaction of 3 GeV ^{12}C , 12 GeV ^{12}C , and 42 GeV ^{20}Ne with ^{238}U . Preliminary results are just becoming available for one of these experiments, the reaction of 42 GeV ^{20}Ne with ^{238}U .

Using techniques described previously (see Section III-A), we measured the target fragment recoil properties using the thick target-thick catcher technique. The target fragment ranges appear to be similar to those ranges observed in p-U interactions and in the interaction of 4.8 GeV ^{12}C or 5.0 GeV ^{20}Ne with ^{238}U . The ratio of the products recoiling forward (F) from the target foil to those recoiling backward (B) is near unity for all products measured to date, a dramatic decrease in F/B when compared to the results of experiments involving the reaction of 4.8 GeV ^{12}C or 5.0 GeV ^{20}Ne with ^{238}U . (See Figure III-I-1.) This decrease in F/B with increasing projectile energy is analogous to similar trends observed in p-U collisions. The decrease may be due to either the occurrence of isotropy in the target fragment angular distributions or the occurrence of sidewise-peaking.

To test these hypotheses, we measured the detailed angular distribution of various target fragments from the interaction of 42 GeV ^{20}Ne with a thin U target. In actuality, 15 identical target-conical catcher assemblies were irradiated simultaneously, the catchers cut into pieces representing the angular ranges 0-30°, 30-50°, 50-70°, and 70-90°, and the catcher pieces of similar angular range combined and counted. As of this date, only the data for two short-lived radionuclides, a typical fission fragment, ^{99}Mo , and a typical light fragment, ^{43}K have been analyzed. These data are shown in Figure III-I-1. The ^{99}Mo angular distribution is isotropic in agreement with previous observations for gross fission fragment angular distributions. This isotropic distribution is consistent with previous notions of RHI-induced fission of U resulting from the most peripheral collisions in which little angular momentum is transferred to the fissioning system.

The ^{43}K angular distribution is sidewise-peaked. This observation is especially exciting in view of theoretical predictions² that exactly such events are the signature of the production of highly compressed states of nuclear matter in the projectile-target interaction although we should note that similar sidewise-peaked light fragment angular distributions have been observed in high energy p-U interactions. We are continuing our analysis of this data to measure the angular distributions of other target fragments and we are hoping for an opportunity to experimentally confirm these observations.

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Figure III-I-1 A summary of data on the spatial distribution of target fragments from the interaction of 42 GeV ^{20}Ne with ^{238}U .

Spatial Distribution of Target Fragments

42 GeV $^{20}\text{Ne} + ^{238}\text{U}$

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V. Publications

A. Articles in Print

1. "An Interactive Computerized System for the Analysis of Gamma Ray Spectra from Heavy Ion Reactions," D.J. Morrissey, R.J. Otto, D. Lee, J.O. Liljenzin, I. Binder, M.M. Fowler, W. Loveland, and G.T. Seaborg.
2. "Target Residues from the Reaction of 8 GeV ^{20}Ne with ^{181}Ta and ^{197}Au , D.J. Morrissey, W. Loveland, M. de Saint-Simon, and G.T. Seaborg, Phys. Rev. C 21, 1783 (1980).
3. "Target Fragment Energies and Momenta in the Reaction of 4.8 GeV ^{12}C and 42 GeV ^{20}Ne with ^{238}U ," W. Loveland, Cheng Luo, P.L. McGaughey, D.J. Morrissey and G.T. Seaborg, Proc. Int'l. Conf. on Nucl. Physics, Lawrence Berkeley Laboratory Report LBL-11118, August, 1980.

B. Articles in Press

1. "Relativistic Heavy Ion Induced Fission of Uranium," W. Loveland, P. McGaughey, D.J. Morrissey, R.J. Otto, R.H. Kraus, Jr., and G.T. Seaborg, Physics and Chemistry of Fission (IAEA, Vienna).

C. Articles Submitted for Publication

1. "The Energy Dependence of ^{209}Bi Fragmentation in Relativistic Nuclear Collisions," K. Aleklett, D.J. Morrissey, W. Loveland, P.L. McGaughey and G.T. Seaborg, Phys. Rev. C (LBL-11273).
2. "Target Fragment Energies and Momenta in the Reaction of 4.8 GeV ^{12}C and 5.0 GeV ^{20}Ne with ^{138}U ," W. Loveland, Cheng Luo, P.L. McGaughey, D.J. Morrissey, and G.T. Seaborg, Phys. Rev. C.
3. "Target Residue Recoil Properties in the Interaction of 8.0 GeV ^{20}Ne with ^{181}Ta ," W. Loveland, D.J. Morrissey, K. Aleklett, G.T. Seaborg, S.B. Kaufman, E.P. Steinberg, B.D. Wilkins, J.B. Cumming, P.E. Haustein, and H.C. Hseuh, Phys. Rev. C (LBL 10010).

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VI. Oral Presentations

1. "Entrance Channel Angular Momentum Dependence of the $^{44m,9}\text{Sc}$ Isomer Ratio," K. Aleklett, W. Loveland, D.J. Morrissey and G.T. Seaborg, 178th ACS National Meeting, Washington, D.C., September, 1979.
2. "Heavy Target Fragmentation in Relativistic Nuclear Collisions," W. Loveland, Chemistry Dept., Brookhaven National Laboratory, March, 1980.
3. "Target Fragment Momenta in the Interaction of Relativistic Heavy Ions with Uranium," W. Loveland, Luo Cheng, D.J. Morrissey and G.T. Seaborg, 179th ACS National Meeting, Houston, Texas, March, 1980.
4. "Production of Gold Isotopes by Relativistic Heavy Ion Reactions with Bismuth," K. Aleklett, D.J. Morrissey, G.T. Seaborg and W. Loveland, 179th ACS National Meeting, Houston, Texas, March, 1980.
5. "Changes in Target Fragmentation in the Energy Region from 7.4-19.0 MeV/A," W. Loveland, R.M. McFarland, P.L. McGaughey, K.J. Moody, R.J. Otto, G.T. Seaborg and R.H. Kraus, Jr., Second Chemical Congress of the North American Continent, Las Vegas, Nevada, August, 1980.
6. "Comparison of the Nuclear Firestreak Model and the Intra-Nuclear Cascade Model," P.L. McGaughey, D.J. Morrissey, W.D. Loveland and G.T. Seaborg, APS Nuclear Physics Division Meeting, Minneapolis, Minnesota, October, 1980.

Appendices

At the request of the Richland Operations Office of the Department of Energy, we have bound copies of reprints and preprints corresponding to work performed during the contract period as part of the Annual Progress Report.