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I. Introduction

In this report, we summarize the highlights of the work done between 1 August, 1989 and 1 August, 1990 that was supported by USDOE Grant No. DE-FG06-88ER40402. The work reported herein is the result of a collaborative effort involving Kjell Aleklett and his research group at the Studsvik Neutron Research Laboratory in Nyköping, Sweden; G.T. Seaborg and his research group at LBL; various individuals at other laboratories and the nuclear chemists at Oregon State University. Each project discussed was the result of a joint effort of the 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 underlined. Some of the work reported herein is in its preliminary stages and use of the data contained in the 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.

In the low energy regime, we assisted the Ghiorso group in their attempt to synthesize element 110.

The intermediate energy research focused on the characterization of the heavy residues, the large target fragments with $A_{\text{frag}} > (2/3) A_{\text{target}}$. In the interaction of 21 MeV/nucleon ^{129}Xe with ^{197}Au , we found evidence suggesting the dominant reaction mechanism was that of deep inelastic scattering. This conclusion was based upon comparing the fragment (Z, A) distributions and energy distributions with low energy data.

In the interaction of 93 MeV/nucleon ^{36}Ar with ^{197}Au , we found the fragment mass distribution to be identical (except for the multifragmentation products) with that resulting from the interaction of 1.8 GeV/nucleon ^{40}Ar with ^{197}Au . This result has suggested to some that this intermediate energy represents the onset of "participant-spectator" physics to describe the reaction mechanism(s). However, a closer examination of the heavy residue longitudinal momenta and the widths of the momentum distributions revealed significant differences when compared to high energy reactions.

Measurements were made using instrumental methods of the fission fragment folding angle distributions and heavy residue spectra for the interaction of 20 MeV/nucleon ^{16}O with ^{197}Au . This measurement was undertaken to test the consistency and relation of these two methods of measuring the

linear momentum transfer. Data taking was finished for a survey measurement of the fragment yields, angular distributions and energy spectra for the interaction of 30-35 MeV/nucleon ^4He , ^{12}C , ^{16}O , ^{40}Ar and ^{84}Kr with ^{197}Au .

In the relativistic energy region, the yields, angular distributions and energy spectra of the target fragments from the interaction of 800 GeV protons with ^{197}Au were found to be consistent with existing data on high energy p-Au interactions. Comparisons of the data with calculations using the Gross microcanonical model for the decay of highly excited nuclei revealed some deficiencies in the model.

We also found limiting fragmentation behavior for the interaction of 13.3 GeV/nucleon ^{28}Si with ^{197}Au except for an unexpectedly large yield of the electromagnetic dissociation product ^{195}Au .

The first direct instrumental measurements of the yields, angular and momentum distributions of spallation products were made for the interaction of 400 MeV/nucleon ^{12}C with ^{197}Au .

Measurements of pulse height defects for 0.24-1.36 MeV/nucleon ^{209}Bi were made, as a necessary calibration for other time-of-flight measurements described in this report.

II. Low Energy Heavy Ion Research

A. The Elements Beyond Uranium

As a culmination of an effort spanning five or more years, we completed a manuscript of a monograph entitled The Elements Beyond Uranium. The monograph will be ~350 pages in length with 135 illustrations. It will be published by John Wiley in October 1990.

The monograph is a concise summary of both the chemical and nuclear properties of the transuranium elements. It consists of ten chapters; introduction; a history of the discovery of the elements; chemical properties; nuclear structure and radioactive decay properties; experimental techniques for studying these elements; nuclear reactions for element synthesis; superheavy elements; presence in nature; practical applications, including weapons; and reflections. The book features new, unpublished material on the discovery of the elements, their radioactive decay properties and strategies for synthesizing new nuclei. (G.T. Seaborg and W. Loveland)

B. Synthesis of Element 110

As an outgrowth of the developments summarized in Section IIA, we have assisted A. Ghiorso and his research group in the U.S. effort to synthesize element 110. The reaction chosen for the synthesis is the $^{209}\text{Bi} (^{59}\text{Co}, \text{xn})^{266,267}110$ reaction. The predicted cross section for this reaction is in the range of 0.5-5 pb. The product nucleus $^{266}110$ is expected to have a half-life $\sim 10^{-5}$ sec while the predicted half-life $^{267}110$ is 10^{-4} sec. The instrument used to detect the reaction products is SASSY 2,¹ a modification of the gas-filled magnetic separator SASSY.² (Figure II.B.1). The incident beam passes through a vacuum window of carbon (coated with aluminum) and strikes a rotating target wheel containing bismuth targets (backed by a thin aluminum layer).

During preliminary tests of the system in 1989, a ^{51}V beam was used to successfully synthesize $^{258,257}\text{Ha}$ via the reaction $^{208}\text{Pb} (^{51}\text{V}, \text{xn})^{258}\text{Ha}$. During June, 1990, we participated in an attempt to synthesize $^{258,259}106$ using the $^{209}\text{Bi} (^{51}\text{V}, \text{xn})^{258,259}106$ reaction at the LBL SuperHILAC accelerator. This later experiment is a stringent test of the target assembly, separator, and accelerator. The nuclide $^{259}106$ is known ($t_{1/2} \sim 480$ ms, $E_{\alpha} = 9.62$ MeV) while the nuclide $^{258}106$ is unknown with a predicted half life of $\sim 10^{-5}$ sec and a decay mode of SF³. Cross section systematics would suggest a production cross section of ~ 200 -300 pb for this reaction which has never been used before. Three thicknesses of Bi targets on the rotating wheel were used simultaneously so as to "bracket the excitation function" of the heavy element products (in that signals from the rotating wheel, recorded with any events would reveal the target (and beam energy) responsible for that event). The accelerator and rotating target assembly performed satisfactorily with 10 μA of 245-250 MeV $^{51}\text{V}^{16+}$ passing through the targets for several hours without any damage or target failure. During this time, no events attributable to $^{258,259}106$ were observed.

Prior to any serious attempt to synthesize element 110, certain additional modifications and tests of the system are to be made. They include: (a) construction and testing of a time-of-flight system to measure the energy of the SuperHILAC beam utilizing parallel plate avalanche counters. This system should easily allow measurement of the beam energy to within 1 MeV, a necessity when the excitation functions for heavy element production are ~ 5 MeV wide, (b) a measurement of the efficiency of SASSY 2 utilizing the known reaction $^{208}\text{Pb} (^{48}\text{Ca}, 2n)^{254}\text{No}$ reaction and (c) completion of the test involving the synthesis of $^{258,259}106$. (A. Ghiorso, W. Ghiorso, D. Lee, R. Leres, W. Loveland, G.T. Seaborg, L.P. Somerville and W.J. Swiatecki).

SASSY2

(Small Angle Separator SYstem 2)

Target to detector distance = 2.5 meters

Figure II.B.1. A schematic drawing of the modified, gas-filled magnetic separator, SASSY 2.

References

1. A. Ghiorso, J. Radioanal. and Nucl. Chem. 124, 407 (1988).
2. A. Ghiorso, S. Yashita, M. Leino, L. Frank, G. Kalnins, P. Armbruster, J.P. Dufour and P.K. Lemmertz, Nucl. Instr. Meth. A269, 192 (1988).
3. Z. Patyk, J. Skalski, A. Sobiczewski and S. Cwiok, Nucl. Phys. A502, 591c (1989).

III. Intermediate Energy Heavy Ion Research

A. The Interaction of 21 MeV/nucleon ^{129}Xe with ^{197}Au .

In nucleus-nucleus collisions at low energies ($E_{\text{proj}} \leq 10$ MeV/nucleon), one knows that as the projectile charge and size increase, the dominant reaction mechanism shifts from complete fusion to deep inelastic scattering. For the collision of heavy nuclei such as xenon-gold collisions, at low energies, one expects the complete fusion cross section to be zero.¹ One also knows that in the collision of light-medium heavy ions (C-Ar) with heavy nuclei, that one observes a transition from complete fusion to incomplete fusion to a spallation-like or multifragmentation reaction mechanisms as the projectile energy increases from 10 to 100 MeV/nucleon.

We thought it would be interesting to characterize the changes in reaction mechanism(s) as a function of increasing projectile energy for a heavy projectile-heavy target system, such as the Xe + Au system, where at low energies the strong Coulomb repulsion prevents the deeper interpenetrations of target and projectile nuclei that lead to fusion-like events. In this report, we present the first results from a part of this study, the characterization of the target-like fragments resulting from the interaction of 21 MeV/nucleon ^{129}Xe with ^{197}Au . This study complements a previous study² of the projectile-like fragments in the interaction of 23.7 and 27 MeV/nucleon ^{129}Xe with $^{\text{nat}}\text{Ag}$ and ^{197}Au . In this latter study,² evidence was presented for the occurrence of a three-body exit channel possibly due to the fission of a quasi-Xe nucleus after a deep inelastic reaction.

This experiment was carried out at the National Superconducting Cyclotron Laboratory (K800) at Michigan State University. The measurement of the target fragment formation cross section and recoil properties were made using radiochemical techniques.³ The target fragment isobaric yield distribution is

shown in Figure III-A-1. The dominant feature of the distribution is the large, broad central peak ($\sigma_f \sim 2300$ mb) presumably reflecting the sequential fission and/or break-up of target-like fragments. The production cross for surviving target-like fragments is 970 mb. Also shown in Figure III-A-1 are the isobaric yields distributions measured⁴ for the interaction of near-barrier (~ 5.6 MeV/nucleon) ^{129}Xe (dashed line) and above barrier (~ 6.6 MeV/nucleon) with ^{197}Au (dotted line⁵). The primary effects of increasing the projectile energy are the increase in total reaction cross section, a broadening of the sequential fission/breakup distribution and a decrease in the yield of surviving target-like fragments.

To interpret the target fragment recoil properties in terms of sensible quantities, we have used the integral catcher analysis method of Tobin and Karol.⁶ In this analysis, we assume the final velocity of each fragment in the laboratory system can be written as $V_{\text{lab}} = V + v_{\parallel}$ where the velocity $v_{\parallel}$ is the average projection of the fragment velocity distribution on the beam axis and V is an average isotropic recoil velocity due to either sequential particle emission or fission or an isotropic component of the velocity distribution in the initial stage of the reaction. As opposed to a conventional analysis of recoil data, the Tobin/Karol method imposes no constraints on target thickness and corrects certain limitations and deficiencies in the conventional analysis.

The deduced values of $v_{\parallel}$ and V are shown in Figure III-A-2. The deduced longitudinal velocities are a small fraction of the complete fusion velocity (v_{CN}), indicating a small momentum transfer in these reactions. The quantity $p_{\parallel}/p_{\text{CN}}$ for $A=24$ fragments is 0.2 (assuming a massive transfer hypothesis) while the systematics⁷ of linear momentum transfer for light ion induced reactions would predict $p_{\parallel}/p_{\text{CN}} = 1.0$ for this reaction for fusion-like processes. But, of course, there are no fusion-like processes and so this result is not surprising. The low fractional linear momentum transfer in this reaction might resemble that seen at much higher energies where a participant-spectator view of the reaction mechanism is generally invoked. However, the data of Figure III-A-2b shows this approach (participant-spectator, abrasion/ablation, etc.) not be correct because the isotropic component of the recoil momentum is significantly larger than the known systematics⁸ of high energy collisions. These systematics for the momentum widths are shown as a dashed line in Figure III-A-2b. In short, the fragments are too "hot" to have been produced in an abrasion/ablation process.

In fact, the observations of the fragment properties in the interaction of 21 MeV/nucleon ^{129}Xe with ^{197}Au are consistent with the idea of the dominant reaction mechanism being that of deep inelastic scattering. For example, the characteristic fractionation⁵ of the yields of the near target fragments into distributions representing quasi elastic and damped collisions can be made (Figure III-A-3). The yields of the high spin isomeric states and the more neutron-deficient gold isotopes are assigned to the damped collision process based upon the higher angular momentum transfer and the larger energy damping. The similar fractionation patterns for the interaction of 21 MeV/nucleon ^{129}Xe with ^{197}Au and the lower energy⁵ (6.8 MeV/nucleon) $^{132}\text{Xe} + ^{197}\text{Au}$ reaction suggests the operation of similar mechanisms. Also, the mean ranges (energies) of the target fragments from the interaction of 6.8 MeV/nucleon ^{132}Xe and 21 MeV/nucleon ^{129}Xe with ^{197}Au are similar. ($R_{\text{proj}} \sim 3.7 \text{ mg/cm}^2 \text{ Al}$ for $Z=73$ fragments with 6.8 MeV/nucleon $^{132}\text{Xe} + ^{197}\text{Au}$ while $R_{\text{proj}} \sim 3.7 \text{ mg/cm}^2$ for $Z=72$ fragments from 21 MeV/nucleon $^{129}\text{Xe} + ^{197}\text{Au}$). The idea of a dominant deep inelastic scattering mechanism for the $\text{Xe} + \text{Au}$ reaction at 21 MeV/nucleon does not disagree with the previous finding of Casey *et al.*⁹ who found evidence for a deep inelastic component in the spectra of heavy residues from the reaction of 12-16 MeV/A ^{32}S with ^{165}Ho (A. Yokoyama, W. Loveland, J.O. Liljenzin, K. Aleklett, D.J. Morrissey, and G.T. Seaborg).

References

1. W.W. Wilcke, J.R. Birkelund, H.J. Wollersheim, A.D. Hoover, J.R. Huizenga, W.U. Schröder and L.E. Tubbs, *At. Data and Nucl. Data Tables* 25, 391 (1980).
2. O. Granier, *et al.*, *Nucl. Phys.* A481, 109 (1988).
3. D.J. Morrissey, D. Lee, R.J. Otto, and G.T. Seaborg, *Nucl. Instrum. Methods* 158, 499 (1978).
4. J.V. Kratz, W. Brüche, G. Franz, M. Schädel, I. Warnecke, G. Wirth, and M. Weis, *Nucl. Phys.* A332, 477 (1979).
5. J.V. Kratz, J. Poitou, W. Brüche, H. Gäggeler, M. Schädel, G. Wirth and R. Lucas, *Nucl. Phys.* A357, 437 (1981).
6. M.J. Tobin and P.J. Karol, *Nucl. Instru. Meth.* A270, 511 (1988).
7. S. Leray, *J. Phys. C4*, #8, 47, 275 (1986).
8. D.J. Morrissey, *Phys. Rev.* C39, 460 (1989).
9. C. Casey, W. Loveland, Z. Xu, L. Sihver, K. Aleklett, and G.T. Seaborg, *Phys. Rev.* C40, 1244 (1989).

Figure III-A-1. The target fragment isobaric yield distribution for the reaction of 21 MeV/nucleon ^{129}Xe with ^{197}Au (solid line, points). The dashed and dotted lines show similar data for the interaction of near barrier, (5.6 MeV/nucleon) ^{129}Xe and above barrier (6.6 MeV/A) ^{136}Xe with ^{197}Au .

Figure III-A-2. (a) The ratio of the average longitudinal fragment velocity, v_{par} to the velocity of the completely fused system for the interaction of 21 MeV/nucleon ^{129}Xe with ^{197}Au . (b) The average value of V , the isotropic fragment velocity component versus product mass number. The dashed line shows the values of V seen in a number of relativistic heavy ion reactions.

Figure III-A-3 The isotope distributions for gold isotopes formed in the reaction of 21 MeV/nucleon ^{129}Xe with ^{197}Au and their decomposition into a quasi-elastic and a damped component. Shown as solid and dashed lines are the corresponding gold isotopic distributions resulting from the interaction of 6.8 MeV/nucleon ^{132}Xe with ^{197}Au .

B. The Interaction of 93 MeV/nucleon ^{36}Ar with ^{197}Au . Participant-Spectator Physics?

Previous studies^{1,2} of the Ar + Au and C + Au systems at intermediate energies have shown the increasing importance of heavy residue formation (relative to fission) with increasing projectile energy (Figure III-B-1). We thought it would be interesting to extend our studies to a significantly higher energy where "participant-spectator" mechanisms for producing target fragments might begin to operate. Accordingly we present, in this report, preliminary results from a measurement of the target fragment yields, angular distributions and energy spectra for the interaction of 93 MeV/nucleon ^{36}Ar with ^{197}Au .

These single particle inclusive measurements took place at GANIL. The entire experiment took 13 minutes of beam, in which 3.1×10^{13} ions were delivered to the target. Following procedures that have been described elsewhere,^{3,4} we calculated the fragment isobaric yield distribution from the measured nuclidic yields. The resulting fragment mass distribution is shown in Figure III-B-2a. The fragment mass yields decrease essentially exponentially from mass numbers near the target to the lightest observed product mass

numbers. Qualitatively this is characteristic of reactions⁵ at much higher energies (Figure III-B-2b). In Figure III-B-2c, we directly compare the fragment isobaric yield distributions from the interaction of 93 MeV/A ^{36}Ar (solid points, solid line) and 1.95 GeV/A ^{40}Ar (dashed line) with ^{197}Au (ref. 5). Apart from the yields of the intermediate mass fragments ($A \lesssim 60$), there are remarkably similar shapes for the fragment isobaric yield distributions for these two reactions induced by projectiles of disparate energy. This agreement appears to be yet another example of the concepts of total projectile kinetic energy scaling of fragment yields and limiting fragmentation. (It is well-known that the fragment yield distributions are similar for the interaction of 3 GeV and 78 GeV protons with ^{197}Au .)

Because of this similarity in mass-yield distributions between the reaction of 93 MeV/nucleon and 1.95 GeV/nucleon Ar with ^{197}Au , we should look at other characteristics of the two reactions to see how they compare. In Figure III-B-3 we compare the measured angular distributions for $A \sim 125$ nuclei from the interaction of 93 MeV/nucleon ^{36}Ar (solid triangles), 85 MeV/nucleon ^{12}C (solid line), 400 MeV/nucleon ^{20}Ne (dashed line) with ^{197}Au . The distribution from the Ar induced reaction is more forward-peaked than the reactions induced by the 1-8 GeV projectiles. Similarly, the longitudinal momentum transfer in the ^{40}Ar induced reaction is much greater than that seen in typical relativistic heavy ion reactions (Figure III-B-4). Yet another demonstration that "participant-spectator" conditions have not been met in the 93 MeV/nucleon $^{40}\text{Ar} + ^{197}\text{Au}$ reaction are the observed widths of the momentum distributions (Figure III-B-5) which are much larger in the reaction under study than typically observed in relativistic heavy ion reactions. Thus, despite the similarity in mass-yield distributions between the reaction of 93 MeV/nucleon $^{46} + ^{147}\text{Au}$ with typical relativistic heavy ion induced fragmentation of ^{197}Au , a "participant-spectator" mechanism is not consistent with other aspects of the data.

However, the increasing projectile energy has led to a diminished probability for fission of the target-like residue (Figure IV-B-1). The production in peripheral collisions of surviving heavy target residues is clearly the most important reaction channel in the Ar + Au system at energies from ~ 50 to 100 MeV/nucleon.

We are currently trying to compare our observations with modern theories of energetic nucleus-nucleus collisions, such as the QMD model of Aichelin et al.

(K. Aleklett, L. Sihver, W. Loveland and J.O. Liljenzin)

REFERENCES

1. W. Loveland, K. Aleklett, L. Sihver, Z. Xu, C. Casey, D.J. Morrissey, J.O. Liljenzin, M. de Saint-Simon, and G.T. Seaborg, Phys. Rev. C41, 973 (1990).
2. K. Aleklett, M. Johansson, L. Sihver, W. Loveland, H. Groening, P.L. McGaughey and G.T. Seaborg, Nucl. Phys. A499, 591 (1989).
3. D.J. Morrissey, D. Lee, R.J. Otto, and G.T. Seaborg, Nucl. Instrum. Meth. 158, 499 (1978).
4. D.J. Morrissey, W. Loveland, M. de Saint-Simon, and G.T. Seaborg, Phys. Rev. C21, 1783 (1980).
5. Wenxin Li, W. Loveland, K. Aleklett and G.T. Seaborg, Oregon State University Nuclear Chemistry Progress Report DOE/ER/70035-7, September, 1984.
6. R.H. Kraus, Jr. et al., Nucl. Phys. A432, 525 (1985).
7. J.B. Cumming, P.E. Haustein and R.W. Stoenner, Phys. Rev. C33, 926 (1986).
8. D.J. Morrissey, Phys. Rev. C39, 460 (1989).

Figure III-B-1. Variation of the fission cross section (solid points) and the heavy residue formation cross section (triangles) with projectile energy for the Ar + Au system. The points at 93 MeV/A are from this work.

Figure III-B-2. (a) Measured fragment isobaric yield distribution for the interaction of 93 MeV/nucleon ^{36}Ar with ^{197}Au . (b) Same as (a) except reaction is 1.95 GeV/nucleon $^{40}\text{Ar} + ^{197}\text{Au}$ (ref. 5). (c) comparison of distributions in (a) and (b).

Figure III-B-3. Comparison of $A \sim 125$ fragment angular distributions for the interaction of 93 MeV/nucleon ^{36}Ar (solid triangles), and 85 MeV/nucleon ^{12}C (ref. 7) (solid line) and 400 MeV/nucleon ^{20}Ne (dashed line) with ^{197}Au .

Figure III-B-4. Comparison of the average longitudinal momentum transfer as a function of mass loss for the interaction of 93 MeV/nucleon ^{40}Ar with ^{197}Au (solid points) and that predicted by the systematics⁸ of momentum transfer in projectile and target fragmentation at relativistic energies (solid line).

Figure III-B-5. Comparison of the average rms fragment momentum from the interaction of 93 MeV/nucleon ^{36}Ar with ^{197}Au (solid points) with that expected from the systematics⁸ of relativistic heavy ion reactions (dashed line).

C. Consistency Test of Two Measures of Linear Momentum Transfer

For intermediate energy nuclear collisions, the measurement of the amount of the projectile's linear momentum transferred to the target nucleus (LMT) can be an important tool in understanding the reaction mechanism(s). Two methods of measuring the LMT have been used. The first method involves measuring the velocity distributions of the heavy target residues (or "evaporation" residues as they are sometimes called). The second method involves the measurement of the fission fragment folding angle distributions. The latter method has been employed extensively^{1,2} for the study of heavy systems while the former method is difficult to employ in these cases because of the low residue energies (~ 100 keV/nucleon for $A_{\text{target}} \sim 200$) and the high residue mass numbers ($A_{\text{res}} > (2/3) A_{\text{target}}$). Recently, however, Aleklett *et al.*³ measured the heavy residue velocity distributions and LMT for a reaction, 85 MeV/nucleon $^{12}\text{C} + ^{197}\text{Au}$, where the LMT had been characterized previously by fission fragment folding angle distributions.⁴ Comparison of the two measurements (Figure III-C-1) shows that for a target nucleus with limited fissility such as gold, the two techniques for measuring LMT give different answers. Presumably the relative probability of fission vs particle emission (Γ_f/Γ_n) changes as a function of the transferred momentum (i.e., E^* , Z , A) causing the fission fragments and heavy residues to sample different portions of the primary target-like fragment population. Thus these two methods of measuring LMT are complementary. Both should be used to get a complete picture of the LMT in any reaction.

Unfortunately, this one reaction, 85 MeV/nucleon $^{12}\text{C} + ^{197}\text{Au}$, where the transferred linear momentum is relatively low and where fission represents a minor deexcitation path for the primary target-like fragment may not be the best place to compare the two techniques of measuring LMT. It is of general interest to see whether the extensive systematics of linear momentum transfer (based mostly upon fission fragment correlation measurements) are altered when heavy residue measurements are taken into account. Contradictory evidence exists in the literature concerning this point.^{5,6} It is of specific interest to examine a situation in which the fission fragment folding angle distribution is double humped. Such distributions have been seen in many systems.⁷⁻¹⁴ The two peaks in the folding angle distributions are qualitatively associated with "central" and "peripheral" collisions. The changes in the relative magnitude of these two peaks as a

function of projectile energy and size have been important in the understanding of the accompanying changes in reaction mechanism.

During February, 1990, we performed an experiment utilizing a typical intermediate energy reaction, 20 MeV/nucleon $^{16}\text{O} + ^{197}\text{Au}$, to test these two measures of LMT in a situation where the folding angle distribution is double-humped. The study was done at the LBL 88" cyclotron and consisted of two separate measurements: (a) the measurement of the fission fragment folding angle distribution, and (b) the measurement of the heavy residue spectra at several different angles using a time-of-flight spectrometer.

A schematic drawing of the experimental setup for the measurement of the fission fragment angular correlations and the heavy residue spectra is shown in Figure III-C-2. The TOF of one fragment (either a fission fragment or heavy residue) was measured using a microchannel plate electron detector and a silicon stop detector at angles 20° , 35° , 45° , and 60° . The correlated fission fragments were detected in a detector array on the opposite side of the beam covering the angular range from 30° to 160° . Approximately 10^8 heavy residue and fission correlation events were recorded in this three day experiment.

Data analysis is underway and should be completed soon. A crucial portion of this analysis involves the calibration of the pulse height defect of the silicon detector for the low energy heavy residues. (see Section V-A of this report for details).

(W. Loveland, A. Yokoyama, J.O. Liljenzin, D.J. Morrissey, G. Skanemark and K. Aleklett)

REFERENCES

1. S. Leray, J. de Phys. 47, C4-275 (1986).
2. C. Gregoire and B. Tamain, Ann Phys. Fr. 11, 323 (1986).
3. K. Aleklett, et al., Nucl. Phys. A499, 591 (1989).
4. U. Lynen, et al., Nucl. Phys. A387, 129 (1982).
5. C. Ceruti et al., Nucl. Phys. A453, 175 (1986).
6. B. Borderie, et al., Z. Phys. A316, 243 (1984).
7. B.B. Back, et al., Phys. Rev. C22, 1927 (1980).

8. J.L. Laville, et al., Phys. Lett. 138B, 35 (1984).
9. E.C. Pollaco, et al., Phys. Lett. 146B, 29 (1984).
10. M. Conjeaud, et al., Phys. Lett. 159B, 244 (1985).
11. Y. Patin, et al., Nucl. Phys. A 457, 146 (1986).
12. C. Volant, et al., Phys. Lett. B195, 22 (1987).
13. S. Harar, Nucl. Phys. A471, 205 (1987).
14. E.C. Pollaco, et al., Nucl. Phys. A488, 319 (1988).

Figure III-C-1. Longitudinal momentum distributions for the 85 MeV/nucleon $^{12}\text{C} + ^{197}\text{Au}$ reaction as measured using (a) the fission folding angle technique (b) heavy residue spectra.

Figure III-C-2. Schematic diagram of the experimental setup for the measurement of the fission fragment folding angles.

D. The Interaction of ~ 30 MeV/nucleon Projectiles with ^{197}Au

In the interaction of 30-35 MeV/nucleon projectiles with ^{197}Au , the fusion cross section is predicted¹ to change dramatically with increasing projectile size. (Figure III-D-1). Some time ago, we began a survey to characterize, in detail, the changes in fusion-like events with increasing projectile size for the interaction of 30-35 MeV/nucleon heavy ions with ^{197}Au . We have previously measured the fragment yields, energies and angular distributions for the interaction of 35 MeV/nucleon ^{12}C , 32 MeV/nucleon ^{40}Ar and 35 MeV/nucleon ^{84}Kr with ^{197}Au . (Typical changes in fragment yield distributions are shown in Figure III-D-2. One observed a shift in the centroid of the fission mass distribution to larger mass numbers with increasing projectile size, a testimony to the occurrence of fusion-like events.)

During the past year, we finished the measurements for this survey by measuring the target fragment yields, angular distributions and energy spectra for the interaction of 30 MeV/nucleon ^4He and ^{16}O with ^{197}Au . The experiments were performed at the LBL 88" cyclotron and involved the use of radiochemical techniques. Counting of the samples has just concluded and data analysis has begun.

(W. Loveland, M. Behm, A. Yokoyama, L. Sihver)

References

1. W.W. Wilcke, J.R. Berkelund, H.J. Wollersheim, A.D. Hoover, J.R. Hulzenga, W.U. Schröder and L.E. Tubbs, At. Data and Nucl. Data Tables 25, 391 (1980).

Figure III-D-1. Variation of $\sigma_{\text{fusion}}/\sigma_{\text{reaction}}$ with increasing projectile size.

Figure III-D-2. Target fragment isobaric yield distributions for the interaction of 35 A MeV ^{12}C (-o-), 32 A MeV ^{40}Ar (-●-) and 35 A MeV ^{84}Kr (-Δ-) with ^{197}Au .

IV. Relativistic Energy Research

A. Gold Target Fragmentation by 800 GeV protons

As part of an effort to extend our knowledge of the fragmentation of the heaviest targets by 800 GeV protons (the highest proton energy available to us) and to test one of the more important of the statistical theories of nuclear fragmentation, we measured the target fragment production cross sections, angular distributions and energy spectra for the fragmentation of ^{197}Au by 800 GeV protons.

The experiments were performed at Fermilab and involved the use of radiochemical techniques. From the target fragment production cross sections, we deduced fragment mass distributions (Figure IV-A-1). From the range distributions of fragments emitted at 72° - 108° with respect to the incident beam, we deduced energy spectra (Figure IV-A-2). Details of the measurements are given in reference 1.

From examining the data shown in Figure IV-A-1, we conclude that, within experimental uncertainties, the mass yield distribution from the reaction of 800 GeV protons with gold appears to be the same as from the reaction of 11.5 GeV protons^{2,3} in accord with limiting fragmentation.⁴ Also the data agree with the semiempirical systematics of spallation yields of Sümmerer and Morrissey.⁵ Similarly, a comparison of the velocity spectrum of the representative target fragment ^{149}Gd from the interaction of 800 GeV protons with gold to the velocity spectrum of ^{149}Tb from the fragmentation of gold by 2.2 GeV protons⁶ shows the spectra to have similar shapes (Figure IV-A-2). Also shown in Figure IV-A-2 is the spectrum of $A=145-155$ fragments calculated using a simple model. In this model, we assumed a group of ^{197}Au nuclei at rest with an excitation energy spectrum given by Glauber multiple scattering theory⁷ and calculated the energy spectra of the spallation residue nuclei due to particle evaporation (taking into account possible de-excitation by fission) using a modified DFF procedure.⁸ There appears to be excellent agreement between the measured and calculated spectra. Similar conclusions can be drawn for the energy spectra of other target fragments. The angular distributions of the target fragments agree well with the systematics⁹ of fragment angular distributions in reactions induced by energetic protons.

In Figure IV-A-3, we compare the measured mass yield distribution with that calculated using the Gross microcanonical model for the decay of hot nuclei.^{7,10,11} The calculated yields are in rough agreement

with the measured yields, but there is an oscillatory structure in the calculated yields that is not observed in reality.

(L. Sihver, K. Aleklett, W. Loveland, P.L. McGaughey, D.H.E. Gross and H.R. Jaqaman)

References

1. L. Sihver, K. Aleklett, W. Loveland, P.L. McGaughey, D.H.E. Gross and H.R. Jaqaman, Phys. Rev. C (submitted for publication). (See Appendices of this report).
2. S.B. Kaufman and E.P. Steinberg, Phys. Rev. C22, 167 (1980).
3. S.B. Kaufman, M.W. Weisfield, E.P. Steinberg, B.D. Wilkens, and D. Henderson, Phys. Rev. C14, 1121 (1976).
4. J. Benecke, T.T. Chon, C.N. Yang and E. Yen, Phys. Rev. 188, 2159 (1969).
5. K. Sümmerer and D.J. Morrissey, Proc. First Intl'l Conf. on Radioactive Nuclear Beams (to be published).
6. V.P. Crespo and J. Cumming, Phys. Rev. C2, 1777 (1970).
7. A.Y. Abul-Magd, D.H.E. Gross, Xu Shu-yan, and Zheng Yu-ming, Z. Phys. A325, 373 (1986).
8. P.L. McGaughey, W. Loveland, D.J. Morrissey, K. Aleklett and G.T. Seaborg, Phys. Rev. C31, 896 (1985).
9. C.F. Wang and N.T. Porile, Phys. Rev. C34, 1911 (1986).
10. D.H.E. Gross, Zhang Xiao-ze and Xu Shu-yan, Phys. Rev. Lett. 56, 1544 (1986).
11. D.H.E. Gross and Zhang Xiao-ze, Phys. Lett. 161B, 47 (1985).

Figure IV-A-1 Isobaric yield distribution for the fragmentation of ${}^{197}\text{Au}$ by 800 GeV p and 11.5 GeV p .^{2,3} The semiempirical systematics for spallation yields due to Summner and Morrissey⁵ are also shown.

Figure IV-A-2 Velocity spectrum of ${}^{149}\text{Gd}$ from the interaction of 800 GeV p with ${}^{197}\text{Au}$. Also shown is the ${}^{149}\text{Tb}$ velocity spectrum from the fragmentation of gold by 2.2 GeV p and a DFF calculation for the 800 GeV $p + {}^{197}\text{Au}$ reaction.

Figure IV-A-3 A comparison of the measured isobaric yield distribution for the fragmentation of ^{197}Au by 800 GeV protons with that calculated using the Gross microcanonical model for the statistical decay of very highly excited nuclei.

B. Target Fragment Mass Distribution for the Reaction of 13.3 GeV/nucleon ^{28}Si with ^{197}Au .

In recent years, a considerable effort has been devoted to the study of ultrarelativistic nucleus-nucleus collisions (where $E_{\text{proj}} > 10 \text{ GeV/N}$). Most of these studies have focussed on the search for a quark-gluon plasma which might be formed in central collisions. Our interest has been in the study of target fragmentation, i.e., the production of large, low energy target-related fragments in such collisions. Our goal has been to look for possible deviations¹ from limiting fragmentation or other behavior patterns established for relativistic p-nucleus and nucleus-nucleus collisions at lower energies. During the past year, we have

revised and reworked the data from the measurement of the target fragment mass distributions for the interaction of 13.3 GeV/nucleon ^{28}Si with ^{197}Au . The results are consistent with limiting fragmentation, within $\pm 20\%$.

The production cross sections of various target fragments from the interaction of 13.3 GeV/nucleon ^{28}Si with ^{197}Au were determined using standard foil activation techniques.^{2,3} These measurements were made in conjunction with a concurrent study¹ of the average recoil properties of many of the same nuclides. The first point of interest in these data is the large cross sections associated with the one and two neutron removal products, ^{196}Au and ^{195}Au . They are $\sigma(^{195}\text{Au}, 13.3 \text{ GeV/N } ^{28}\text{Si}) 174.6 \pm 6.5 \text{ mb}$; $\sigma(^{196}\text{Au}, 13.6 \text{ GeV/N } ^{28}\text{Si}) 570.8 \pm 14.1 \text{ mb}$. Comparison with previously published data^{4,5,6} would indicate that electromagnetic dissociation is probably responsible for the enhanced cross sections. If we estimate^{4,6} the nuclear part of the one neutron removal cross section is $\sim 137 \text{ mb}$, we would then deduce electromagnetic dissociation cross section of $\sim 434 \text{ mb}$ for one-neutron removal, for the ^{28}Si induced reaction. The calculated Weizsäcker-Williams electromagnetic dissociation cross section for this reaction is $\sim 450 \text{ mb}$, in good agreement with the data. The two neutron removal cross section is somewhat larger in the ultrarelativistic reaction compared to "ordinary" relativistic reactions. For example, the measured cross section⁵ for producing ^{195}Au in the reaction of 2.1 GeV/N ^{20}Ne with ^{197}Au is 114 mb compared to our observation of $175 \pm 7 \text{ mb}$ for the 13.3 GeV/nucleon $^{28}\text{Si} + ^{197}\text{Au}$ reaction. (From upper limits for the production of ^{195}Hg and $^{195\text{m}}\text{Hg}$, we can rule out the production of ^{195}Au by decay of its $^{195\text{g,m}}\text{Hg}$ parents.) If we estimate the nuclear part of the two neutron removal cross section is $\sim 65 \text{ mb}$, then we would deduce an electromagnetic dissociation cross section of $\sim 110 \text{ mb}$ for the ultrarelativistic reaction. This is substantially more than the Weizsäcker-Williams prediction of $\sim 68 \text{ mb}$ although the ratio of two neutron removal cross section to one neutron removal by electromagnetic dissociation of the target (~ 3.9) is in fair agreement with the same ratio for projectile electromagnetic dissociation (~ 3.6) for the 14.6 GeV/nucleon $^{28}\text{Si} + ^{208}\text{Pb}$ reaction.⁷ It has been suggested⁸ that one may produce multi-photon giant resonance excitations in ultrarelativistic collisions, leading to enhanced two neutron removal processes, although the calculated magnitude⁹ of such excitations is not large enough to account for our observations.

The mass yield distribution for the interaction of 13.3 GeV/nucleon ^{28}Si with ^{197}Au is shown in Figure IV-B-1a, with a solid curve to guide the eye through the data. In figure IV-B-1b we compare the isobaric yields for the 13.3 GeV/nucleon $^{28}\text{Si} + ^{197}\text{Au}$ reaction to the isobaric yields for the reaction of 11.5 GeV protons with ^{197}Au . For the fragments from $A=50$ to $A=194$, the average ratio of the mass yield for producing a given fragment in the ^{28}Si induced reaction compared to the proton-induced reaction was 2.6 ± 0.7 , in good agreement with the ratio of soft spheres cross sections (2.5) for these reactions. The yields of the intermediate mass fragments ($A < 50$) are enhanced in the heavy ion induced reaction.

The isobaric yield distributions may be integrated to place lower limits on the fraction of events resulting in large ($A > 40$) fragments of the target nucleus being produced. The results of such an integration for the ^{28}Si induced reaction assuming a multiplicity of one for all events with $A > 40$ gives 4400 mb. The soft spheres cross section¹⁰ for this reaction is 4320 mb. Assuming our measurement of this cross section is correct, one implication is that some events have a multiplicity greater than one. This observation would be consistent with the observation of Warwick *et al.*¹¹ who found two or more large fragments associated with "deep spallation" events in relativistic heavy ion reactions with Au.

(W. Loveland, M. Hellström, L. Sihver, and K. Aleklett)

REFERENCES

1. W. Loveland, *et al.*, Phys. Rev. C37, 1311 (1988).
2. D.J. Morrissey, W. Loveland, M. de Saint-Simon, and G.T. Seaborg, Phys. Rev. C21, 1783 (1980).
3. D.J. Morrissey, D. Lee, R.J. Otto, and G.T. Seaborg, Nucl. Instrum. Methods 158, 499 (1978).
4. M.T. Mercier, *et al.*, Phys. Rev. C33, 1655 (1986).
5. J.C. Hill, F.K. Wohn, J.A. Winger, M. Khayat, M.T. Mercier, and A.R. Smith, Phys. Rev. C39, 524 (1989).
6. J.C. Hill, F.K. Wohn, J.A. Winger and A.R. Smith, Phys. Rev. Lett. 60, 999 (1988).
7. J. Barette, *et al.*, Phys. Rev. C41, 1512 (1990).
8. G. Baur and C.A. Bertulani, Phys. Lett. B174, 23 (1986).
9. G. Baur and C.A. Bertulani, Phys. Rev. C34, 1654 (1986).
10. P.J. Karol, Phys. Rev. C11, 1203 (1975).
11. A.I. Warwick, *et al.*, Phys. Rev. C27, 1083 (1983).

Figure IV-B-1 (a) Target fragment mass yield distribution for the fragmentation of ^{197}Au by 13.3 GeV/nucleon ^{28}Si . (b) The ratio of the mass yields of Au target fragments in reactions induced by 372 GeV ^{28}Si and 11.5 GeV protons. The solid line shows the soft spheres model prediction of the ratio of total reaction cross sections.

C. Momentum Distributions of Spallation Products from the Interaction of 400 MeV/nucleon ^{12}C with ^{197}Au .

One of the most important, but poorly understood relativistic reaction mechanisms is that of spallation. Qualitatively spallation involves peripheral collisions in which a small amount of mass is removed or "spalled" from the target nucleus, leaving a large nuclear fragment that de-excites by particle emission and/or fission. While the yields of the spallation products have been successfully described^{1,2} by a variety of models, such as the intranuclear cascade model, these same models do not correctly describe the kinematic properties of these products.

For example, the intranuclear cascade model grossly over-estimates the magnitude of the residue velocities in both p-nucleus and nucleus-nucleus collisions (Figure IV-C-1). Complicating this picture is the

fact that there have never been any direct physical measurements of the spallation residues in "normal" kinematics. This may be significant in that almost all the available data on the kinematics of spallation has been derived from model-dependent analyses of the average recoil properties of the spallation residues, as measured using radiochemical techniques. In most of these analyses, the transverse momentum of the residues is assumed to be zero. The validity of this assumption is not known in most cases and has been questioned in light of a recent observation³ of large transverse momenta for spallation residues produced in the fragmentation of 1.2 GeV/nucleon ^{139}La by ^{12}C .

Thus we have begun a program to directly measure the spallation residue momentum distributions using physical techniques which also allow the correlation of these distributions with other observables such as the residue excitation energy (as sensed by the neutron multiplicities, etc.)

During the past year, we utilized the LBL Bevalac, to measure the spallation residue yields, angular and momentum distributions for the interaction of 400 MeV/nucleon ^{12}C with ^{197}Au . The spallation residues (and other reaction products) emerging from a $150\text{ }\mu\text{g}/\text{cm}^2$ ^{197}Au target were detected by a time-of-flight spectrometer with a 20 cm flight path. The start detector was a microchannel plate detector (utilizing isochronous e^- paths) and the stop detector was a Si surface barrier detector. Spallation residue spectra were recorded at angles of 20° , 35° , 55° and 75° with a total of $\sim 4 \times 10^7$ valid events being recorded.

After an auxiliary measurement of the pulse height defect in our detectors (see Section V), analysis of these data is underway.

(W. Loveland, A. Yokoyama, D.J. Morrissey, K. Aleklett).

References

1. Y. Yariv and Z. Fraenkel, Phys. Rev. C20, 2227 (1980); C24, 488 (1981).
2. X. Campi and J. Hufner, Phys. Rev. C24, 2199 (1981).
3. F.P. Brady et al., Phys. Rev. Lett. 60, 1699 (1988).
4. W. Loveland et al., Phys. Rev. C24, 464 (1981).

Figure IV-C-1. Longitudinal velocities⁴ of target fragments from the interaction of 400 MeV/nucleon ^{12}C with ^{238}U .

V. Technical Developments

A. Pulse Height Defects for Very Low Energy, Very Heavy Ions

In Section III C and IV C of this report, we report the use of time of flight techniques to measure the energies, masses, etc. of the heavy target residues from intermediate and relativistic nuclear collisions. A crucial part of such measurements is to measure the energy of the heavy residue after it traverses the time-of-flight apparatus. Because we wish to ultimately use our apparatus in heavy ion storage rings where the experimental apparatus must be bakeable and the vacuum must be $\sim 10^{-10}$ torr, we have chosen to measure the heavy residue energies using silicon detectors. Thus we need to know the pulse height defects for the low energy (10-500 keV/nucleon) heavy ($A \sim 100$ -200) residues.

Using the unique characteristics of the LBL 88" cyclotron, we ran low intensity beams of $^{209}\text{Bi}^{11+}$ (0.25 MeV/A), $^{209}\text{Bi}^{15+}$ (0.46 MeV/A), $^{209}\text{Bi}^{18+}$ (0.66 MeV/A), $^{209}\text{Bi}^{20+}$ (0.82 MeV/A) and $^{209}\text{Bi}^{26+}$ (1.36 MeV/A) into our time-of-flight apparatus, as well as various energy ^{16}O beams and measured the associated pulse height defects. The calibration was done in situ during the study of heavy residue linear momenta in the interaction of 20 MeV/nucleon ^{16}O with ^{197}Au (Section III C). Radioactive sources of ^{238}Pu , ^{252}Cf and ^{148}Gd were used to obtain pulse height versus energy calibrations for α -particles. The response curve for α -particles was extended using a precision pulse generator. Initial ion energies were determined from the cyclotron frequencies and the beam analysis system. The detector being calibrated was a totally depleted 960 Ω -cm silicon surface barrier detector with a depletion depth of 89.6 μ .

The measured pulse height defects are shown in Figure V-A-1 along with various prescriptions¹⁻³ for the pulse height defects. While the prescription of Ogihara et al.³ does the best overall job of representing the data, we have chosen to use the prescription of Moulton et al.² because it represents the energy dependence of the pulse height defect best. We have used the data of Figure V-A-1 to define a scaling factor for our detector relative to the detector used by Moulton et al. and use their prescription to calculate the defects for ions of different Z, A and E.

(W. Loveland, A. Yokoyama, J.O. Liljenzin, D.J. Morrissey, G. Skanemark and K. Aleklett).

REFERENCE

1. T. Kitahara, H. Geissel, Y. Laichter and P. Armbruster, Nucl. Instrum. Meth. 196, 153 (1982).
2. J.B. Moulton, J.E. Stephenson, R.P. Schmitt, and G.J. Wozniak, Nucl. Instrum. Meth. 157, 325 (1978).
3. M. Ogihara, Y. Nagashima, W. Galster and T. Mikumo, Nucl. Instrum. Meth. A251, 313 (1986).

Figure V-A-1. The measured total pulse height defect for ^{209}Bi ions as a function of the ion energy. Top: The solid line indicates the prescription of ref. 1. Middle: The solid line indicates the data of ref. 2. Bottom: The solid line indicates the prescription of ref. 3.

VI. Personnel

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During the past year, we have had the privilege of collaborating with a number of scientists from other institutions. The following list summarizes the names of many of these individuals (and their home institutions) who contributed to work described in this report.

K. Aleklett	Studsvik Neutron Research Laboratory, Nyköping, Sweden
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L.P. Somerville	Lawrence Berkeley Laboratory
W.J. Swiatecki	Lawrence Berkeley Laboratory

VII. PublicationsA. Articles in Print

1. "Non-equilibrium Fission and Heavy Residue Production in the Interaction of 12-16 MeV/nucleon ^{32}S with ^{165}Ho ," C. Casey, W. Loveland, Z. Xu, L. Sihver, K. Aleklett and G.T. Seaborg, Phys. Rev. C, 40, 1244 (1989).
2. "Heavy Residue Spectra in the Interaction of 85 MeV/nucleon ^{12}C with ^{197}Au ", K. Aleklett, M. Johansson, L. Sihver, W. Loveland, H. Groening, P.L. McGaughey and G.T. Seaborg, Nucl. Phys. A 149, 591 (1989).
3. "Non-Equilibrium Fission Processes in Intermediate Energy Nuclear Collisions", W. Loveland, C. Casey, Z. Xu, G.T. Seaborg, K. Aleklett and L. Sihver, in 50 Years With Nuclear Fission, J.W. Behrens and A. D. Carlson, Eds. (ANS, LaGrange Park, 1989), pp. 698-704.
4. "Environmental Sciences", W. Loveland in Lanthanide Probes in Life, Chemical and Environmental Sciences, J.-C. G. Bünzli and G. R. Chappin, Eds. (Elsevier, Amsterdam, 1989), pp. 391-410.
5. "Heavy Residue Linear Momenta in Intermediate Energy Krypton-Gold Collisions", K. Aleklett, W. Loveland, M. de Saint-Simon, L. Sihver, J.O. Liljenzin and G.T. Seaborg, Phys. Lett. B236, 404 (1990).
6. "Changes in Target Fragmentation Mechanisms with Increasing Projectile Energy in Intermediate Energy Nuclear Collisions", W. Loveland, K. Aleklett, L. Sihver, Z. Xu, C. Casey, D.J. Morrissey, J.O. Liljenzin, M. de Saint-Simon and G.T. Seaborg, Phys. Rev. C41, 973 (1990).

B. Articles Submitted for Publication

1. "Radiochemistry," W. Loveland in Encyclopedia of Physics, R.G. Lerner and G.L. Trigg, Ed. (VCH, New York).
2. "Target Fragment Mass Distributions for the Reaction of 13.3 GeV/N ^{28}Si with ^{197}Au ", W. Loveland, M. Hellström, L. Sihver and K. Aleklett, Phys. Rev. C. (accepted for publication)
3. "Gold Target Fragmentation by 800 GeV Protons," L. Sihver, K. Aleklett, W. Loveland, P.L. McGaughey, D.H.E. Gross and H.R. Jaqaman, Phys. Rev. C.
4. The Elements Beyond Uranium, G.T. Seaborg and W. Loveland, (Wiley, New York, 1990) ~350 pages- to be published October 1990.
5. "Nuclear Chemistry", W. Loveland, in Encyclopedia of Physical Science and Technology, R.A. Meyers, ed. (Academic, San Diego)

C. Oral Presentations

1. "Heavy Residue Spectra and Linear Momentum Transfer in Intermediate Energy Nucleus-Gold Collisions," K. Aleklett, J.O. Liljenzin, W. Loveland, M. de Saint-Simon, G.T. Seaborg and L. Silver, 1989 International Nuclear Physics Conference, Sao Paulo, Brazil, August 1989.
2. "Heavy Residue Spectra and Linear Momentum Transfer in Intermediate Energy Nuclear Collisions," W. Loveland, K. Aleklett, G.T. Seaborg and L. Silver, 1989 International Chemical Congress of Pacific Basin Societies, Honolulu, Hawaii, December 1989.
3. "Heavy Residue Production in Intermediate Energy Au-Xe Collisions", A. Yokoyama, W. Loveland, K. Aleklett, J.O. Liljenzin, and D.J. Morrissey, Oregon Academy of Science, February, 1990.
4. "Nuclear Science and Engineering Education at a University Research Reactor," W. Loveland, 200th ACS National Meeting, Washington, D.C., August 1990.

Appendices

At the request of the Richland Operations Office of the U.S. Department of Energy, we have included copies of reprints and preprints (not previously submitted) corresponding to work performed during this period as part of the Annual Progress Report.

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