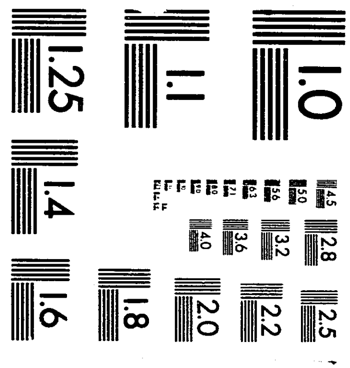
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NUCLEAR CHEMISTRY PROGRESS REPORT
OREGON STATE UNIVERSITY

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I. Introduction

In this report. we summarize the highlights of the work done between August 1, 1992 and July 1, 1993 that was supported by USDOE Grant No. DE-FG06-88ER 40402. The work reported herein is the result of a collaborative effort between the nuclear chemists at Oregon State University and a number of other individuals and research groups. Of special note are our long-time collaborators, Kjell Aleklett of the Studsvik Neutron Research Laboratory in Nyköping, Sweden, J.O. Liljenzin of the Chalmers University of Technology in Göteborg, Sweden, D.J. Morrissey of Michigan State University and G.T. Seaborg of LBL. 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 here 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 is part of a project involving the study of low energy (<10 MeV/nucleon), intermediate energy (10-100 MeV/nucleon) and relativistic heavy ion reactions (>250 MeV/nucleon).

Our work in the low energy regime centered around the study of the heaviest elements. We conducted an analysis of the data from the U.S. experiment to synthesize element 110. No conclusive evidence was found for the synthesis of a new element and upper limits were set for the production cross section. (As part of this data analysis, the pulse height defects for the detectors used to measure the Super HILAC beam energy, along with other detectors, were measured.)

We conducted a detailed examination of various possibilities to synthesize new heavy nuclei using radioactive nuclear beams. The synthesis of new n-rich isotopes of the transactinides appears to be feasible although the use of stable beams seems to be a better approach to the synthesis of the superheavy nuclei.

Most of our effort was spent in the study of intermediate energy nuclear collisions. We extended our study of Xe-Au collisions, making more detailed measurements of the target-like fragments (TLFs) and extending our measurements to a new projectile energy, 26 MeV/nucleon. We compared the measured properties of the TLFs to a number of phenomenological models of this reaction. We were surprised to find a general lack of agreement between the predictions of these models and the measured TLF properties. In an attempt to understand this disagreement, we have begun a new study of the properties of the TLFs produced in another heavy system, 29 MeV/nucleon ^{208}Pb + ^{197}Au. The PLFs from this system have been studied extensively as have other features of the reaction. These features have been successfully described using the nucleon exchange model and we thought it to be an excellent test of our understanding of TLF properties to measure the TLF properties in this system.

We completed our study of the heavy residues from energetic (77 and 95 MeV/nucleon) Ar-Th collisions. While we were surprised at the number of the surviving heavy residues of this relatively fissionable target nucleus, we found that the yields and energies of the heavy residues were such that they could not be the "missing" portion of the fusion-like collisions that disappeared from folding angle distributions in Ar-Th collisions above 35 MeV/nucleon.

We made further measurements of ^{16}O-^{197}Au collisions at 22 and 31 MeV/nucleon. These measurements, which were undertaken to prepare us for the use of the Swedish heavy ion storage ring CELSIUS at Uppsala and to try to understand the sharp decrease in the fission cross section (with a concomitant increase in the heavy residue production cross section) with this variation of projectile energy. Preliminary analysis of the data at the lower energy gives the transferred angular momentum and polarization of the heavy residue spin.

As part of our study of the properties of the heavy target residues using inverse kinematics and the A1200 fragment separator at Michigan State University, we (in collaboration with Wozniak, et al.) studied the interaction of 20 MeV/nucleon ^{197}Au with C, Al and Ti. Analysis of this experiment is under way.

In a year characterized by several experiments, we also completed our study of the interaction of 60 MeV/nucleon Kr with ^{197}Au. We found the properties of the TLFs from this reaction to be similar to those found in relativistic nuclear collisions. The intranuclear cascade model failed to adequately describe the data at this relatively low energy although BUU model calculations seemed to work.

Finally, we obtained our first results from our ultrarelativistic heavy ion reaction study, experiment E844 at the BNL AGS complex. Preliminary results verified our past observation that the intermediate mass fragments from the interaction of 14 GeV/nucleon ^{28}Si with ^{197}Au, are backward-peaked in the laboratory system.

II. Low Energy Heavy Ion Research

A. Element 110

Last year, we described[1] the attempt to synthesize element 110 by the $^{59}Co + ^{209}Bi$ reaction. During the past year, we have extensively analyzed the data tapes from that experiment. In addition, we performed a complementary experiment (see Section V of this report) to measure the pulse height defects for ~300 MeV ^{59}Co interacting with the "energy monitor" detectors used in the experiment. The conclusions of that experiment (Section V) allowed us to have confidence in our previous measurements[1] of the projectile energies used in the experiment.

During the analysis of the data, an interesting but inconclusive event was seen. The interesting event occurred at about 1730 on Sunday 8 September, 1991 during run RA1017, a relatively short run involving 5.7 mCoul but involving the lowest projectile energy used in the entire experiment 291.1 MeV. In this event, a recoil passed through the dE/dx detector consistent with the expected dE/dx of element 110. The recoil stopped in detector 28 (in the middle of the focal plane) with an energy deposit of 34 MeV (uncorrected for pulse height defect) [The energy of an 110 recoil at the center of the Bi target would be expected to be 64 MeV]. After a time of 4 μsec, an 11.6 MeV α-particle was detected in detector 28. An 8.1 MeV α-particle was detected at the same position in detector 28 some 150 ms later (see Figure II-A-1).

A possible scenario is shown in Figure II-A-1. An atom of element 110 implants in the appropriate focal plane detector with the correct value of dE/dx and E. The decay of ^{267}110 is observed. After observation of this decay, the ADC is known to be dead for 280 μsec, not allowing observation of the decay of ^{263}108. The nucleus ^{259}106 then decays, depositing most but not all of its α-energy in detector 28.

The problem with this event is that the subsequent decays in the chain (Figure II-A-1), i.e., that of ^{255}Rf, ^{251}No, ^{247}Fm, etc., were not observed. (After the decays described above, the first event in detector 28 occurred 355 sec later.) If ^{255}Rf had fissioned spontaneously, one would not observe the daughter decays, but one should have ~100% probability of observing one of the two fission fragments. Therefore, we cannot associate this event conclusively with the formation of element 110.

Another possible interpretation of this event, which is qualitatively correct but not quantitatively right, involves the formation by a deep inelastic transfer reaction of very n-deficient nuclides expected to decay with high α-energies. Viola, et al.[3] have shown these reactions can occur with picobarn cross sections. The α-decay energies are expected to be high and the chain could terminate with p emission which would be missed.

The interpretation of this experiment is not easy because of the range of projectile energies used in the experiment (Figure II-A-2). If all projectile energies are taken as equally effective in producing isotopes of element 110, then the upper limit cross section (95% confidence level) for the production of an isotope of element 110 in the ^{59}Co + ^{209}Be reaction is 6 x 10^{-37} cm. However, the Q value[2] for the ^{59}Co + ^{209}Bi → ^{267}110 + n reaction[2] is -221.3 MeV. One might expect that only laboratory projectile energies of less than 303 MeV (E* < 15 MeV) would be "effective" in inducing the "1-n out" reaction. In that case, the upper limit cross section (95% confidence level) is 4 x 10^{-36} cm^2. This latter estimate is close to the predicted maximum cross section[1] for this reaction. Given the very high, measured efficiency of the SASSY2 separator of ~85%, further attempts at the synthesis of element 110 should involve more favorable reactions.

(A. Ghiorso, D.C. Hoffman, R. Gaylord, W. Ghiorso, K. Gregorich, T. Hamilton, N. Hannink, C. Jarzynski, C. Kacher, B. Kadkhodayan, S. Kreek, M. Lane, D. Lee, R. Leres, W. Loveland, A. Lyon, P. McMahon, M. Neu, M. Nitschke, M. Nurmia, G.T. Seaborg, T. Sikkeland, L.P. Somerville, W.J. Swiatecki, A. Türler, P. Wilmarth, A Wydler, and S. Yashita)

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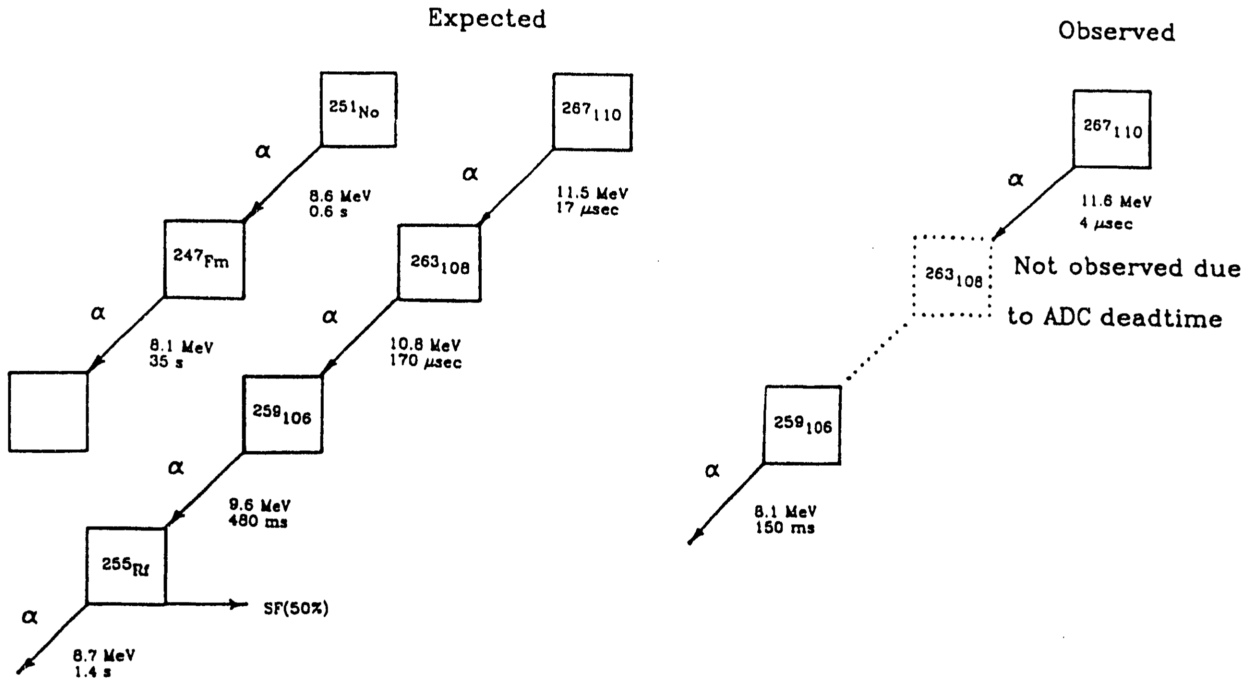

Figure II-A-1. Decay sequence for $^{267}110$ and the "interesting event."

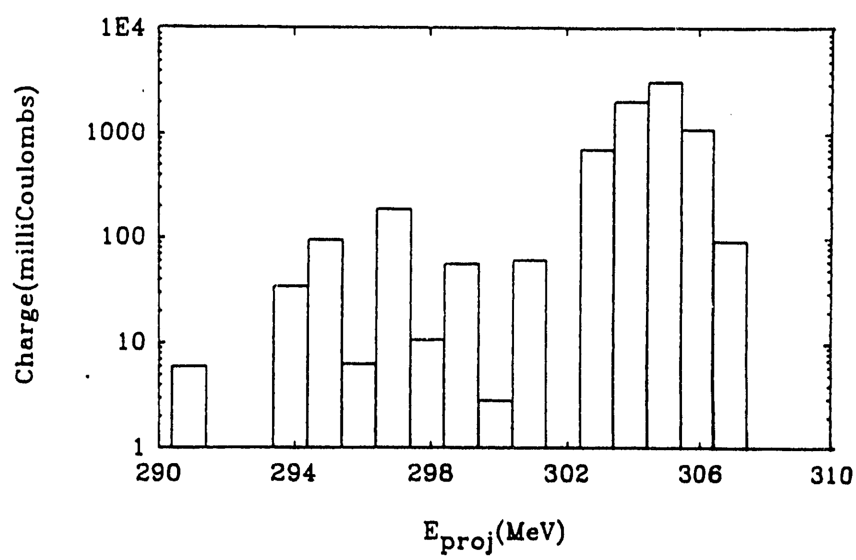

Figure II-A-2. Distribution of projectile energies, as calculated at the center of the target for the experiment.

B. Synthesis of Heavy Nuclei with Complete Fusion Reactions Involving Radioactive Nuclear Beams

The use of radioactive nuclear beams to produce new transuranium nuclei or larger quantities of existing nuclei has been suggested as a motivation for radioactive beam facilities. The desire to use radioactive beams in the synthesis of heavy nuclei, particularly those of n-rich nuclei, is quite understandable. In general, the known isotopes of the heaviest elements tend to be n-deficient (relative to β-stability). If one could produce more n-rich isotopes of a given element, one would expect increased stability (Figure II-B-1). This increase in stability could amount to one or more orders of magnitude which, given the short halflives, could be very important for studies of the chemical and atomic properties of these elements. It has also been suggested that the use of n-rich projectiles would lead to enhanced fusion cross sections, either by a simple lowering of the interaction barrier for a given projectile-target combination or by an enhanced probability for transfer of n-rich clusters.

Because of the keen interest, based upon sound expectations, I decided to evaluate quantitatively the possibilities for synthesis of heavy nuclei with radioactive nuclear beams. Because I chose to employ a brute force approach, considering every possible combination of stable or readily available radioactive target nuclei and all proposed radioactive beam nuclei, I settled on using a set of semi-empirical formulas for cross section calculations, along with appropriate choices of nuclear masses and semi-empirical prescription of nuclear de-excitation (Γ_n/Γ_f values). (A more fundamental approach,[6] using models for complete fission and the statistical de-excitation of the product nuclei would have been prohibitive from the point of view of computer time.) To validate this simplistic approach, I considered a number of heavy element synthesis reactions including known cases involving radioactive beams and compared predictions of the semi-empirical formalism with measurements. I used this formalism to evaluate the production rates of heavy nuclei expected in radioactive beam facilities. I restrict attention in this report to synthesis using complete fusion reactions. A fuller account in which multinucleon transfer reactions, deep inelastic transfer, etc. are considered has been prepared.[12]

I chose to represent the complete fusion cross section using a formalism developed by Armbruster.[7] The cross section for s-wave fusion at the Bass barrier V_B, is given as .

$$\sigma_{fus} = \pi \lambdabar^2 \, P_{\ell=0}(V_B) \qquad (1)$$

where

$$P_{\ell=0}(V_b) = 0.5 \, \exp\left[-71\,(x_{mean} - x_{thr})\right] \qquad (2)$$

and

$$x_{thr} = 0.71$$
$$x_{mean} = 2 \, x \, (k^2 + k + k^{-1} + k^{-2})^{-1/2} \qquad (3)$$

with

$$x = \left((Z_1 + Z_2)^2/(A_1 + A_2)\right)/(Z^2/A)_{crit}$$

$$(Z^2/a)_{crit} = 50.883 \left[1 - 1.7826\left\{\frac{(N_1 + N_2 - Z_1 - Z_2)}{(N_1 + N_2 + Z_1 + Z_2)}\right\}^2\right] \quad (4)$$

$$k = \left[\frac{A_1}{A_2}\right]^{1/3}$$

This represents a parameterization of the concept of a dynamical hindrance of fusion developed by Swiatecki, et al.[8] Estimates of the fusion cross sections made using equations 1-4 might be considered lower limits since higher partial waves are neglected and possible fusion enhancements with n-rich projectiles are neglected. On the other hand, this one dimensional fusion barrier approach has been shown[9] to overestimate expected fusion cross sections for symmetric reactions involved deformed species such as the n-rich fission fragments. Evidence will be presented for canceling errors in this approximation.

Once formed, the fusion products can de-excite by particle emission or fission. The excitation energy of the fusion products was calculated assuming the reaction took place at the Bass barrier[10] with Q values determined using the latest mass values from Möller and Nix.[1] (Although the masses of Liran and Zeldes[11] give a superior fit to the known heavy element masses, the physics behind the Möller-Nix tables was thought to be superior and thus more appropriate for extrapolation into regions of unknown nuclei. A parallel set of calculations using the Liran-Zeldes masses has been done and the results of that calculation do not differ significantly from that reported here.) Using the same rationale as used for the fusion calculations, an abbreviated calculation of the effect of de-excitation was made. Specifically,

$$\sigma_{xn} \approx \sigma_{fus} \left[\frac{\overline{\Gamma_n}}{\Gamma_f}\right]^x P_x \quad (5)$$

where $[\overline{\Gamma_n}/\Gamma_f]$ is assumed to be energy independent. The mean values of $[\overline{\Gamma_n}/\Gamma_f]$ were taken as arithmetic averages of the Γ_n/Γ_f prescriptions of Sikkeland, et al.,[13] and Cherepanov, et al.[14] The probability of evaporating x neutrons, P_x, was taken from the Jackson model.[15]

To test this crude model for fusion cross sections, we compare (Figure II-B-2) the measured and calculated production cross sections for the reactions used to synthesize elements 101-109. The general agreement (within a factor of 10) between the calculated and observed cross sections for most of these xn reactions seems acceptable in view of the approximations in the calculations and uncertainties in the measurements. This agreement is also consistent with previous approaches to predict heavy element xn cross sections. For some nuclei, the calculated and observed values of the cross sections differ by 2-3 orders of magnitude. This can be taken as a cautionary note regarding the formalism used herein.

Some years ago, Unik, et al.,[16] measured the cross sections for producing actinide nuclei in the U beam stops of a high energy proton accelerator. This experiment can be thought of as a crude prototype of the ISL. The heaviest actinide found was ^{248}Cf with an abundance of 1.2 x 10^4 atoms. Using the formalism described above, along with measured values[17] for the spectrum and yield of ^{14}C and dE/dx values for ^{14}C in ^{238}U, one calculates an expected yield of 1.8 x 10^5 atoms of ^{248}Cf from the ^{238}U (^{14}C, 4n) reaction. Given the uncertainties in describing the production of these nuclides in a very thick target, this agreement seems satisfactory. It should be noted that this formalism gives generally lower estimates of the production cross sections for heavy nuclei than that made by Iljinov, et al.[21] (Table II-B-1).

Two proposed radioactive beam facilities are the ISL,[18] a spallation-ISOL facility and PIAFE,[19] a fission-ISOL facility. Using the formalism described above, I have evaluated the production of heavy nuclei ($Z \geq 100$) in these facilities. For the ISL facility, I have assumed that all beams whose halflives exceed 10s would be available at the design intensities.[18] For PIAFE, I have used the beam intensities after the first cyclotron[19] as representative of those needed for heavy element production. I have considered all stable nuclei and all available heavy nuclei as target materials with target thicknesses of 1 mg/cm^2 except for the heaviest elements, where smaller, realistic thicknesses were assumed. I calculated the heavy nuclei production rates for all possible target-projectile combinations.

The results are shown in Figures II-B-3 and II-B-4. In general, the heavy element production rates at ISL (Table II-B-2) are greater than those expected from PIAFE, due to the availability of lower Z beams (C-Na) and the higher projected intensities of even the n-rich fission fragment nuclei. Focussing on the ISL results first, we note that my estimated heavy element production rate for ^{264}104 of ~27 atoms/day is consistent with that estimated, using a very different approach, in the ISL proposal (of 22 atoms/day). Synthesis of new n-rich isotopes of elements 104 (10-100 atoms/day) and element 105 (5-20 atoms/day) seems feasible. The production rates for new isotopes of elements 106 and 107 seem marginal (~1-5 atoms/day and 0.5-1 atom/day, respectively). Typical best production reactions involve asymmetric reactions such as ^{246}Cm (^{20}O, 4n), ^{249}Bk (^{20}O, 4n), ^{252}Cf (^{20}O, 4n). For elements 108 and above, the predicted production rates decrease from 0.1 atoms/day (108) to 0.02 atoms/day (112 and above), i.e., 1 atom every 2 weeks to 2 months. In the fusion model used in the calculations, the best synthesis reactions are symmetric radiative capture reactions, such as ^{138}Ba (^{142}Ba, γ). The predicted fusion cross section is very low (0.7 x 10^{-36} cm^2) but the product are produced "cold." In the calculations for PIAFE (Table II-B-3), the predicted production rates are much lower (0.2-5 atoms/day for element 104) for the lighter transactinides but "catch up" for the heavier transactinides. For example, the "best" synthesis reaction for ^{282}112 at ISL is the ^{138}Ba (^{144}Ba, γ) reaction with a predicted rate of ~0.004 atoms/day while at PIAFE, the preferred reaction is ^{142}Ce (^{140}Xe, γ) with a predicted rate of 0.02 atoms/day. For the heaviest nuclei, the preferred "cold" synthesis involves the familiar use of targets near ^{208}Pb, such as the reaction ^{208}Pb (^{93}Kr, γ). (Detailed tabulations of the "best" synthesis reactions are available upon request.)

The "figure of merit" in these efforts is to compare the best predicted heavy element production rates with radioactive beams with those predicted for stable nuclear projectiles. Using the same formalism as used for the radioactive beam cases, I have evaluated heavy element production rates using stable projectile nuclei[12] (with the assumption of beam intensities of 1 particle μa) and compare the results of the two calculations in Figure II-B-5. One sees advantages for the synthesis of the n-rich lighter transactinides by using radioactive beams, but one also sees that stable projectiles are better suited for attempts to synthesize elements 110 and above (Table II-B-4).

Various authors[22-24] have suggested that there will be significant enhancements to the fusion cross sections for n-rich projectiles due to a lowering of the fusion barrier and the excitation of the soft dipole mode. (It has been pointed[25] out that consideration of the dynamics for $Z_pZ_t >$ 1600 will substantially decrease any projectile fusion enhancement for n-rich projectiles.) Two possible candidate reactions for heavy element synthesis whose consequences have been calculated are ^{54}Ca + ^{244}Pu reaction and the ^{70}Fe + ^{208}Pb reaction. Using the formalism described in this paper (with no fusion enhancement) leads to predicted heavy element production rates of 1×10^{-12} and 3×10^{-8} atoms/day, respectively, for the (^{54}Ca, 4n) and (^{70}Fe, 2n) reactions. Inclusion of the calculated fusion enhancements [24,25] leads to estimated ISL production rates of 5×10^{-9} and 5×10^{-8} atoms/day, respectively, for the (^{54}Ca, 4n) and (^{70}Fe, 2n) reactions. Even if we lowered the energy of the ^{54}Ca projectile by 20 MeV to use the (^{54}Ca, 2n) reaction (with no assumed loss of fusion probability) the predicted production rate would only be 5×10^{-3} atoms/day. If one takes the view that predicted production rates of new heavy nuclei must be ~0.1-1 atoms/day, then the needed fusion enhancements for using radioactive beams to synthesize the heavy nuclei can be read from Figures II-B-3 and II-B-4.

In conclusion, we see that suggestions for producing new heavy nuclei with RNB can and should be evaluated quantitatively using known information about RNB intensities. At this juncture it would appear that RNBs could be useful in synthesizing the lighter n-rich transactinides, but are not a viable path to new heavy elements.

(W. Loveland)

NOTE ADDED IN PROOF

Since this account was finished, it has been reported (Aleklett, private communication) that PIAFE ion source tests at Studsvik and beam transport calculations (Faust) have shown the PIAFE beam intensities in ref. 19 are too low by a factor of at least ten. If this is true, the heavy element production rates shown in Figure II-B-4 and Table II-B-3 should be multiplied by at least a factor of 10.

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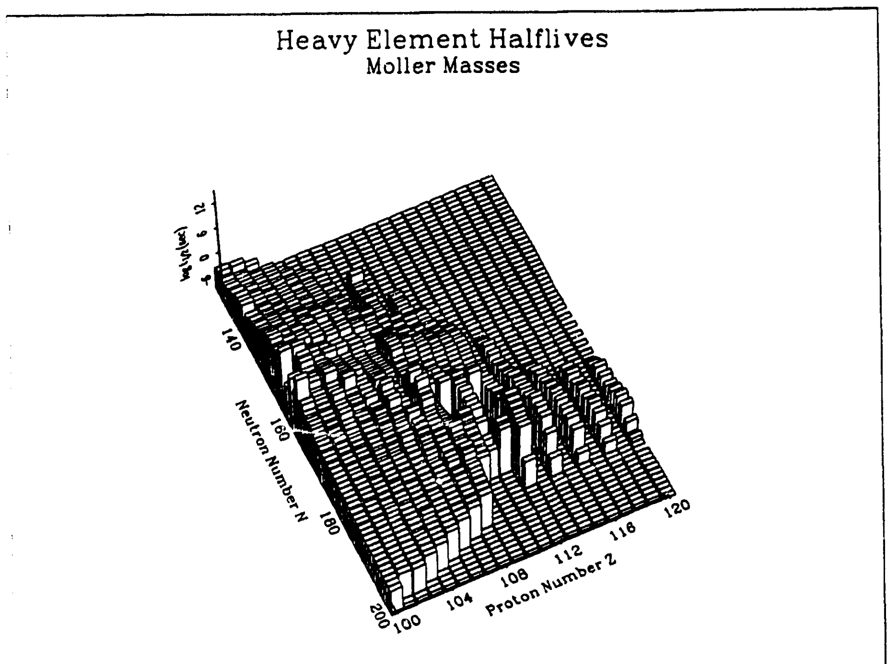

Figure II-B-1. Heavy element halflives. Masses are from Möller and Nix,[1] α-decay systematics from Hatsukawa, et al.,[2] spontaneous fission halflives from Lojewski and Baran,[3] EC halflives from Moody[4] and β-halflives from Staudt, et al.[5]

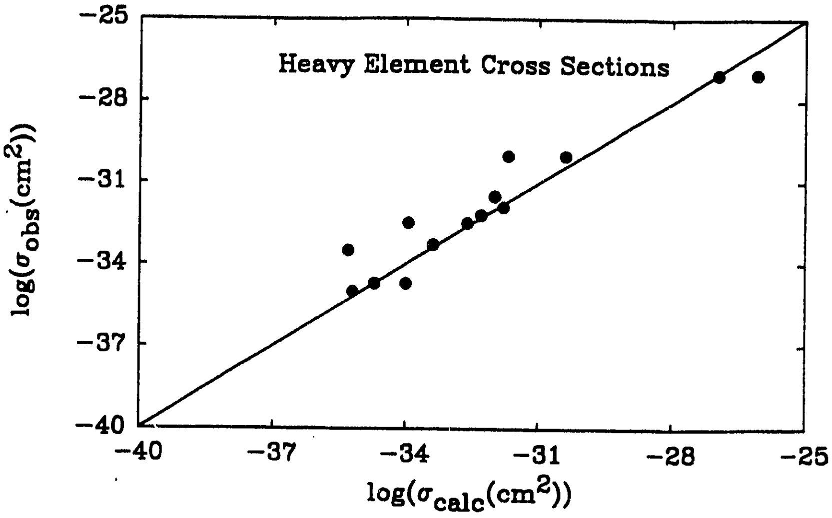

Figure II-B-2. Comparison of observed and calculated xn cross sections for the production of isotopes of elements 101-109.

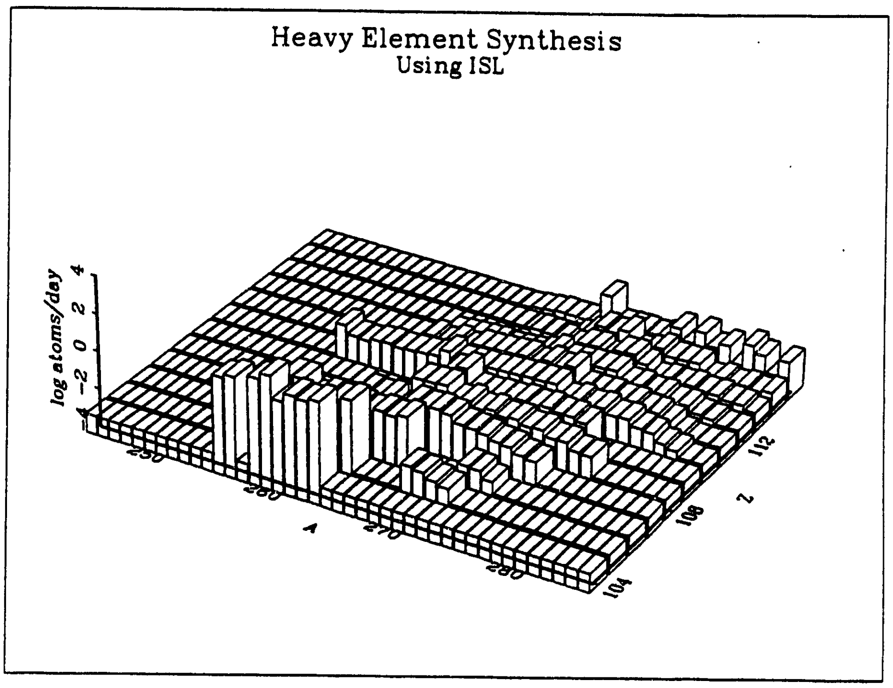

Figure II-B-3. Heavy nuclide production rates using ISL beams.

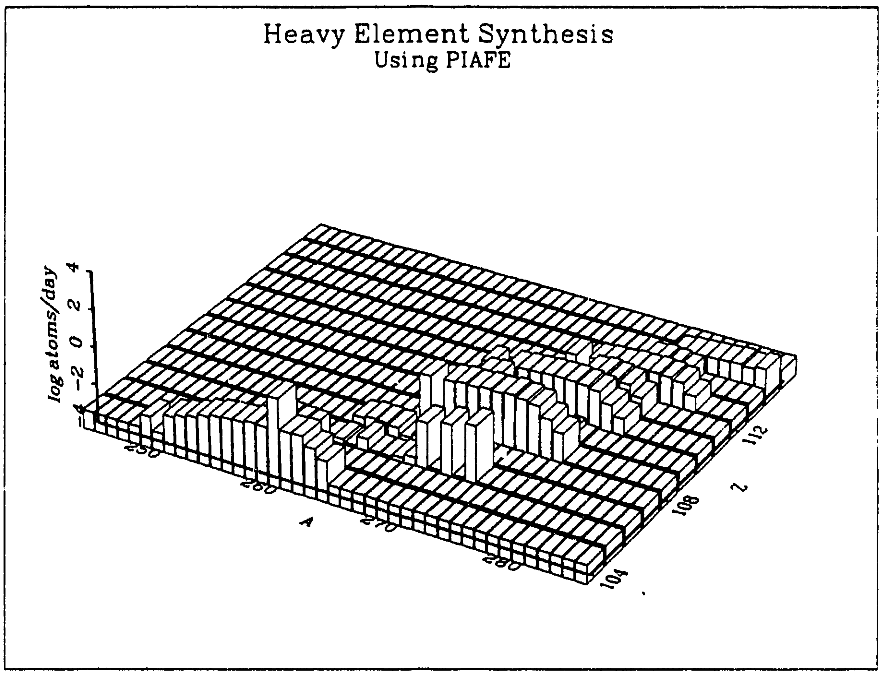

Figure II-B-4. Heavy nuclide productions rates using PIAFE beams.

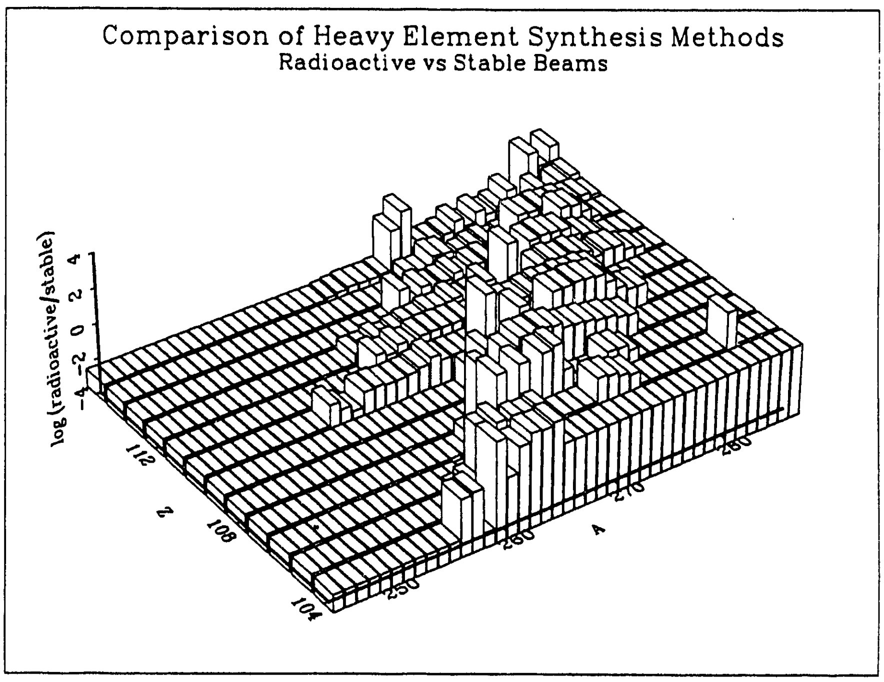

Figure II-B-5. The ratio of the heavy element production rates using radioactive beams to those using stable nuclei.

Table II-B-1. Comparison of Iljinov, et al., calculations and mine.

Rxn	Predicted Cross Sections (cm^2) Iljinov, et al.	This Work
^{244}Pu (^{22}O, 4n) $^{262}102$	3×10^{-30}	5×10^{-31}
^{244}Pu (^{23}F, 5n) $^{262}103$	1×10^{-30}	1.4×10^{-32}
^{244}Pu (^{23}F, 4n) $^{263}103$	6×10^{-31}	1×10^{-31}
^{244}Pu (^{24}Ne, 4n) $^{264}104$	2×10^{-32}	2×10^{-33}
^{244}Pu (^{26}Ne, 5n) $^{265}104$	4×10^{-32}	5×10^{-33}
^{254}Es (^{14}C, 3n) $^{265}105$	3×10^{-32}	3×10^{-32}
^{254}Es (^{15}C, 3n) $^{266}105$	2×10^{-32}	3×10^{-32}
^{249}Bk (^{22}O, 4n) $^{267}105$	4×10^{-32}	2×10^{-33}
^{244}Pu (^{28}Mg, 4n) $^{268}106$	4×10^{-33}	3×10^{-35}
^{244}Pu (^{29}Mg, 4n) $^{269}106$	5×10^{-33}	4×10^{-35}
^{249}Bk (^{24}Ne, 4n) $^{269}107$	5×10^{-34}	8×10^{-36}
^{208}Pb (^{63}Mn, 2n) $^{269}107$	3×10^{-32}	1×10^{-36}
^{232}Th (^{44}Ar, 4n) $^{272}108$	9×10^{-34}	3×10^{-39}
^{208}Pb (^{66}Fe, 2n) $^{272}108$	3×10^{-32}	1×10^{-37}

Table II-B-2. "Best Case" Reactions -- ISL

^{246}Cm (^{20}O, 4n) $^{262}104$	11 atoms/day
^{252}Cf (^{14}C, 3n) $^{263}104$	180 atoms/day
^{248}cm (^{20}O, 4n) $^{263}104$	27 atoms/day
^{242}Pu (^{24}Na, 4n) $^{262}105$	3 atoms/day
^{242}Pu (^{25}Na, 4n) $^{263}105$	4 atoms/day
^{253}Es (^{14}C, 3n) $^{264}105$	59 atoms/day
^{249}Bk (^{20}O, 4n) $^{265}105$	6 atoms/day
^{252}Cf (^{20}O, 4n) $^{268}106$	0.4 atoms/day
^{252}Cf (^{19}O, 4n) $^{267}106$	0.3 atoms/day
^{138}Ba (^{142}Ba, γ) $^{280}112$	0.006 atoms/day

Table II-B-3. "Best Case" Reactions -- PIAFE

^{124}Sn (^{139}Xe, n) ^{262}104	0.2 atoms/day
^{124}Sn (^{140}Xe, n) ^{263}104	0.1 atoms/day
^{124}Sn (^{141}Xe, n) ^{264}104	0.04 atoms/day
^{123}Sn (^{140}Xe, n) ^{262}105	0.03 atoms/day
^{124}Sn (^{140}Cs, n) ^{263}105	0.0004 atoms/day
^{124}Sn (^{141}Cs, n) ^{264}105	0.0007 atoms/day
^{124}Sn (^{142}Cs, n) ^{265}105	0.0004 atoms/day
^{128}Te (^{137}Xe, γ) ^{265}106	1 atom/day
^{130}Te (^{137}Xe, γ) ^{267}106	2 atoms/day
^{130}Te (^{138}Xe, γ) ^{268}106	2 atoms/day
^{130}Te (^{139}Xe, γ) ^{269}106	2 atoms/day
^{130}Te (^{141}Xe, n) ^{270}106	0.006 atoms/day
^{142}Ce (^{138}Xe, γ) ^{280}112	0.03 atoms/day

III. Intermediate Energy Heavy Ion Research

A. The Interaction of 21-44 MeV/nucleon Xe with Au

Last year, we reported[1] the first results of our studies of Xe-Au collisions at 34 and 44 MeV/nucleon. During the past year, we have made an additional measurement at 26 MeV/nucleon. We have also compared our measurements with predictions of various phenomenological models of intermediate energy nucleus-nucleus collisions. The following excerpt from a manuscript that is being published in Physics Letters B describes the completed work.

"The fragment isobaric yield distributions measured in this work along with previously-known data for Xe-Au collisions are shown in Figure III-A-1. One notes a large increase in the yields of intermediate mass fragments IMFs) (A<60) possibly due to multifragmentation.[2,3] As seen in other intermediate energy reactions,[4] one also notes an increase in the yield of TLFs (A>140) and decrease in the yield of sequential fission products as the projectile energy increases. (As the projectile energy goes from 21 to 26 to 34 to 44 MeV/nucleon, σ_f goes from 2460 to 2210 to 1330 to 850 mb while σ_{TLF} goes from 2770 to 2890 to 3170 to 4190 mb.) Processes leading to the survival of large TLFs are a large and increasingly important fraction of the reaction cross section as the projectile energy increases. As seen[4] in the interaction of 21 MeV/nucleon ^{129}Xe with ^{197}Au, the TLF N/Z ratios and the fractionation of the yields of the Au isotopes into high spin (12-) and low spin (2-) states is the same as observed for the interaction of 6.8 MeV/nucleon ^{136}Xe with ^{197}Au. In this latter case, the dominant mechanism for producing TLFs in deep inelastic scattering.

The TLF angular distributions for the 45 MeV/nucleon ^{129}Xe + ^{197}Au reaction (Figure III-A-2) change with increasing mass loss from the target from sidewise peaked (A=195-196, due to quasielastic scattering, quarter-point angle (lab) is ~86°) to intermediate angle peaking (A=171-188, due to deep inelastic scattering), to forward peaked (A≤169, presumably due to incomplete fusion/fragmentation). This forward focussing of the TLF angular distribution with increasing mass loss from the target is consistent with increasing momentum and energy transfer.

This pattern is exactly what one sees in the distribution of mean TLF energy vs. product mass number A (Figure III-A-3a). One also sees, for a given mass removal from the target nucleus, a decreasing fragment kinetic energy with increasing projectile energy. (The range of values for the fragment energies for the 26 MeV/A Xe + Au reaction are consistent with the deduced range of fragment energies for the similar 28 MeV/A Xe + Bi reaction.[2]) All the TLF energies are a small fraction of those expected if the deep inelastic reactions were completely damped. In a sense the TLF energies are a measure of the degree of damping or dissipation in the collision. Using the two-step model used in the data analysis, these mean fragment velocities can be broken down into the components $v_{\parallel}$ and V (Figure III-A-3c).

Qualitatively, one might expect a decrease in the TLF energies with increasing projectile energy due to increased pre-equilibrium emission and shorter reaction times. It is interesting to see how the predictions of various phenomenological models of intermediate energy reactions compare with the measurements. Pre-equilibrium model[5] calculations were made for the Xe +

Au reaction at Xe energies of 21, 26, 34, 44 MeV/A and gave values of $v_{\parallel}/v_{cn}$ of 0.887, 0.835, 0.775, and 0.702, respectively. These values are considerably larger than those shown in Figure III-A-3c because the events shown in Figure III-A-3c do not represent central collisions as assumed in the model. Perhaps more significantly, the relative magnitudes of ($v_{\parallel}/v_{cn}$) also differ in the calculations and the measurements. It would appear that pre-equilibrium emission cannot solely account for the decrease in TLF energies although it may be playing a role. The dissipative dynamics model[15] (DDM) makes quantitative predictions about the relative roles of dissipative processes and fragmentation events as a function of the projectile energy. The predictions of this model, shown in Figure III-A-3b, do not show the proper trend of decreasing TLF energy with increasing projectile energy nor are the observed magnitudes of TLF energies predicted. A similar comment applies to the predictions of a nucleon transport model.[6]

Considerable success has been achieved in describing intermediate energy nuclear collisions using a heavy ion transport model,[7] which solves the Boltzmann-Uehling-Uhlenbeck (BUU) equation using the test particle method. It is interesting to use this model to simulate the first few hundred fm/c of the collision during which the primary hot TLF is formed. We show the results of such a simulation in Figure III-A-3b. While we have not tried to simulate the later stages of the reaction in which the primary TLFs decay by multifragmentation or particle emission or fission, we thought it was interesting (and surprising) to see no predicted difference in the primary distributions for the interaction of 21 and 44 MeV/A Xe + Au."

(W. Loveland, K. Aleklett, R. Yanez, A. Srivastava, and J.O. Liljenzin)

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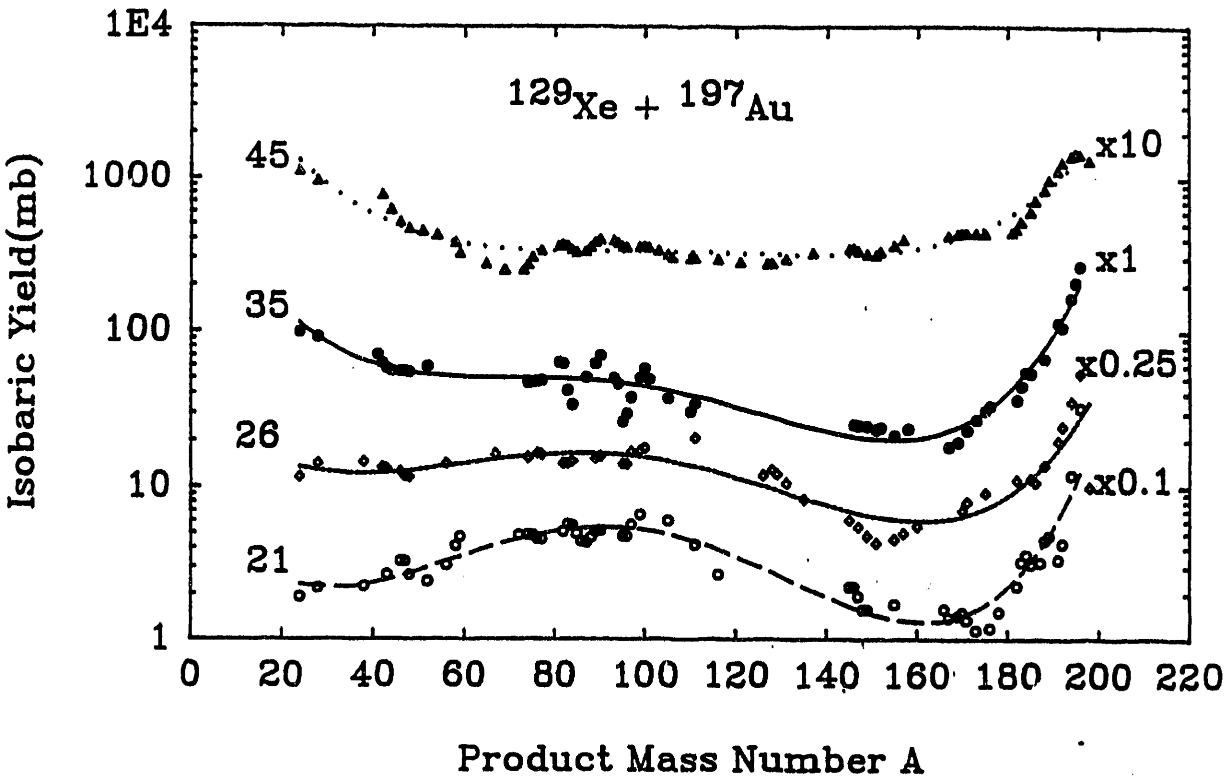

Figure III-A-1. Target fragment isobaric yield distributions for the reaction of 21, 26, 34 and 44 MeV/nucleon ^{129}Xe with ^{197}Au. The data and curves are displaced for convenience in viewing. The data are uncertain to ±10%.

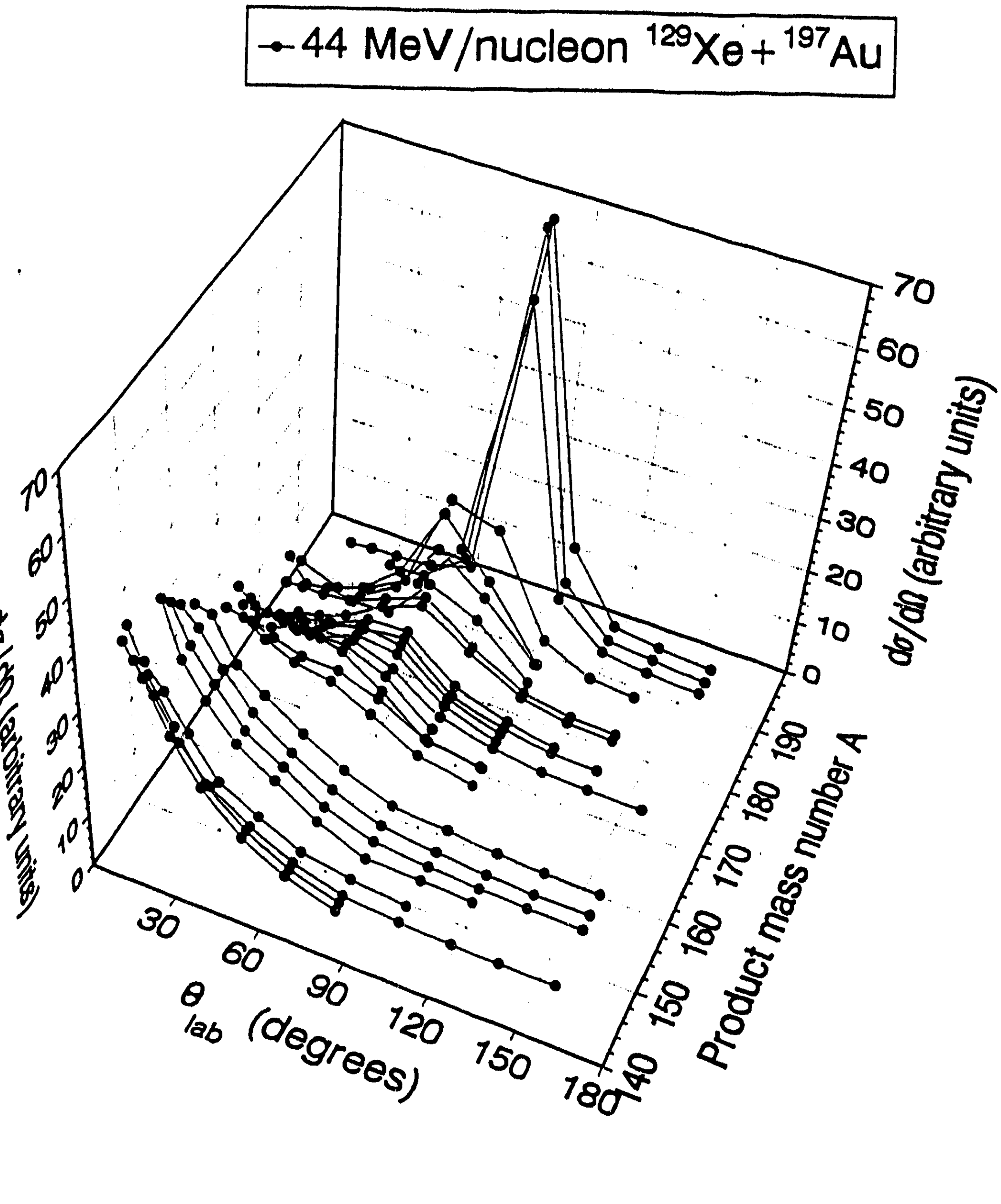

Figure III-A-2. A three-dimensional representation of the target fragment angular distributions for the reaction of 44 MeV/nucleon ^{129}Xe with ^{197}Au.

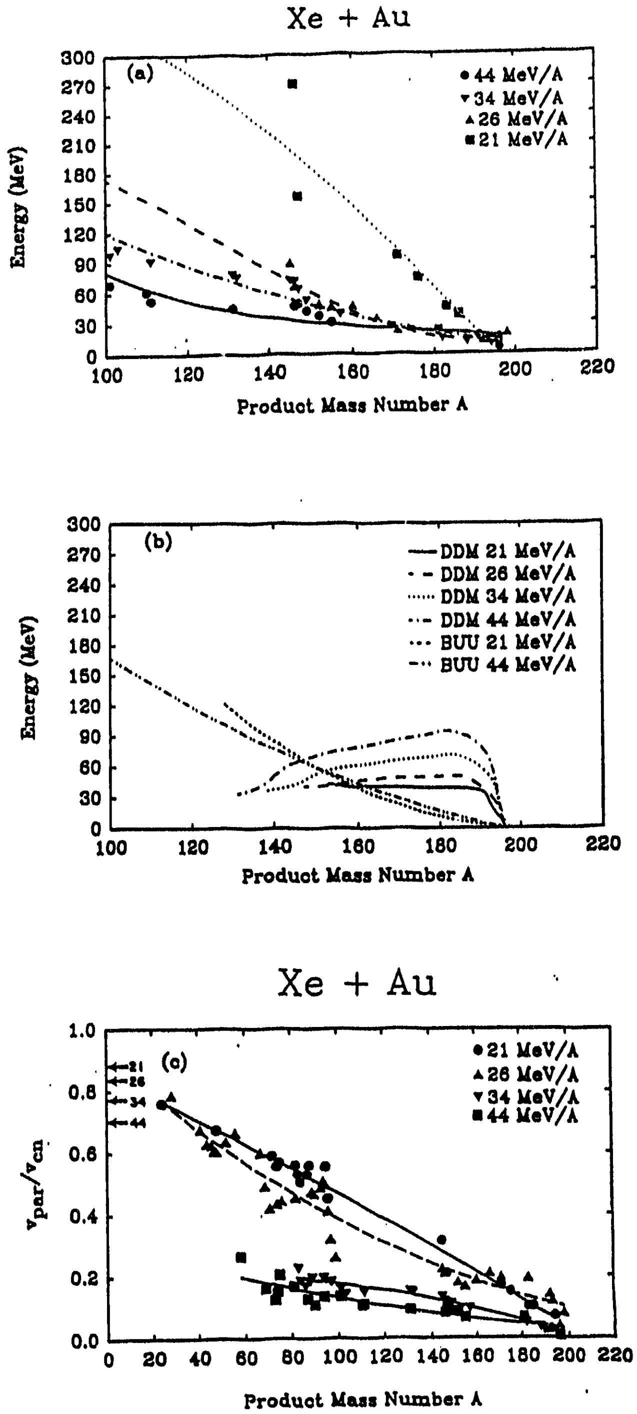

Figure III-A-3. (a) The measured laboratory frame target fragment kinetic energies for the reaction of Xe with ^{197}Au. (b) The TLF energies as predicted by various models. (c) The ratio $v_{\|}/v_{cn}$ vs. product mass number A for Xe-Au collisions. The arrows indicate the predictions of a pre-equilibrium model.

B. The Production of Target-Like Fragments in the Interaction of 60 MeV/nucleon ^{86}Kr with ^{197}Au

At low energies (E_{proj} < 10 MeV/nucleon), Kr-Au reactions result primarily in quasi-elastic and deep inelastic collisions. As the projectile energy is raised to 35-45 MeV/nucleon, one sees both highly dissipative collisions and some fragmentation-like behavior.[1-6] Among the projectile-like fragments (PLFs), one observes, at angles outside of the grazing angle, a number of fragments that have suffered a large kinetic energy loss in the collision, along with significant mass and change loss ($\Delta A \sim 35$, $\Delta Z \sim 12$). The target-like fragment partners of these PLFs appear to decay by fission. The evaporation residues (A_{frag} >140) observed[2] in 35-45 MeV/A Kr-Au collisions have very low kinetic energies and appear to have resulted from peripheral, two-body reactions. In 100 MeV/nucleon Fe + Au and Nb-Au collisions,[8] and 200 MeV/nucleon Kr + Au collisions,[9] PLFs and fragments from the sequential fission of TLFs are describable by the intranuclear cascade model presumably reflecting the dominant role of nucleon-nucleon collisions.

In view of the changes in reaction mechanism that occur between 35-44 MeV/A Kr + Au and 100 MeV/A Fe, Nb + Au collisions, we thought it might be interesting to examine Kr-Au collisions at a projectile energy of 60 MeV/nucleon. Because we have observed previously that at projectile energies of 44 MeV/nucleon, that most collisions resulted in the production of a surviving TLF, we decided to focus our attention on these fragments. Because of the superior energy resolution and sensitivity for detecting these low energy fragments, we used radiochemical techniques.

Last year,[10] we reported that the mean TLF energies (A_{frag} = 145-190) were very low and follow the dependence on fragment mass and projectile energy characteristic of peripheral two-body reactions. We have finished our analysis of the target-like fragment mass distributions and angular distributions. (Figure III-B-1 and Figure III-B-2). A small but discernible peak in the fragment mass distribution can be attributed to fission. Its' magnitude (1000 mb) is greater than that observed[9] for the interaction of 50 MeV/nucleon Fe and Nb with ^{197}Au (165±35 and 400±60 mb, respectively). A much larger fraction of the reaction cross section (3800 mb) can be associated with the production of surviving target-like fragments. Having this large fraction of the primary TLFs decay by fast particle emission rather than fission is qualitatively consistent with previous INC calculations.

To test whether INC calculations can quantitatively reproduce the data on the residue distributions, we have used the Yariv-Fraenkel intranuclear cascade model[12] to calculate the properties of the residues in the 60 MeV/nucleon ^{86}Kr + ^{197}Au reaction. The resulting primary fragment distributions are shown in Figure III-B-3. These distributions are substantially different than those calculated by Blaich et al.[11] for the more energetic 100 MeV/nucleon Nb + Au collisions. Because of the low excitation energies of the primary TLFs, calculated de-excitation of these nuclei[13] does not produce the measured fragment mass distribution (Fig. III-B-1). We conclude that mean field effects not taken into account in the intranuclear cascade model are important in this reaction.

To test these effects, we calculated the properties of the TLFs for this reaction using the BUU model.[14] Reasonable agreement between the measured fragment mass distribution (Fig. III-B-1) and the fragment energies (Fig. III-B-4) is seen.

(A. Srivastava, W. Loveland, K. Aleklett, J.O. Liljenzin and R. Yanez)

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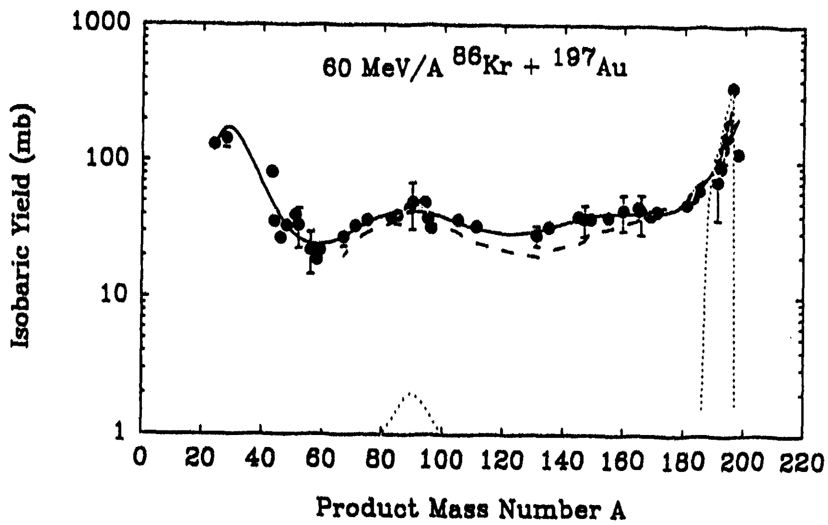

Figure III-B-1. Measured and calculated fragment mass distribution for the reaction of 60 MeV/nucleon ^{86}Kr with ^{197}Au. Dotted line is the INC calculation, the dashed line the BUU calculation.

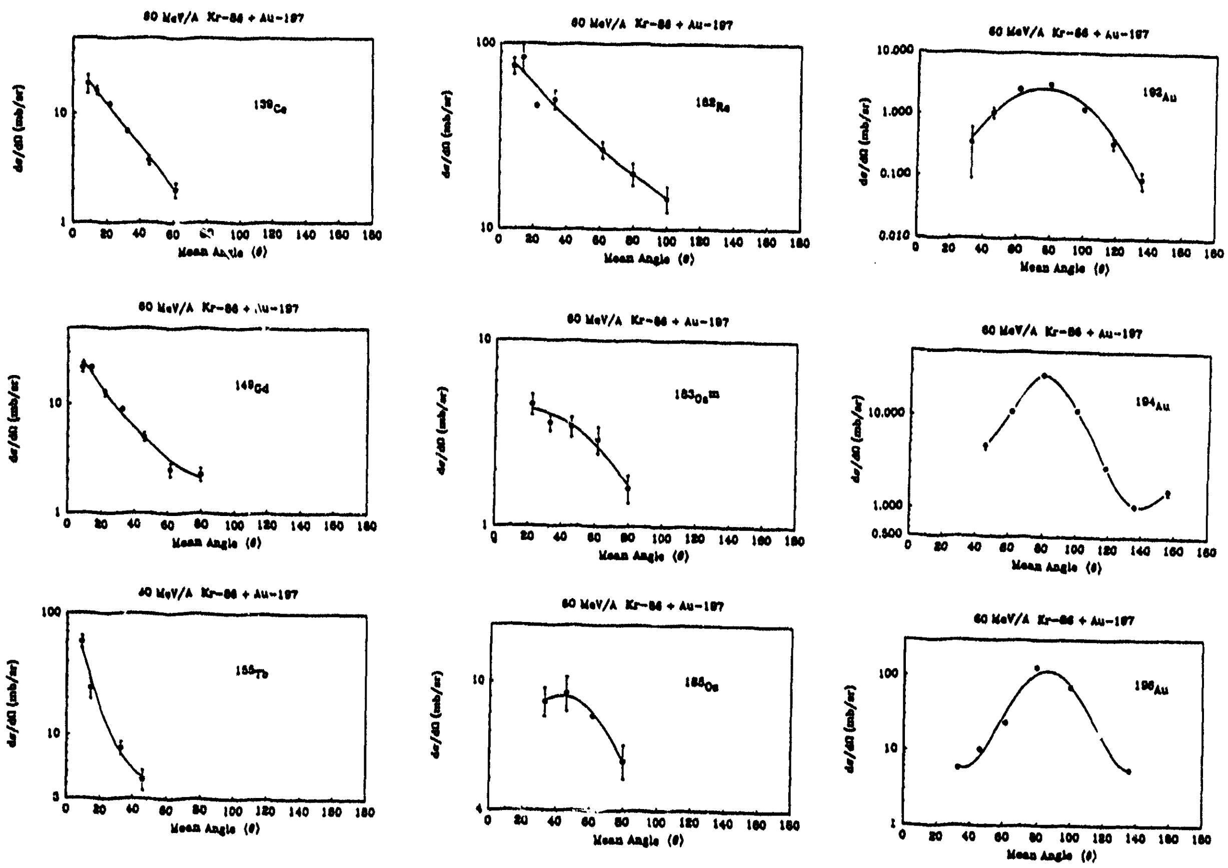

Figure III-B-2. Fragment angular distributions for the reaction of 60 MeV/nucleon ^{86}Kr with ^{197}Au.

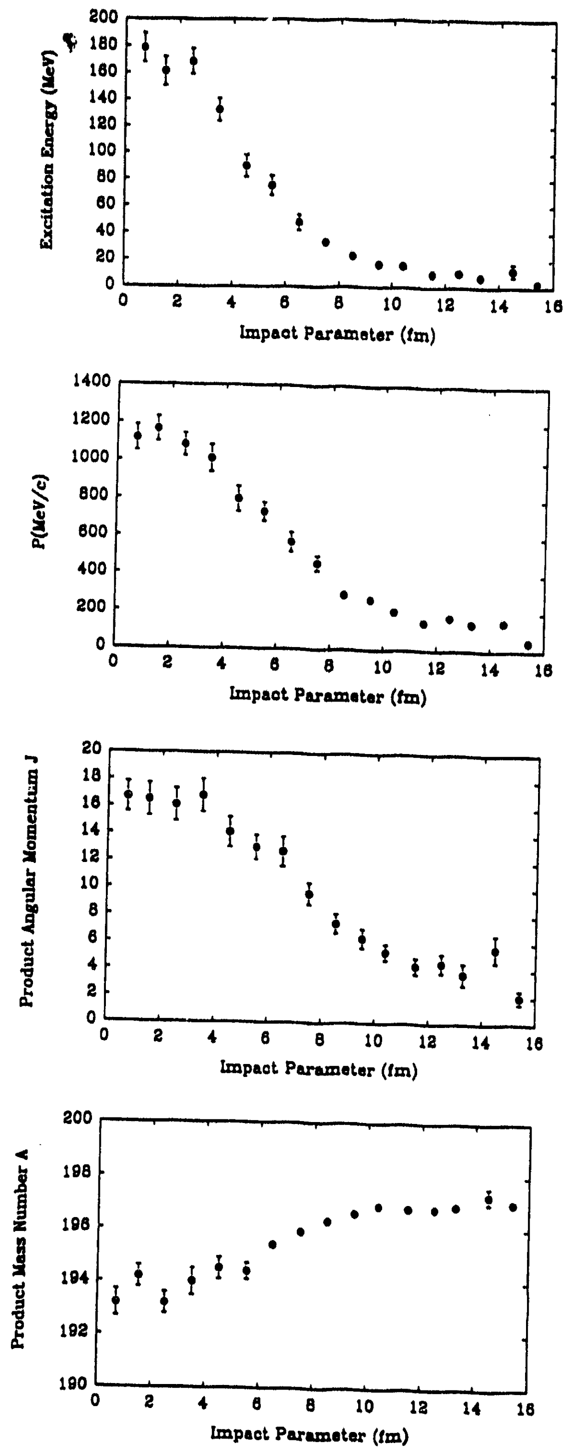

Figure III-B-3. Results of intranuclear cascade calculations for 60 MeV/nucleon $^{86}Kr + ^{197}Au$. The four graphs show (a) excitation energy, (b) momentum, (c) angular momentum, and (d) TLF mass number.

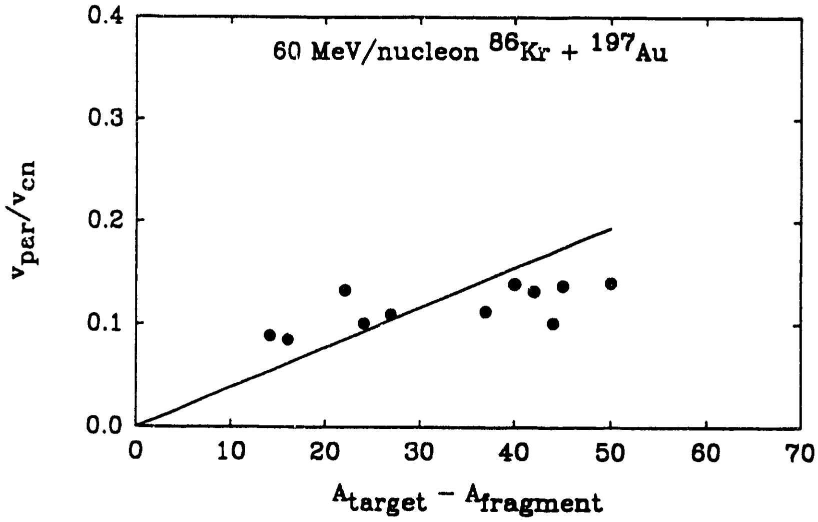

Figure III-B-4. Measured and calculated (BUU) ratio of fragment longitudinal velocity as a function of mass loss from the target nucleus.

C. Intermediate Energy Ar-Th Collisions

The Ar + Th reaction has played an important role in our understanding of intermediate energy nuclear collisions. Measurements[1,2] of the fission fragment folding angle distributions for this reaction showed the disappearance of fusion-like events at a projectile energy of 39-44 MeV/nucleon. Originally this disappearance was linked to the idea of the maximum excitation energy that could be contained in a nucleus, but similar studies[3] of the Ni + Th reaction showed the persistence of fusion-like events up to E* ~900 MeV, a value greater than that achieved in the Ar + Th reaction. Measurement[4,5] of the neutron multiplicities for the Ar + Th reaction showed a constant average multiplicity with Ar energy varying from 27 to 77 MeV/nucleon and the occurrence of similar multiplicity distributions. So it was clear that large multiplicity (large p transfer, fusion-like) events were occurring at projectile energies above 40 MeV/nucleon even though they seemed to be absent from the folding angle distributions.

Two possible reaction exit channels in which one might find the "missing" fusion-like events were the heavy residues and true multifragmentation events that do not leave a heavy target residue [The frequently used term "intermediate mass fragments" can include lower Z (Z = 1-5) fragments whose production also includes that of a heavy target-like fragment]. Independent evidence was found[6-9] that the time scale of fission events for the Ar + Th system was $\sim 10^{-20}$ sec which is long compared to the time for neutron emission of $\sim 10^{-22}$ sec. Thus fission was expected to be severely inhibited for E* > 50-75 MeV.

We thought it would be useful to measure, using radiochemical techniques, the gross cross sections for heavy residue and intermediate mass fragment production, and their momenta for the Ar + Th reaction at energies (77 and 95 MeV/A) where the fusion-like events were absent from the folding angle distributions, but present in the neutron multiplicities. The use of radiochemical techniques to study the heavy residue properties was to insure that no residues would be missed due to detection thresholds, etc.

Thick targets of Th metal (~56 mg/cm^2) were surrounded by 18 mg/cm^2 Mylar catcher foils and irradiated in the external Ar beams from GANIL. Two Ar energies, 77 and 95 MeV/nucleon, were used. A short (~10 m) and a long irradiation (~1 hr) was performed at each energy with typical Ar fluences of 3 x 10^{13} and 2 x 10^{14}, respectively. The irradiated target and catcher foils were analyzed by off-line γ-ray spectroscopy. Using techniques described previously,[10] target fragment mass distributions were deduced from the γ-ray spectrometric data. (Figure III-C-1 and III-C-2.)

The two isobaric yield distributions are similar. Integration of the region from A = 60 to A = 155 and A = 160-215 gives fission (multiplicity = 2) and heavy residue (multiplicity = 1) production cross sections of 3400 and 900 mb for 77 MeV/nucleon ^{40}Ar + ^{232}Th and 3100 and 700 mb for 95 MeV/nucleon ^{36}Ar + ^{232}Th.

The integral catcher analysis method of Tobin and Karol[11] was used to deduce the average longitudinal momentum transfer associated with various fragments (Figure III-C-3). The intermediate mass fragments are the events which correspond to fusion-like events while the momentum transfers leading to the heavy residues are low. (For fusion-like events in the ^{36}Ar (95 MeV/A) + ^{232}Th system, one would expect $\overline{v_{\parallel}/v_{CN}}$ ~0.4.)

This association of the "missing" high linear momentum transfer events with the lighter fragments is consistent with theoretical predictions[12] and studies of heavy residues in other systems[13] which showed a disappearance of fusion-like residues at Ar projectile energies less than 44 MeV/A. Other studies[14] of heavy residue production at higher projectile energies have shown very low residue energies corresponding to their formation in low momentum transfer events. The aforementioned neutron multiplicity measurements indicated a cross section for fusion-like events of ~2 b for the Ar + Th system which is in rough agreement with the estimated lower Z fragment cross sections of $\sigma_{rxn} - \sigma_t - \sigma_{HR}$ ~1200 and 1600 mb for the 77 and 95 MeV/nucleon Ar-induced reactions, respectively.

(R. Yanez, K. Aleklett, J.O. Liljenzin, W. Loveland, and A. Srivastava.)

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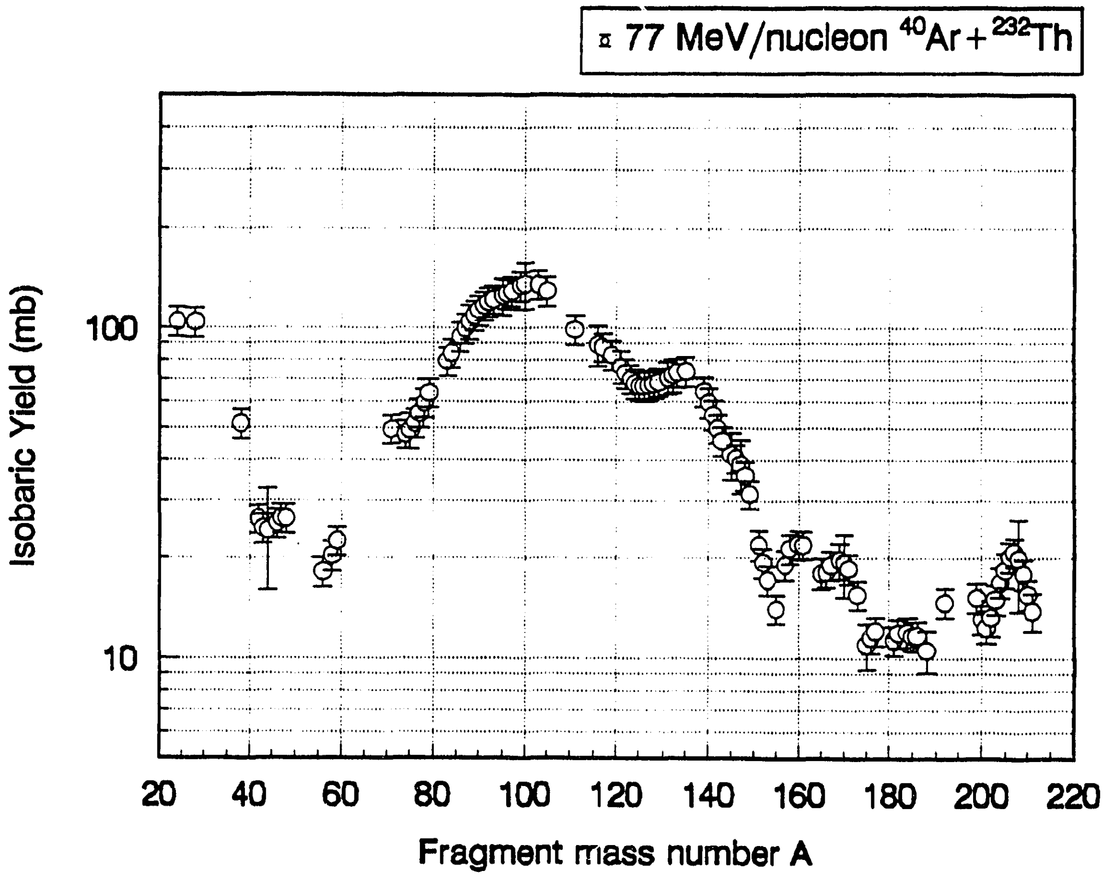

Figure III-C-1. Target fragment mass distribution for the 77 MeV/nucleon ^{40}Ar + ^{232}Th reaction.

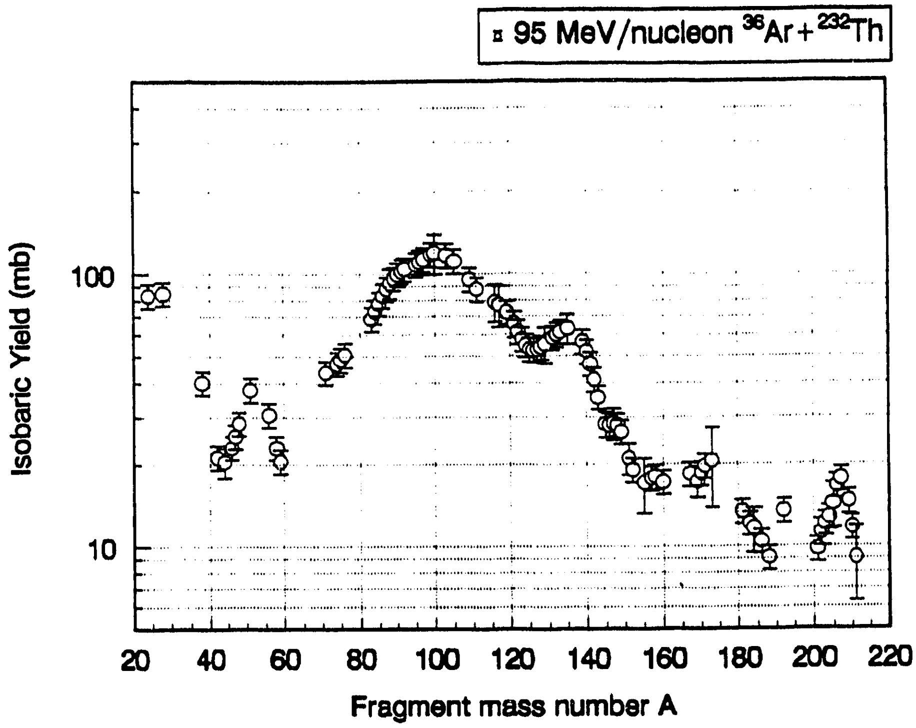

Figure III-C-2. Target fragment mass distribution for the 95 MeV/nucleon $^{36}Ar + ^{232}Th$ reaction.

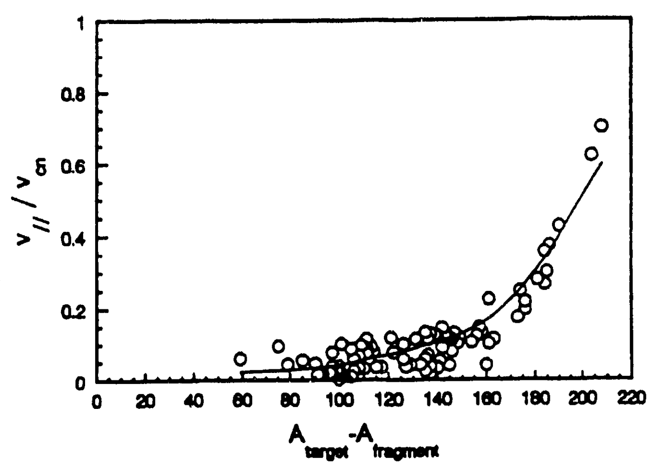

Figure III-C-3. Target fragment longitudinal velocity (as a fraction of v_{CN}) vs. the mass removed from the target nucleus for the reaction of 95 MeV/nucleon ^{36}Ar with ^{232}Th.

D. Target-Like Fragments from the Interaction of 29 MeV/nucleon ^{208}Pb with ^{197}Au

One of the most interesting nucleus-nucleus collisions that has been studied in recent years is that of 29 MeV/nucleon ^{208}Pb with ^{197}Au. This reaction should allow extensive dissipation of energy without significant nuclear compression. The neutron-rich character of the projectile may, in the case of dissipative collisions, allow study of the relaxation of the N/Z degree of freedom in a higher energy collision. Extensive studies of the neutron multiplicities, intermediate mass fragments and the projectile-like fragments (PLFs) and the correlations between these observables have been made.[1-7]

To complement these studies, we decided to measure the yields, angular distributions and energies of the target-like fragments (TLFs) from this reaction. Since it had previously been shown[7] that the properties of the PLFs from this reaction could be adequately understood using the nucleon exchange model,[8] we hoped that a comparison of the predictions of this model for the TLFs and our data would help us to understand the deficiencies in our treatments of TLFs in dissipative Xe-Au collisions (see Section IIIA of this report).

Using radiochemical techniques, and the 29 MeV/nucleon ^{208}Pb beam at GANIL, we did four separate measurements of TLF properties for the ^{197}Au (^{208}Pb, X) reaction. We measured: (a) the yields and recoil properties of the TLFs, (b) the angular distribution of the TLFs, (c) the differential range distributions (energy spectra) of the TLFs emerging at various angles (0-90°) with respect to the incident beam direction, and (d) re-measured the low energy tails of the PLF energy distributions so as to separate the PLF and TLF contributions to the yield of a given product. The integrated particle exposures for these four experiments were: (a) 3.26×10^{13} ions, (b) and (c) 1.31×10^{14} ions, and (d) 2.85×10^{13} ions, respectively. Since the irradiations were performed a few days before the writing of this report, counting of the samples is in progress.

(R. Yanez, K. Aleklett, J.O. Liljenzin, W. Loveland, A.N. Ham, and A. Srivastava)

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E. The Interaction of 22 and 32 MeV/nucleon ^{16}O with ^{197}Au

We have previously shown[1] that as the projectile energy increases from 20-40 MeV/nucleon in asymmetric heavy ion-heavy target reactions, the yield of surviving target-like fragments (the heavy residues) increases significantly while the fission cross section proportionately decreases. The question we wish to answer involves "where has all the fission gone and why has it gone?" To help answer this question and to demonstrate the feasibility of reaction studies at the Swedish heavy ion storage ring CELSIUS, we initiated a set of experiments at the TSL laboratory in Uppsala. Our goal in these experiments is to characterize the fission process in the reaction of 22 and 32 MeV/nucleon ^{16}O with ^{197}Au to see what features, if any, of the fissioning nuclei change as the fission cross section decreases by approximately a factor of two. This characterization involves measuring the fission fragment in-plane and out-of-plane angular correlations in coincidence with projectile-like fragments. A second goal of the experiment was to gain familiarity with the equipment, electronics, and data acquisition hardware to be used at the CELSIUS project (although this experiment only involved the ring injector synchrocyclotron and not the storage ring itself).

Last year, we made our first measurements of in-plane and out-of-plane PLF-fission correlations as well as fission-fission and PLF-fission-fission coincidence for the reaction of 22 MeV/nucleon ^{16}O with ^{197}Au. We reported[2] the fission folding angle and mass distributions as a function of PLF Z and reaction Q value.

The relevant geometry of our angular correlation measurements is shown in Figure III-E-1. In Figure III-E-2 we show the measured in-plane and out-of-plane fission angular distributions for the 22 MeV/nucleon ^{16}O + ^{197}Au reaction summed over all PLF Q and Z values. Laboratory angles and cross sections have been converted to calculated rest frame of the recoil nucleus on an event-by-event basis. (The in-plane angle ϕ and the out-of-plane angle θ relative to the normal to the reaction plane are defined in Figure III-E-1.) The data shown in Figure III-E-2 correspond to an average PLF Z, A of 3 and 6, respectively and an average excitation energy of the recoil nucleus of 45 MeV.

The magnitude and orientation of the angular momentum of the fissioning nucleus can be extracted from the fission fragment angular distributions. The out-of-plane distribution is sensitive to the magnitude of the angular momentum while its orientation is derived primarily from the in-plane distribution.

The fission angular distribution in the rest frame of the fissioning nucleus is given by[3,4]

$$W(\theta,\phi) \;\alpha\; \frac{1}{S} \exp\left[\frac{-I_z^2 \cos^2\theta}{2\,S^2}\right] \tag{9}$$

where

$$S^2 = K_o^2 + (\sigma_x^2 \sin^2\phi + \sigma_y^2 \cos^2\phi)\sin^2\theta + \sigma_z^2 \cos^2\theta \tag{10}$$

This assumes the angular momentum distribution can be represented as

$$P(I) \;\alpha\; \exp\left[-\left(\frac{I_x^2}{2\sigma_x^2}+\frac{I_y^2}{2\sigma_y^2}+\frac{(I_z-\bar{I}_z)^2}{2\sigma_z^2}\right)\right] \tag{11}$$

The mean square projection of the angular momentum on the nuclear symmetry axis, K_o^2, was taken from the systematics[5] of the variation of K_o^2 with excitation energy, E*, relative to the fission barrier, B_f, for U

$$K_o^2 = 19.4\,(E^* - B_f) \tag{12}$$

and scaled from U to Au by the ratio of the moments of inertia at the saddle point. The measured distributions were fit using a Simplex method to yield values of the mean angular momentum $\bar{I}_z$ and the alignment parameter (polarization), P_{zz}, where

$$P_{zz} = \frac{3}{2}\frac{\overline{I_z^2}}{\overline{I^2}} - \frac{1}{2} = \frac{2\langle I_z^2\rangle - \langle I_x^2\rangle - \langle I_y^2\rangle}{2\langle I^2\rangle} \tag{13}$$

The deduced values are $\langle I_z\rangle = 21\ \hbar$, $\sigma_x = 0$, $\sigma_y = 21.4$, $\sigma_z = 3.7$, $P_{zz} = 0.98$. Thus the transferred spin is modest (and in good agreement with observations[6] made for the reaction of 20 MeV/A ^{16}O with ^{154}Sm) and the alignment is essentially complete.

To complete this experiment, we performed a second measurement this year at 22 MeV/nucleon (to increase the number of observed events) and made a complete measurement at a projectile energy of 32 MeV/nucleon. Due to an improved data acquisition system and longer running times, the total number of measured events increased substantially compared to the previous run. Analysis of these data is in progress.

(W. Loveland, D.J. Morrissey, K. Aleklett, R. Yanez, J.O. Liljenzin, D. Jerrestam, E. Hagebø and L. Westerberg)

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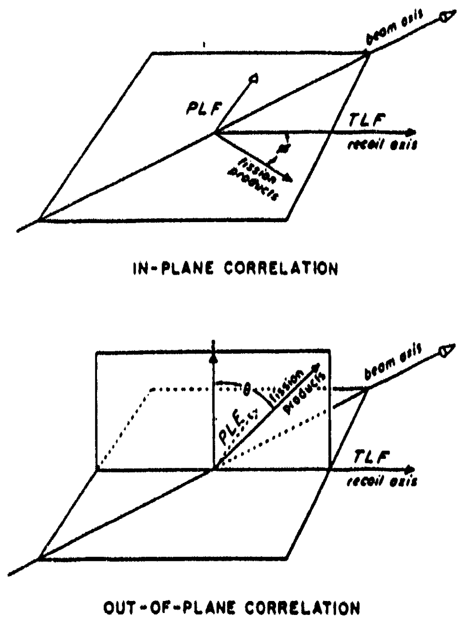

Figure III-E-1. Geometry of the experiment. After Dyer, et al.

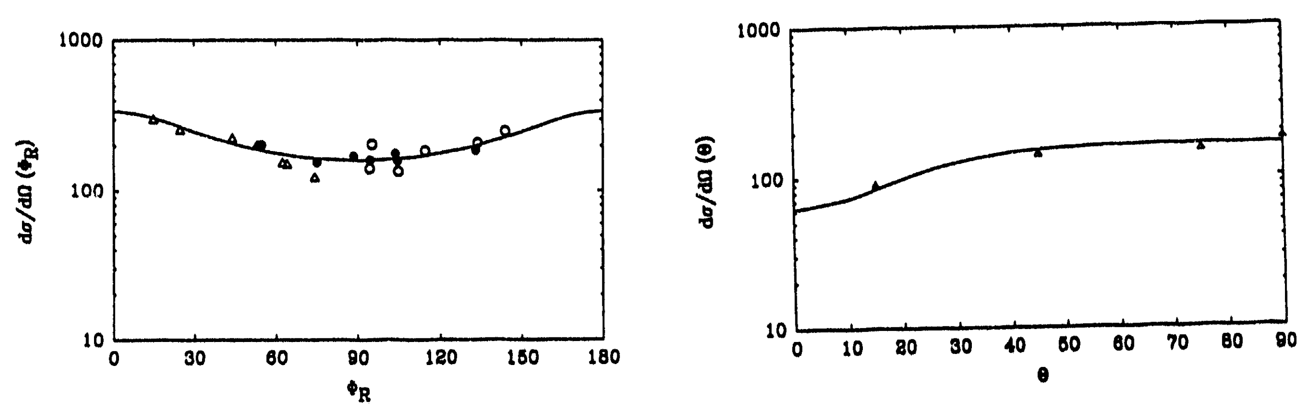

Figure III-E-2. Fission fragment angular correlations measured in and out (ϕ = 70°) of the reaction plane. The solid curve represents the fit to the data with J = 21 (see text).

F. Au Projectile Fragmentation at 20 MeV/nucleon

Recent studies[1] of the fragmentation of ^{129}Xe and ^{238}U projectiles using the MSU A1200 projectile fragment spectrometer have demonstrated the existence of a new, very powerful tool for the study of heavy residues and fission fragments formed in asymmetric nuclear collisions at intermediate energies. We began a series of measurements of heavy residue production in the fragmentation of 20 MeV/nucleon ^{197}au.

The experimental apparatus (the A1200 spectrometer) is shown in Figure III-F-1. The ^{197}Au beam was accelerated in the K1200 cyclotron and struck the production target (C, Al, ^{48}Ti). The resulting projectile fragments (and fission fragments) from the primary interaction were momentum and mass analyzed by the A1200 spectrometer and were stopped in a three-element silicon telescope placed in the focal plane of the spectrometer. The Z, A, and momentum of each fragment was calculated from the fragment time-of-flight and the telescope signals along with the spectrometer parameters. Typically, ~200 nuclides were seen for each reaction. This measurement should provide the first high resolution, systematic characterization of these residues for intermediate energy Au + X reactions.

(I. Lhenry, K. Hanold, G. Wozniak, A. Veeck, W. Loveland, T. Day, and the A1200 spectrometer group)

References

1. K. Hanold, private communication.

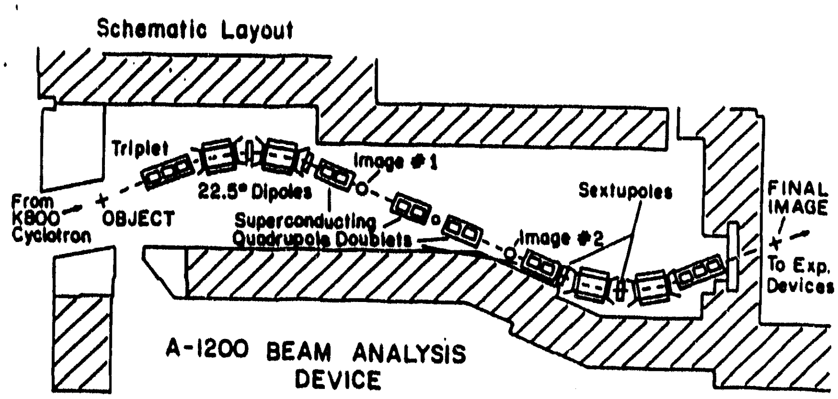

Figure III-F-1. The MSU A1200 fragment spectrometer.

IV. Relativistic Heavy Ion Research

A. "Backsplash"

One interesting, but not well understood observation in the study of ultrarelativistic nucleon collisions was the finding[1] by us that the ratio of the fraction of an intermediate mass fragment (^{24}Na) recoiling forward (F) in the laboratory frame from a thick target to those recoiling backward (B) was less than one ("backsplash"). (F/B (^{24}Na) $\approx$ 0.85 $\pm$ 0.02). This result was observed for the 14 GeV/nucleon ^{16}O + ^{197}Au reaction. Such an observation must imply an unusual backward-peaked IMF angular distribution. A similar observation[2] was made by Grabez for the 5 GeV/nucleon ^{4}He + Ag reaction.

Last year we performed BNL experiment E844 to measure the detailed angular distributions of the rare gas nuclides ^{127}Xe and ^{37}Ar formed in the fragmentation of ^{197}Au by 14 GeV/nucleon ^{28}Si. During the past year, counting of the samples has proceeded. (The measurements are very difficult involving the use of low background proportional counters which operate with one gaseous sample as part of the counting gas with typical counting times being several months.)

The first data from these measurements is now available. F/B ratios of 0.78 and 1.76 were measured for ^{37}Ar and ^{127}Xe fragments. Corresponding values of 2W (F+B) are 9.37 and 2.04 mg/cm^2 Au. Figure IV-A-1 shows how these data fit into what is known[3,4,5,6,7,8] about relativistic and ultrarelativistic p-nucleus and nucleus-nucleus collisions leading to Ar-like fragments. When combined with the previous measurement[1] for ^{24}Na (Figure IV-A-2), it seems clear that at high enough projectile energies in nucleus-nucleus collisions (and possible p-nucleus collisions), the intermediate mass fragments are emitted preferentially backwards <u>in the laboratory frame</u>.

While many people (ourselves included) have invoked the concept of limiting fragmentation to describe the cross sections for fragment formation in ultrarelativistic collisions, that is clearly not the case when one considers the kinematic properties of the fragments. Furthermore, while sidewise-peaked fragment angular distributions have been observed before, the backward-peaked fragment angular distributions implied by F/B values of 0.85 and 0.78 for fragments as massive as ^{24}Na or ^{37}Ar are difficult to explain.

Analysis of the angular distribution data is in progress. A full distribution for the backward hemisphere (5 points) should be obtainable. Unfortunately, in counting the forward hemisphere samples, our Ar samples were contaminated due to the concurrent use of the mass spectroscopy equipment by the BNL solar neutrino group. Only the sample at 18° was recoverable. (We will have full forward and backward distributions for the ^{127}Xe samples.) In view of the unusual results in the gross F/B measurements, the shapes of the angular distributions should be of great interest.

(J.B. Cumming, P.E. Haustein, R.W. Stoenner, <u>W. Loveland</u> and K. Aleklett)

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8. S.B. Kaufman, E.P. Steinberg and M.W. Weisfield, Phys. Rev. C18, 1349 (1978).

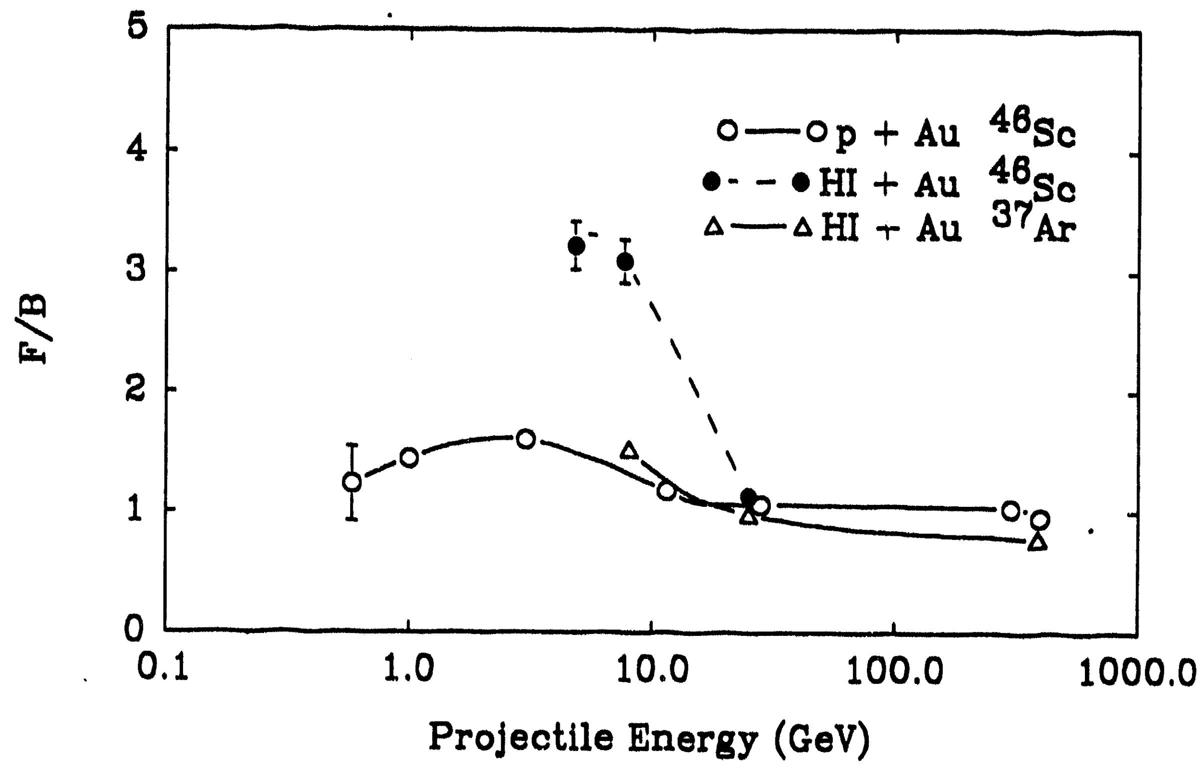

Figure IV-A-1. F/B ratios vs. projectile energy for the production of Ar/Sc fragments from gold.

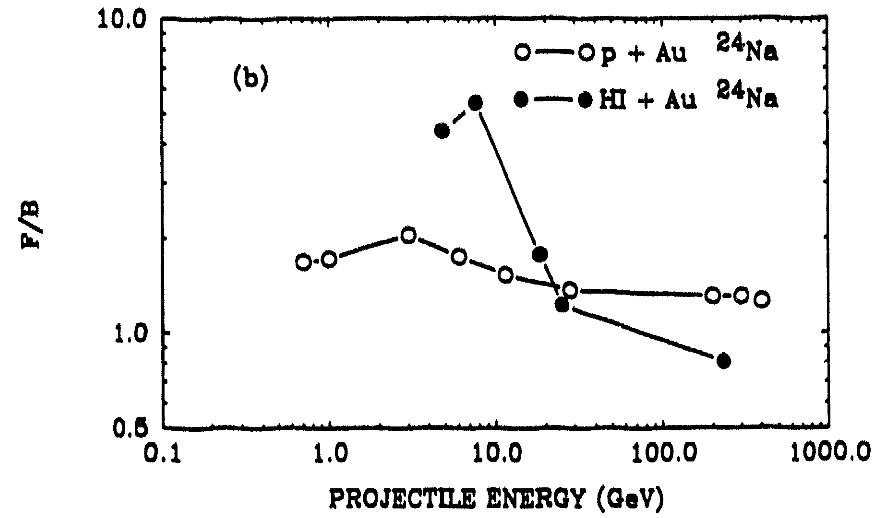

Figure IV-A-2. F/B ratios vs. projectile energy for the production of ^{24}Na from gold.

V. Technical Developments

A. Pulse Height Defect Measurements for Very Heavy Ions

One of the most important corrections when one studies heavy target residues using semiconductor detectors is the pulse height defect (PHD). For very low energy heavy nuclei (~100 keV/A Au) this correction can be of the same order as the measured energy. A few years ago, we measured the pulse height defect for several silicon surface barrier detectors that we had or were going to use to detect heavy residues in intermediate energy and relativistic nuclear collisions. Specifically, we measured[1] the pulse height defect for 0.25, 0.46, 0.66, 0.82 and 1.36 MeV/A ^{209}Bi ions interacting with a set of Ortec totally depleted heavy ion series silicon surface barrier detectors (~450 mm^2 in area with a depletion depth of ~100 μ). We compared our results with a variety of prescriptions for estimating pulse height defects.[2-4] We found the best overall agreement with the prescription of Moulton et al.[2] We have used the functional form of the dependence of the PHD upon ion Z, A and E along with a scaling factor to estimate PHD corrections for our heavy residue measurements.

In August, 1991, one of our calibrated detectors was used[5] in the experiment to synthesize element 110. The PHD for this detector for ~300 MeV ^{59}Co was measured to be ~2 MeV while the Moulton prescription would have predicted ~10 MeV. This uncertainty in the pulse height defect (and the implied uncertainty in the ^{59}Co beam energy) would have serious consequences in attempts to synthesize heavy nuclei. We became concerned that one of these measurements of PHD was wrong. To check this, we remeasured the PHD for several different ions interacting with the detectors using the unique capabilities of the LBL 88" cyclotron.

The detectors studied and their properties are shown in Table V-A-1. The detectors were all silicon surface barrier detectors, operated at the nominal bias voltages suggested by their manufacturers. The Ortec detectors had entrance windows of ~40 $\mu g/cm^2$ Au. Previous measurements had shown the total dead layers on the front of these detectors to be equivalent to an energy loss of ~10 keV for a 8.785 MeV α, i.e., approximately half the loss is due to the gold layer and half is due to a Si dead layer. The total dead layer on the LBL detector was measured to correspond to an energy loss of 15 keV for an 8.785 MeV α-particle.

The detectors were calibrated using radioactive sources (^{148}Gd, ^{238}Pu, ^{252}Cf) and a precision pulse generator. [This calibration was checked using low mass ions such as 21.90 ^{16}O and 73.46 MeV ^{14}N, whose pulse height defect is expected to be essentially zero.] The heavy ion beams were extracted from the cyclotron and magnetically analyzed prior to striking the detectors. The beam optics used corresponded to a "high resolution" configuration with narrow slits before and after the analyzing magnet. The beam energies were determined two ways: (a) from the cyclotron frequency and (b) the magnetic analysis system. These measurements typically agreed within ±0.3%. The pulse height response of each of the five detectors was measured for 1.36, 0.80, 0.29 MeV/A ^{209}Bi, 1.37 and 0.80 MeV/A ^{136}Xe and 5.07 MeV/A ^{59}Co. The pulse height defect was calculated from these measurements as

$$PHD = E_0 - E = \Delta E_w + \Delta E_N + \Delta E_R$$

where E_0 is the true energy of the ions, E the measured energy based upon the α-particle calibration, ΔE_w the energy loss of the ions in the total detector dead layer, ΔE_N the energy loss by nuclear collisions, and ΔE_R, the recombination effect. Although it is possible to divide the observed PHD into its three components using range-energy relations and information about nuclear stopping, we chose simply to compare the total PHD with previous measurements and prescriptions. The measured data are shown in Table V-A-2.

The measured PHDs are generally similar for ^{209}Bi and ^{136}Xe interacting with the detectors, but exhibit large variations for ^{59}Co. This ion is in the region where the PHDs are going to zero and thus, perhaps, the extreme sensitivity to small variations in detector parameters might be expected. It is important to note that all measurements of detectors 3 and 5 agree with previous measurements by us[1] and Ghiorso, et al.[5]

In Figure V-A-1, we compare the measured pulse height defects with those predicted from the frequently used prescription of Moulton, et al.[2] The error in the total fragment energy due to using the Moulton, et al., prescription for estimating PHDs is ~10% in the worst case for Bi, and generally less, ~5% in the worst case for ^{136}Xe and ^{59}Co. These sort of errors are unlikely to pose problems in the measurement of heavy residue energies, but could, in the case of sub-barrier fusion such as in the element 110 experiment, cause changes of orders of magnitude in the results.

(W. Loveland, R. Yanez, K. Aleklett, J.O. Lijenzin and A. Ghiorso.)

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5. A. Ghiorso, et al., Phys. Rev. Lett. (submitted for publication).

Table V-A-1. Properties of Detectors Studied

Detectors	Manufacturer	Totally Depleted	Depletion Depth (μ)	Area (mm^2)	Resistivity of Si (Ωcm)
1	Ortec	Yes	93.7	450	960
2	Ortec	Yes	90.1	450	960
*3	Ortec	Yes	89.6	450	960
4	Ortec	No	133	450	1800
5	LBL (Ortec)	No	100	65	3000

* Used to measure beam energies in the element 110 experiment.

Table V-A-2. Measured Pulse Height Defects

Detector Number	Measured PHDs				
	1	2	3	4	5
285.1 MeV ^{209}Bi	49.4	47.2	49.6	41.0	39.4
107.7 MeV ^{209}Bi	26.0	26.6	---	25.6	24.4
60.8 MeV ^{209}Bi	12.7	13.0	13.9	12.7	9.4
186.3 MeV ^{136}Xe	14.9	14.9	20.0	14.1	13.0
108.9 MeV ^{136}Xe	9.4	9.7	13.0	10.0	8.7
299.1 MeV ^{59}Co	36.8	15.8	2.7	0	0

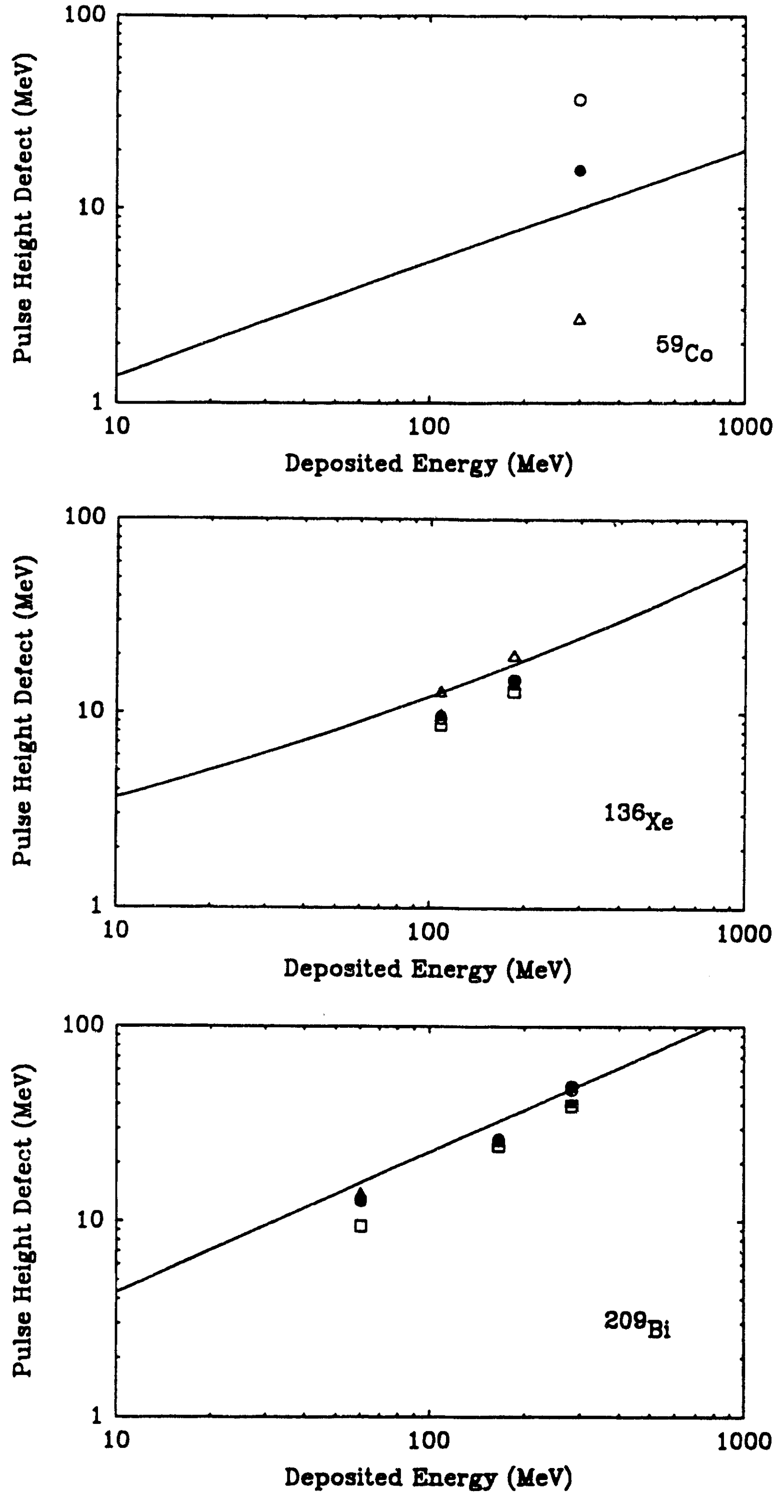

Figure V-A-1. Measured values of PHDs compared to Moulton et al.[2] prescription.

VI. Personnel

W. Loveland	Professor of Chemistry
Alok Srivastava	Postdoctoral Research Associate
Ricardo Yanez	Visiting Scientist, Sweden
Travis Day	Graduate Research Assistant
Bernard Clairmont	Student Research Assistant
Neil Ham	Student Research Assistant

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
E. Hagebø	University of Oslo, Oslo, Norway
K. Hanold	Lawrence Berkeley Laboratory
D. Jerrestam	Studsvik Neutron Research Laboratory
I. Lhenry	Lawrence Berkeley Laboratory
J. O. Liljenzin	Chalmers University of Technology Göteborg, Sweden
L. G. Moretto	Lawrence Berkeley Laboratory
D. J. Morrissey	Michigan State University
G. T. Seaborg	Lawrence Berkeley Laboratory
A. Veeck	Lawrence Berkeley Laboratory
L. Westerberg	University of Uppsala Uppsala, Sweden
G. J. Wozniak	Lawrence Berkeley Laboratory

VII. Publications

A. Articles in Print

1. "Target Fragments from the Interaction of 21 MeV/nucleon ^{129}Xe with ^{197}Au," A. Yokoyama, W. Loveland, J.O. Liljenzin, K. Aleklett and D.J. Morrissey, Phys. Rev. C46, 647 (1992).

2. "The Use of Radioanalytical Techniques to Study Intermediate Energy, Relativistic and Ultrarelativistic Nuclear Collisions," W. Loveland, K. Aleklett, J.O. Liljenzin and G.T. Seaborg, J. Radioanal. Nucl. Chem. 160, 181 (1992).

3. "Heavy Residue Properties in Intermediate Energy Heavy Ion Interactions with Gold," K. Aleklett, R. Yanez, W. Loveland, A. Srivastava, and J.O. Liljenzin, Prog. Part. Nucl. Phys. 30, 297 (1993).

4. "Nuclear Science and Engineering Education at a University Research Reactor," W. Loveland, J. Radioanal. Nucl. Chem. 171, 177 (1993).

5. "Properties of Target-like Fragments in Xe-Au Collisions at Intermediate Energies," W. Loveland, K. Aleklett, R. Yanez, A. Srivastava, and J.O. Liljenzin, Phys. Lett. B276, 311 (1993).

B. Articles Accepted for Publication

1. "Production of Transuranium Nuclides with Radioactive Nuclear Beams," W. Loveland, Proc. 3rd Int'l Conference on Radioactive Nuclear Beams (World).

2. "Radioactivity," W. Loveland, in Encyclopedia of Applied Physics, G.L. Trigg, Ed. (VCH Publishers).

3. "Transmutation," W. Loveland, in Encyclopedia of Chemistry, J.J. Lagowski, Ed. (MacMillan).

4. "Transuranium Elements," W. Loveland, ibid.

5. "Nuclear Stability," W. Loveland, ibid.

C. Oral Presentations

1. "New Methods of Synthesizing Heavy Nuclei," W. Loveland, Dept. of Chemistry, UC-Berkeley, October, 1992.

2. "Synthesis of the Heaviest Nuclei," W. Loveland, Dept. of Chemistry, Reed College, October, 1992.

3. "Production of Transuranium Nuclides with Radioactive Nuclear Beams," W. Loveland, Third Int'l Conf. on Radioactive Nuclear Beams, E. Lansing, MI, May, 1993.

4. "Target-like Fragment Energies in Nucleus-Nucleus Collisions," W. Loveland, ACS National Meeting, Chicago, IL, August, 1993.

5. "Synthesis of Heavy Nuclei Using n-Rich Radioactive Beams," W. Loveland, ACS National Meeting, Chicago, IL, August, 1993.

6. "Attempted Synthesis of Element 110 by the ^{59}Co + ^{209}Bi Reaction," W. Loveland, A. Ghiorso and the Element 110 Collaboration, APS Nuclear Physics Meeting, Asilomar, CA, October, 1993.

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.

Reprints + Preprints removed

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