NUCLEAR RESEARCH WITH HEAVY IONS

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Morton Kaplan
Principal Investigator

Department of Chemistry ^{122 2000}
Carnegie-Mellon University
Pittsburgh, Pennsylvania 15213

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ABSTRACT

The experimental research program consists of several interrelated parts:

(1) Reactions of Very Heavy Ions with Complex Nuclei; (2) Studies of Compound Nucleus Reactions Induced by Heavy Ions; and (3) Recoil Studies of Heavy Ion Reactions. Using solid-state detector telescopes and gas-ionization detector telescopes we have studied the emission of ^1H , ^2H , ^3H , ^4He and heavy fragments from the reactions of 720 MeV ^{86}Kr with ^{197}Au . Coincidence measurements between light charged particles and a heavy fragment indicate that most of the observed ^4He particles are evaporated by equilibrated Kr^* -like and Au^* -like excited products from deep inelastic reactions, but a significant number of pre-equilibrium ^4He particles seem to be emitted in directions normal to the separating fragments. Studies of angular correlations between two heavy fragments provide strong evidence for sequential fission of the Au^* -like reaction fragments, and the probability of this process has been estimated as a function of Q , the energy damping in the primary collision. Parallel studies of charged particle emission, fission, and evaporation residues in compound nucleus reactions map out the de-excitation characteristics of highly excited heavy nuclei as functions of E^* and J . Results are presented for the compound nucleus ^{194}Hg formed at matched excitation energies via different entrance channels.

Morton Kaplan
Principal Investigator

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I. INTRODUCTION

During the past contract year, the nuclear science research program sponsored by Contract EY-76-S-02-3246 has concentrated on studies of nuclear reactions between heavy ions and complex nuclei. The experimental aspects of the research have been carried out using the SuperHILAC and 88" Cyclotron accelerator facilities of the Lawrence Berkeley Laboratory, in a continuing collaboration with groups from Stony Brook and Columbia University. We had reached an effective and efficient stage of operation as a team when we were struck with the sudden death of our senior member, Jack Miller, during a cyclotron experiment in December 1976. Although this was a great shock to all of us, the program had already established a definitive direction and had gained sufficient momentum for us to close ranks and proceed with our planned studies. With cooperation from many sides, we have maintained a viable group and have gone forward to a successful and productive year of experimental results. In August 1977, the Nuclear Chemistry Division of the American Chemical Society held a memorial symposium in honor of Jack Miller. The current work of our group has been presented at this symposium in the form of six invited papers, and the abstracts of these talks have been collected in a later section of this report.

The main thrust of the program is the investigation of reactions between very heavy ions and target nuclei, using measurements of charged particle emission as a probe of dynamics and mechanism. In particular, we have been studying reactions of 720 MeV $^{86}\text{Kr} + ^{197}\text{Au}$ at the SuperHILAC using combinations of solid-state detector telescopes and gas-ionization detector telescopes to detect and identify the light charged particles and heavy fragments, respectively.

Initially we concentrated on obtaining good singles data, but more recently we have collected fairly complete coincidence data at selected angles between light charged particles and a heavy Kr-like fragment, and between two heavy fragments from deep inelastic collisions. In addition to continuing improvements in experimental setup and techniques, we have made considerable progress in the data handling and analysis phases of the research. By means of transformations to the moving frames of the heavy fragments, and by comparison of spectra with calculations, we are attempting to assign the detected protons and alpha particles to specific emission sources. Our analysis indicates substantial evaporation of light charged particles from each of the separated heavy excited reaction partners (Kr^* and Au^*), but there is also evidence for significant pre-equilibrium emission of alpha particles from the zone of the deep inelastic encounter. The correlation between heavy fragments both in and out of the reaction plane, and comparisons to singles counting rates, provides a measure of reactions with three (or more) heavy fragments in the exit channel, predominantly sequential fission of the highly excited Au^* fragment from a two-body collision.

Even though we are able to interpret the experimental results from $^{86}\text{Kr} + ^{197}\text{Au}$ to a moderately high degree, it becomes apparent that relatively little is known about the equilibrium de-excitation properties of Kr^* and Au^* -like fragments excited to $\sim 100\text{-}200$ MeV. Even less is known about the variation of exit channel characteristics (charged particles, fission, etc.) with excitation energy and angular momentum. If we had a good experimental knowledge of these dependences, then it might be possible to use charged particle emission data as an indicator of energy and angular momentum deposition and distribution in deep inelastic reactions of very heavy ions. Hence we are carrying out a parallel experimental program at the 88" Cyclotron, in which we produce compound nuclei via selected entrance channels to serve as models of highly excited complex

systems, and we systematically study the de-excitation patterns using the same experimental techniques we employ at the SuperHILAC. Results from these experiments yield information on the behavior of heavy-nuclei at high energy and spin, which is very important in understanding the compound nucleus reactions of heavy ions themselves, but in addition we obtain direct experimental data to use as input for calibrating statistical model parameters, which are needed in our calculations relevant to the Kr + Au reactions (or other very heavy ion reactions).

With the motivation just described, we have performed detailed studies of the compound nucleus ^{194}Hg , produced via heavy ion reactions at the 88" Cyclotron. Differential cross sections for charged particle evaporation, fission, and evaporation residues have been obtained from ^{194}Hg compound nuclei formed in ^{12}C and ^{19}F entrance channels at energies chosen to yield matched excitations in ^{194}Hg . For these systems, we believe we have been able to separate the effects of energy and angular momentum in the entrance channel on the de-excitation properties in the exit channel. We are dealing here with excitation energies in the range 100-150 MeV and angular momenta up to about $76 \hbar$ in the compound nucleus entrance channel. We find that increasing spin at constant excitation energy leads to enhanced fission probability, as one might expect from theoretical predictions. However, increasing excitation energy at roughly constant angular momentum does not appreciably affect the fission probability, even though there are significantly more chances for fission to occur. Rather, we find a large increase in charged particle emission, which must drain charge from the compound nuclei and thereby inhibit large increases in fission probability. Thus, it would seem that the previously noted decreases in neutron emission probability at higher excitation energies are due not to enhanced fission competition, as suggested, but instead to increased competition from charged particle evaporation. This result serves to underscore the importance of including

charged particle emission fully in statistical model calculations, even for high Z systems, if one hopes to have any confidence in the theoretical descriptions.

We have recently successfully performed a heavy-ion recoil experiment at the SuperHILAC, in which ^{20}Ne ions were used to bombard ^{60}Ni targets in a stacked foil arrangement. This run served to test a newly adapted foil-irradiation facility and beam line, and also yielded a good set of recoil range measurements and cross sections for the residual reaction product ^{72}Se . The data strongly support a compound-nucleus mechanism for this reaction, and provide evidence for the emission of alpha particles in the de-excitation process at the lower energies.

During the past year, the improved performance and reliability of the LBL accelerators has contributed greatly to the success of our experimental runs. The expanded capabilities and continued excellent performance of the Mod Comp IV data acquisition systems at both the SuperHILAC and the Cyclotron Laboratories has made it possible for us to conduct our complex multiparameter coincidence experiments with improved efficiency and reduced uncertainty. We particularly appreciate the ongoing efforts of the LBL staff personnel in these areas. Other than upgrading and periodic replacement of charged particle detectors and nuclear electronics modules, no major changes in equipment or instrumentation have been made this year either in our laboratories at Carnegie-Mellon University or at the Lawrence Berkeley Laboratory. The principal investigator, Professor Morton Kaplan, devoted one-half time to the research project during the academic year and full time for two months in the summer. Dr. Jane W. Ball, research associate, has spent full time on the program all year. As much of the program is a group collaborative effort, we are pleased to acknowledge the contributions of our co-workers in various aspects of the research. These are Professor John M. Alexander and Dr. M. Rajagopalan from Stony Brook; Drs. Doug Logan and N. H. Lu, and

Gary Catchen and Peggy McMahon from Columbia University; Dr. Ludwik Kowalski from Montclair State College; and Dr. Mike Zisman from LBL.

In the succeeding pages, we shall describe in more detail the several experiments and the research results outlined above.

II. REACTIONS OF VERY HEAVY IONS WITH COMPLEX NUCLEI.

A. EMISSION OF LIGHT CHARGED PARTICLES IN DEEP INELASTIC COLLISIONS BETWEEN 720 MeV $^{86}\text{Kr} + ^{197}\text{Au}$.

The nuclear reactions of $^{86}\text{Kr} + ^{197}\text{Au}$ at energies considerably above the coulomb barrier give primarily products of deep inelastic processes in which there is relatively little net mass transfer but considerable loss of energy into internal degrees of freedom. The angular distribution of inelastic Kr-like fragments is relatively broad, and one might expect that the highly excited nuclei will emit charged particles and neutrons as they dissipate their excess energy and angular momentum. Some time ago we began a program to study the charged particles emitted in reactions of very heavy ions, specifically $^{86}\text{Kr} + ^{197}\text{Au}$ at 720 MeV, in the belief that the measurements would provide insight into the mechanistic aspects of deep inelastic collisions.

The experiments are carried out in the 30" dia. Users' scattering chamber at the SuperHILAC accelerator of the Lawrence Berkeley Laboratory. Light charged particles are detected and identified by one or more solid-state telescopes (SST) each consisting of three Si surface-barrier detectors (typically 45 μm , 500 μm , and 5,000 μm). Signals from each detector are recorded on magnetic tape as individual parameters in an event-by-event mode. When heavy fragments are to be measured, we use one or two gas telescopes (GT) each containing a Fowler-Jared gas-ionization ΔE detector and a Si surface-barrier E (stopping) detector. Energy calibrations of the several detector systems are obtained using alpha particles from ^{212}Pb (ThB) sources, elastically scattered beam projectiles, and fission fragments from ^{252}Cf .

We have measured energy spectra and angular distributions for ^1H , ^2H , ^3H , and ^4He emitted in reactions of 720 MeV $^{86}\text{Kr} + ^{197}\text{Au}$. Data were obtained at laboratory angles from 10° to 145° . Some of these data were shown as Figs. 19, 20, and 21 in last year's annual report, COO-3246-16 dated October 1976, and need not be repeated here. From the singles data, we find that for all reactions

of 720 MeV $^{86}\text{Kr} + ^{197}\text{Au}$ the abundance of light charged particle emission is as follows: ^4He 34%; ^1H 29%; ^2H 6%; and ^3H 4%. The general features of the energy and angular distributions of these particles are consistent with the hypothesis that most of them are emitted in the equilibrium de-excitation of the excited deep-inelastic products formed in these reactions. More quantitative comparisons are being made by means of Monte Carlo calculations in which we simulate the evaporation of the light charged particles from the fully accelerated reaction products. Initially we used as input data (1) the energy and angular distributions of the heavy fragments in the $\text{Kr} + \text{Pb}$ reactions as reported by Vandenbosch, et al., and (2) the energy spectra in the equilibrium emission of light particles from Kr-like and Au-like excited fragments as estimated from a combination of theory and experimental results for excited nuclei similar to those under study here. We have now improved the input data for the calculation by (1) using our own measurements of angular and energy distributions of heavy fragments from $\text{Kr} + \text{Au}$ (see below), and (2) obtaining high quality energy spectra of light particles emitted from model equilibrium compound nuclei produced in our parallel cyclotron program. Although the calculations are still in progress, we have obtained results for ^4He emission which allow several conclusions. The Monte Carlo calculations imply that most alpha particles (in singles) are evaporated from separated fragments. However, the calculations cannot account (by evaporation) for the presence of high energy alphas at small angles. The comparisons between calculation and experiment can serve to distinguish equilibrium evaporation of charged particles from the pre-equilibrium or direct emissions. This latter feature becomes much more well-defined when the calculation and experiment both refer to charged particle emission in coincidence with a heavy fragment detected at a specified angle.

Experimental energy spectra for Kr-like fragments detected at several angles are shown in Fig. 1. These data were obtained from the reactions of 720 MeV

Figure 1.

$^{86}\text{Kr} + ^{197}\text{Au}$ using the gas telescopes described above. At the more forward angles the deep inelastic reaction products can be seen at energies below the prominent elastic peak. At 35.7° , near the grazing angle, there is still a significant contribution from elastic or quasi-elastic processes. However, at 40.7° , which is beyond the grazing angle, there is essentially no quasi-elastic component and virtually all of the detected events are from deep-inelastic reactions. These features of the Kr-like heavy-fragment spectra dictated our choices of 36° and 42° as trigger angles to be used in coincidence experiments between light charged particles and heavy fragments. Some of the more interesting results from the coincidence studies are described in the next section.

II. B.

A COINCIDENCE STUDY OF ^4He AND HEAVY FRAGMENTS
 IN REACTIONS OF 724 MeV ^{86}Kr WITH Au:
 DIRECT AND EVAPORATION MECHANISMS

J. M. Miller[†], G. L. Catchen^{††}, and D. Logan
 Department of Chemistry
 Columbia University, New York, NY 10027

M. Rajagopalan, J. M. Alexander
 Department of Chemistry, State University of New York at
 Stony Brook, Stony Brook, NY 11794

M. Kaplan
 Department of Chemistry
 Carnegie-Mellon University
 Pittsburgh, PA 15213

M. S. Zisman
 Lawrence Berkeley Laboratory
 Berkeley, CA 94720

Abstract

The production of ^4He in coincidence with a heavy fragment has been studied with a solid state telescope and a gas telescope. For heavy fragments detected at 36° and 42° , we have mapped coincident emission of ^4He from 80° to 320° in the reaction plane. We find evidence for alpha evaporation from both fragments and for a significant number of pre-equilibrium ^4He particles at c.m. angles near to 90° from the detected heavy fragment with average c.m. energy of ≈ 30 MeV.

Our purpose here is to explore the qualitative features of mechanisms for production of ^4He in the reaction $724 \text{ MeV } ^{86}\text{Kr} + ^{197}\text{Au}$. Britt and Quinton¹ found, for ^{12}C and ^{16}O induced reactions, large cross sections for ^4He evaporation from the compound nucleus and, in addition, a large number of forward-peaked high-energy particles which were attributed to projectile breakup. Galin et al.² found no such direct ^4He emission in the reaction $^{40}\text{Ar} + ^{77}\text{Se}$. It is well known that reactions between very heavy nuclei give little, if any, complete fusion reactions, but instead give rise to a continuous range of energy loss values from near zero to near maximum.³ As yet, however, no experiments have probed even the qualitative features of ^4He production mechanisms for Kr reactions.

The highly negative Q values for $^{86}\text{Kr} + ^{197}\text{Au}$ reactions demand that large excitation energies be deposited in the composite system. That part which equilibrates in the separating fragments will surely lead to evaporation of neutrons and light charged particles. Also, of course, there may be ^4He ejected prior to equilibrium from the frictionally heated contact zone or by rapid collective modes of the composite system.³ We have no clear idea of what kinds of pre-equilibrium processes will appear, but we do know quite a lot about the evaporation processes from compound nuclei of similar energies and spins, for example ^{75}Br and ^{194}Hg .^{4,5} Thus our approach is to detect ^4He particles in coincidence with heavy fragments and then ask whether or not their characteristics can be accounted for by evaporation from fragments or the compound nucleus. Our analysis tries to set an upper bound for the evaporation component and therefore a lower bound to the pre-equilibrium component.

Beams of ^{86}Kr ($\approx 20 \text{ nA}$) were provided by the Lawrence Berkeley Laboratory SuperHILAC; they were monitored by a Faraday cup after passage through the Au target of 2.66 mg/cm^2 . We used a Fowler-Jared gas telescope,⁶ GT ($\approx 2 \text{ msr}$), to

detect and measure ΔE and E of the heavy fragment and a three-member solid-state telescope, SST (45 μm , 500 μm , 5 mm; 17 msr), to detect the light charged particles. A time-to-amplitude converter was started by the second detector in the SST and stopped by the E detector in the GT. These six parameters were recorded on tape and analyzed off-line to give atomic numbers and energies of heavy and light particles for each coincident event. The values of ΔE and E from the gas telescope were used to identify Z and energy of one heavy fragment. Energies and pulse height defects for the E detector were calibrated by the elastically scattered ^{86}Kr beam and fission fragments from ^{252}Cf . The ΔE values deposited in the gas were also calibrated by elastic ^{86}Kr . We have used the Northcliffe-Schilling⁷ tables to estimate Z normalized to the elastic scattering of ^{86}Kr . We then assigned the most stable mass to each Z for the detected fragment. (Z uncertainties are ± 3 units as estimated from the energy resolution). Also, we made certain assumptions to estimate the pre-evaporation mass of the detected fragment and its kinematic partner. For this purpose we assumed a mass loss of 1 amu per 12 MeV of Q , apportioned between the fragments according to the ratio of their masses. The fragment velocities, we assumed, to be unchanged by evaporation or other processes.

Our trigger GT detector was placed at 36° (or 42°) which means the kinematic partners (assuming two-body kinematics) were scattered from 300° to 340° depending on the Q value. The smaller GT angle, 36° , is only slightly greater than the grazing angle, $\theta_{1/4}$, and thus there was a large quasi-elastic peak for the heavy fragments.⁸ However, at 42° this peak was not present in the singles spectra and the heavy fragment energies indicate that $> 95\%$ of the reactions have energy loss values of ≥ 200 MeV. The vector diagram in Fig. 2 shows typical velocities for the detected fragment Kr^* . Added to each fragment velocity is a ^4He velocity typical of an evaporation spectrum. Our ^4He detection threshold was ≈ 9 MeV corresponding to the circle at 2.1 cm/ns. This figure shows that ^4He

evaporated from the detected Kr^* fragment will only be efficiently detected at 81° for our choice of SST angles. Those evaporated from the kinematic partners Au^* will be easily detected for $\theta_{\text{SST}} \geq 225^\circ$ but only with reduced efficiency for the other angles. (Even at 81° some contribution to the observed ^4He spectrum will be derived from evaporation from the Au^* .)

To test for the presence of evaporated charged particles we transformed the laboratory differential cross sections $d^3\sigma/d\Omega_{\text{Kr}^*}d\Omega_\alpha d\epsilon_\alpha$ into the moving frames of the detected and undetected fragment as well as into the c.m. For this transformation, the laboratory differential cross section for each event was multiplied by the ratio of the solid angle in the laboratory to that in the moving frame. The resulting differential cross sections were grouped in 3 MeV intervals as shown in Fig. 3. Figure 2 shows the strong kinematic velocity shifts and illustrates the large differences between laboratory angles and those with respect to the directions of the moving fragments (β_d and β_u). Nevertheless, the half width of the β distribution for a given laboratory configuration is between 5° and 15° (i.e., a rather well localized distribution in the moving frame.)

In Table 1 we summarize some other aspects of the experimental results. Average Q values range from -250 to -290 MeV for the 36° trigger angle and -290 to -325 MeV for the 42° trigger angle. Standard deviations of the Q distributions are ≈ 100 MeV at 42° and ≈ 180 MeV at 36° . Average Z values for the detected fragment range from 39 to 46 with second moments of ≈ 8 -12 units. The coincident detection of ^1H or ^4He with a heavy fragment of $\langle Z \rangle \approx 40$ rather than ≈ 57 rules out major contributions from evaporation prior to fission of a compound nucleus of $Z = 115$.

Now we wish to determine the maximum possible contributions of ^4He evaporation processes at each angle of observation. We make use of two properties

of evaporation from ^{75}Br and ^{194}Hg : (1) the energy spectrum peaks somewhat above the barrier energy and is bound between 0.5 and 2 times the barrier; (2) the angular distribution is essentially isotropic for ^{194}Hg , and slightly forward-backward peaked for ^{75}Br .^{4,5} We look first at $\geq 200^\circ$ at the energy spectrum of ^4He in the frame of the undetected fragment. As mentioned above, at these angles we expect a high detection efficiency for evaporation from Au^* and none from Kr^* . In the left hand column of Fig. 3 we see that, at the angle 270° , the energy spectrum in the frame of Au^* ranges from 8 to 30 MeV as expected of evaporation from the observed Z distribution.⁵ As an upper limit we have attributed this whole spectrum to ^4He evaporation, and we have subtracted it from that shown for the Au^* frame at each other angle of observation. This subtraction was performed for each energy bin in the Au^* frame; the cross section corresponding to individually subtracted events was removed from each respective energy bin both in the Au^* frame and in the center of mass frame.

Similarly, next we turn to 81° where, from Fig. 2, we expect maximum efficiency for detection of ^4He evaporation from Kr^* . In Fig. 3 we see that the energy spectrum in the frame of the detected fragment Kr^* (after subtraction of the Au^* contribution) ranges from 5 to 20 MeV as expected of evaporation.⁴ Thus we have attributed this whole spectrum to ^4He evaporation and we have subtracted it from that shown for the Kr^* frame at each other angle. As expected this subtraction has only a very small effect because our low-energy cutoff had already removed most of these events.

The residual integrated c.m. cross sections at each angle are listed in the fifth column of Table I. For angles of 135° - 205° and $\geq 315^\circ$ we find a significant number of events with ^4He energies greater than those attributable to evaporation from the fragments. These events must correspond to ^4He particles which were not emitted from the excited, equilibrated fragments. The last column

in Table I gives the average angle of emission of these pre-equilibrium alpha particles with respect to the detected heavy fragment (Kr^*) in the c.m. system. In this frame they are emitted with greatest probability between 60° and 125° relative to the Kr^* . Their average c.m. energy is ≈ 30 MeV or near to the coulomb barrier for $Z = 115$. This angular preference is reminiscent of the alpha particles emitted in low-energy fission, and the coulomb fields of the separating fragments may be responsible for the focusing here as well. The presence of similar pre-equilibrium particles for the reaction $^{40}Ar + ^{77}Se$ may have been attributed to evaporation from the compound nucleus.²

In this series of experiments we also detected protons and have analyzed the results in the same way. Evaporation can account for almost all protons observed in coincidence with the GT at 36° . The total number of protons is roughly comparable to that of 4He ; the number of events which could not be attributed to fragment evaporation seems to be greater for 4He .

We re-emphasize that the results given in Table I and Fig. 3 have been obtained by subtraction of the maximum cross sections attributable to evaporation. There could, of course, be additional emissions prior to equilibrium but with energies and angles that allow them to be included with those from evaporation. We will report separately the energy and angular distributions of 1H , 2H , 3H and 4He detected in the singles mode.

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† Deceased.

†† 1976-1977, J. L. R. Morgan Predoctoral Fellow.

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Table I. Experimental Results

θ_{SST} deg	N^c	$-\langle Q \rangle$ MeV	$S_{\text{c.m.}}^o$ ^d mb/sr ²	$S_{\text{c.m.}}^r$ ^d mb/sr ²	$\delta_{\text{c.m.}}^e$ deg
81 ^a	68	252	18.3	$\equiv 0$	30
135 ^a	34	250	18.2	13.1	80
205 ^a	35	277	17.5	$\equiv 0$	130
225 ^a	30	288	17.5	1.7	150
315 ^a	63	257	23.0	9	245
81 ^b	60	305	14.2	$\equiv 0$	15
135 ^b	30	322	5.5	4.9	60
160 ^b	16	305	4.3	3.5	80
200 ^b	30	295	9.4	7.7	110
270 ^b	36	299	8.6	$\equiv 0$	195
315 ^b	92	302	13.1	7.8	235
323 ^b	20	323	12.6	10.3	245

^a GT was at 35.7°

^b GT was at 41.7°

^c Number of coincident events recorded between ${}^4\text{He}$ (≥ 9 MeV) and a heavy fragment (≥ 120 MeV).

^d $S_{\text{c.m.}} \equiv (d^2\sigma/d\Omega_{\text{Kr}^*} d\Omega_{\alpha})_{\text{c.m.}}$ with superscript o for observed and r for residual after subtraction of the maximum contribution of evaporation from the fragments.

^e $\delta \equiv \langle \theta_{\alpha} \rangle_{\text{c.m.}} - \langle \theta_{\text{Kr}^*} \rangle_{\text{c.m.}}$

Figure Captions

Fig. 2. Velocity vector diagram of a typical hard reactive collision.

Velocities are given in cm/ns. The fragment labeled Kr^* was detected in a GT at $\theta_{\text{lab}} = 36^\circ$ ($\theta_{\text{c.m.}} \approx 65^\circ$). The undetected fragment Au^* recoiled at $\theta_{\text{lab}} = 300\text{-}340^\circ$, depending on the Q value. The velocities of ^4He particles emitted at coulomb barrier energies are shown.

Their angles of emission with respect to the fragment velocities β_d and β_u are also shown. The SST for ^4He detection was situated at the indicated angles with ^4He velocity threshold of ≈ 2.1 cm/nsec. The lab system ^4He velocities for the cases shown are well above this detection threshold at 81° or 270° .

Fig. 3. Values of $d^3\sigma/d\Omega_{\text{Kr}^*} d\Omega_{\alpha} d\epsilon_{\alpha}$ vs. energy in the frame of the undetected fragment Au^* , the detected fragment Kr^* , and the c.m. The vector diagram on the right gives for the α and Kr^* the lab angles and average velocities for each spectrum in that row. Shaded areas are attributed to evaporation from the fragments.

Figure 2.

Figure 3.

II. C. COINCIDENCE STUDIES OF HEAVY FRAGMENTS IN REACTIONS OF 720 MeV

 ^{86}Kr WITH Au

In the reactions of energetic Kr ions with heavy target nuclei, there is a high probability for "sticky" collisions in which the primary reaction products differ very little in mass from the incident projectile and target respectively but there is a large kinetic energy loss into internal degrees of freedom. This process is indicated schematically in Fig. 4(a) for Kr + Au collisions. For this system at an initial ^{86}Kr energy of 720 MeV, the energy damping, or $-Q$, exhibits a broad distribution from 0 (for elastic reactions) to about 450 MeV or more. These Q 's must be taken up as internal excitation energy of the two separating fragments, and it is reasonable to expect that heavy nuclei like Au could readily acquire enough excitation energy and angular momentum to undergo fission. This chain of events we call sequential fission, and is distinctly different from fusion-fission in which two (fission) fragments are formed by scission of a compound nucleus. In the former case, one would observe three Kr-like fragments ($\text{Au}/2 \approx \text{Kr}$), while the latter would yield two fragments with $A \sim 140$ and $Z \sim 57$.

The "heavy-heavy" coincidence experiments to be described here were initiated to determine the relative frequency of three-fragment vs. two-fragment events, and to measure the probability of sequential fission as a function of Q . (This information is also helpful in analyzing data from light charged particle-heavy fragment coincidences, and even singles data for heavy fragments.) A schematic diagram of the experimental configuration is shown in Fig. 4(b). Two gas telescopes were used to detect the heavy fragments and provide Z identification. The trigger detector was placed at a fixed angle (36° or 41°) and the sweeper detector was swept through a series of angles to measure the angular correlations both in the reaction plane and out of the plane. In these experiments a very thin Au target was used (0.20 mg/cm^2) to

Figure 4.

minimize energy degradation of the heavy Au-like fragments. Both the target and the gas ionization chambers were thin enough to record the Au elastic peak in the sweeper detector when the trigger detector was placed at 20° during calibration runs with elastic Kr projectiles. A thin Ag target was also used to calibrate the counter telescopes.

Figure 5 illustrates several of the features associated with the heavy fragments. On the left side of the figure we show the energy spectra of heavy reaction products recorded by the trigger telescope (in singles) at two selected angles, 36° and 41° . These are the same spectra which were shown in more detail in Fig. 1, Section IIA of this report. The choice of these two angles as trigger angles is based upon the significant change in the relative intensities of deep-inelastic and quasi-elastic components between 36° and 41° . The right side of Fig. 5 gives the expected angular distributions of the binary partners of fragments detected by the trigger telescope. These predictions were made on an event-by-event basis using the standard relationships of binary kinematics. It will be of interest to compare these curves with the actual angular correlations recorded in the coincidence experiments.

The mass identifications of the heavy-fragment coincidence events were performed in two ways. The first method yields the final masses of the individual fragments based on their Z identification by (dE/dx) and E measurements in the gas telescopes. These masses, labeled A_Z , were obtained by assuming that the detected fragments are the nuclides close to the valley of β -stability. The second method of identification was based on binary kinematic relationships, which lead to the result:

$$\frac{A_T}{A_S} = \frac{E_S}{E_T} \times \frac{\sin^2 \theta_S}{\sin^2 \theta_T}$$

where the subscripts T and S refer to the trigger and sweeper telescopes,

Heavy-fragment coincidence study

Figure 5.

respectively, and A and E are the mass numbers and kinetic energies of the fragments. By assuming that $A_T + A_S = 283$ (the total mass), the values of A_T and A_S could be calculated event-by-event for all the observed coincidence events. The masses deduced from this analysis, after correction for the evaporation of light particles, are labeled A_k (where k is symbolic for the binary kinematics).

With this procedure all events from a given set of angles θ_S and θ_T could be organized into a mass-mass matrix (A_Z vs. A_k) as illustrated in Fig. 6(a). Despite occasional ambiguities and relatively poor statistics (maximum of 350 coincidences per run), we found that four kinds of events could be clearly identified in this way. First are those (I) where Kr-like fragments were detected in the trigger telescope. Second are those (II) which may be due to fusion-fission events. Third are those (III) where Au-like fragments managed, somehow, to reach the trigger detector. And fourth are those (IV) for which the values of A_Z and A_k differed significantly. We ascribe the events from the last group to sequential fission, the great discrepancy between A_Z and A_k being the consequence of applying binary kinematics to nonbinary events. The several groups of events are labeled in Fig. 6(a). In each experimental run (set of detector angles), the events which are located close to the 45° line in the mass-mass matrix are binary while those which are away from this line are nonbinary. We can combine the data for a fixed trigger angle and several sweeper angles in order to determine the angular correlations for the different groups of events. The resulting angular correlation functions for groups I and IV are presented in Fig. 6(b). Although this analysis is preliminary, the comparison between group I events and group IV events is striking. The angular correlation functions for the nonbinary events (IV) are quite flat both in and out of the reaction plane (sweeping limits from 30° to 70° in the plane and up

Heavy-Heavy Coincidence Experiments

Figure 6.

to 10° out of plane). This is in sharp contrast to the relatively well-defined maximum for the group I binary events.

We can summarize our initial observations from the correlated heavy-fragment experiments as follows:

- 1) There is a large group of Kr-like products at 36° (and 41°) in coincidence with Au-like products at larger angles.
- 2) There is a smaller group of deeply inelastic products of similar masses obeying 2-body kinematics.
- 3) There is a small group of Au-like products at 36° (and 41°) in coincidence with Kr-like products at larger angles.
- 4) There is a group of products that do not obey 2-body kinematics, presumably from sequential fission.

For the first group, the fraction of observed partners can be used as a measure of the evaporation residue fraction that survives fission competition. From our preliminary results, it appears that the nonbinary events (sequential fissions) are much more frequent than has been reported. We estimate a lower limit of 30% of all the deep inelastic collisions observed at $\theta_T = 36^\circ$.

We have attempted to extract from our data an excitation function for the sequential fission events; that is, the dependence of sequential fission probability on the inelastic energy transfer Q in the collision. Our procedure for doing this can be illustrated by reference to Fig. 7, which is based upon data collected at a trigger angle of 36° . Fig. 7(a) is an energy spectrum of events seen in the trigger detector, with the abscissa labeled as $-Q$ to point out the correspondence between detected fragment kinetic energy and the excitation of the system. Fig. 7(b) gives the angular correlation curves for the heavy fragments. The solid curve, labeled A in the figure, is the expected angular correlation predicted from binary kinematics and shown previously on

Figure 7.

the right side of Fig. 5. The dashed curve, labeled B, is the measured angular correlation for real binary events observed in the coincidence experiments [group I events in Fig. 6(a)]. The two curves have been normalized at their maxima to account for differences in binning procedures, and curve A will probably be made slightly broader by considering effects of particle evaporation.

Let us now consider why the two curves, A and B, are so different in shape. This is because in reality many partners of trigger fragments will undergo fission and hence not be detected in the coincidence experiments. Note that the ratios AB/AC of the amplitudes of the two curves in Fig. 7(b) increase rapidly as the sweeping angle becomes smaller. To understand this, one has to realize that smaller angles correspond to higher excitation energies in the primary fragments. In assigning Q values (and excitation energies E^*) to individual angles, we used binary kinematics for the predominant fragments as indicated by the observed Z distributions in Fig. 7(c). Once the relationship between θ_s and the excitation energy of Au-like fragments has been established, the excitation function for sequential fission can be obtained by plotting the AB/AC ratios vs. E^* , as shown in Fig. 7(d) by the dashed curve. For comparison, we have included fission data for the compound nucleus ^{194}Hg (the solid curve is from Sikkeland, et al. and the two open circles are from our own work). The agreement between the two excitation functions is remarkably good, and strongly suggests that the heavy reaction products in deep inelastic collisions of $^{86}\text{Kr} + ^{197}\text{Au}$ are about as fissionable as the compound nuclei from the $^{12}\text{C} + ^{182}\text{W}$ system at corresponding excitation energies. From what we know (see Section IIIB) about the angular momentum dependence of fission probability for such systems, it is tempting to infer that the Au-like products of deep inelastic collisions must emerge with intrinsic spins comparable to the corresponding compound nuclei. We hope that more refined analysis of our data and new results from our continuing experiments will determine the strength and validity of the tentative conclusions reported here.

III. STUDIES OF COMPOUND NUCLEUS REACTIONS INDUCED BY HEAVY IONS.

A. FORMATION AND DECAY OF ^{194}Hg AT HIGH EXCITATION ENERGIES.

As part of our program of measuring the de-excitation properties of model compound nuclei, we have been carrying out detailed studies of ^{194}Hg compound nuclei produced in heavy ion reactions at the 88" Cyclotron of the Lawrence Berkeley Laboratory. Our objective is to map out the patterns in the exit channels as functions of excitation energy and angular momentum in the entrance channels. We have studied the two reactions

$$^{12}\text{C} + ^{182}\text{W} \text{ at } E_{\text{lab}} = 121 \text{ and } 167 \text{ MeV,}$$

and

$$^{19}\text{F} + ^{175}\text{Lu} \text{ at } E_{\text{lab}} = 135 \text{ and } 184 \text{ MeV,}$$

which yield ^{194}Hg compound nuclei at the two excitation energies 98 MeV and 142 MeV. Although the bombarding energies were chosen to give matched excitation energies, the angular momentum distributions in the several entrance channels are quite different. In fact, the combinations are such that for these systems it is possible to make a reasonable separation of effects due to excitation energy from those due to angular momentum. For each reaction, we have measured differential cross-sections for charged particle emission, fission, and evaporation residues, using solid-state detector telescopes for the light particles and gas telescopes for the heavy fragments. The analysis and interpretation of the cross-section results is presented in the next section (IIIB.) of this report. Here we shall simply present some samples of the large body of data which has not yet been thoroughly treated.

Figure 8 presents the alpha particle spectra observed at backward angles for the ^{12}C and ^{19}F induced reactions at a ^{194}Hg excitation energy $E^* = 98 \text{ MeV}$. The data have been transformed into the center-of-mass system, and in this frame the emission energies for the different reactions and angles in Fig. 8

Figure 8.

are all in excellent agreement as expected for evaporation spectra from the same compound nuclei. Similar data are shown in Fig. 9 for the two reactions at an excitation energy $E^* = 142$ MeV. Again, the c.m. energy spectra appear to be very nearly identical for the two reactions. Comparison of Figs. 8 and 9 brings out several features of the alpha particle spectra at the two excitation energies. With increasing E^* , the magnitudes of the differential cross-sections increase markedly. The low energy sides of the energy spectra do not seem to change significantly between 98 and 142 MeV, which is consistent with the idea that this part of the spectra is determined primarily by coulomb barrier effects in the emitting nucleus. The maxima in the energy spectra are shifted slightly to higher energies and the high-energy sides of the spectra are considerably broadened in going from 98 to 142 MeV in excitation energy. These characteristics also are qualitatively what one would expect from a statistical model description of evaporation from an equilibrated compound nucleus.

We are beginning to make more quantitative comparisons between the observed charged particle spectra in these reactions and the predictions of statistical model calculations using the code Grog II. Some preliminary results are shown for alphas and protons in Fig. 10. These curves show the sensitivity of the calculations to variations in the "standard" input parameters of the model. One can arbitrarily play with the parameters to get better or worse agreement with the data, but this in itself does not necessarily mean very much. What we hope to do is make use of a large collection of data to calibrate the calculations and derive a consistent set of model parameters. One may then begin to ask meaningful questions about the physical significance of the parameters and the model itself in understanding the behavior of nuclei at high excitation.

Figure 11 shows the angular distributions of fission fragments measured

Figure 9.

Figure 10.

Figure 11.

for these reactions at the two excitation energies. As the primary interest here was in determining the fission cross-sections for the several reactions (i.e., the fission probability as a function of E^* and J), we shall defer the discussion of these results to the next section.

III. B. ENERGY AND SPIN DEPENDENCE OF FISSION, ^1H AND ^4He EMISSION
FROM ^{194}Hg COMPOUND NUCLEI*

J. M. Miller[†], D. Logan, and G. Catchen^{††}

Department of Chemistry, Columbia University, New York, NY 10027

M. Rajagopalan and J. M. Alexander

Department of Chemistry

State University of New York at Stony Brook, Stony Brook, NY 11794

M. Kaplan and J. W. Ball

Department of Chemistry

Carnegie-Mellon University, Pittsburgh, PA 15213

M. S. Zisman

Lawrence Berkeley Laboratory, Berkeley, CA 94720

L. Kowalski

Montclair State College, Upper Montclair, NJ 07043

Abstract

Reactions of ^{12}C and ^{19}F have been used to produce ^{194}Hg compound nuclei at excitation energies of 98 and 142 MeV. Differential cross sections for ^1H and ^4He emission, fission and evaporation residues have been determined. This combination of entrance channels permits the separation of energy and spin effects on the exit channels. Fission probability clearly increases with angular momentum at fixed energy. However there is no increase in the cumulative fission fraction from 98-142 MeV. The probability of ^1H and ^4He evaporation increases rapidly with energy and seems to shield the system from fission.

We present here an initial report on the behavior of high-spin compound nuclei of mass number ≈ 200 . In particular we focus on a phenomenological analysis of the measured cross sections for complete fusion, fission and compound-nucleus evaporation of ^1H and ^4He . This study was undertaken to shed light on the very puzzling and apparently contradictory picture of fission-evaporation competition at high excitation and spin.^{1,2} In addition, the information may contribute to an understanding of two processes which accompany the very inelastic reactions between very heavy nuclei: emission of light charged particles and fission.³

The strategy of the experiment has been previously described;⁴ it depends upon forming a compound nucleus at a particular excitation energy through two different entrance channels with different distributions of angular momentum. In the present instance ^{194}Hg was formed via the entrance channels $^{12}\text{C} + ^{182}\text{W}$ and $^{19}\text{F} + ^{175}\text{Lu}$, and bombarding energies were selected to yield excitation energies of 98 and 142 MeV. Measurements were made of the energy and angular distributions of evaporation residues (ER), fission fragments, ^1H and ^4He produced in these reactions. By comparisons of the results for different entrance channels one may infer the cumulative decay fractions for these various modes of de-excitation from compound nuclei in several domains of energy and spin. We examine the separate dependences on energy and spin.

Beams of ≈ 1 to 100 nA of ^{12}C and ^{19}F were provided by the LBL 88" cyclotron. Self supporting targets of ^{182}W (98%, 450 $\mu\text{g}/\text{cm}^2$) and ^{175}Lu (370 and 1420 $\mu\text{g}/\text{cm}^2$) were prepared by evaporation. Their thicknesses were measured by Rutherford scattering (both absolute and by reference to a weighed Au foil) and in some cases by weight. The beam intensity was monitored by a Faraday cup as well as by two Si detectors located in the reaction plane about 20° to the beam axis. ^1H and ^4He were observed with a three-member Si detector telescope (45 μm , 500 μm and

5000 μm), and fission products and heavy evaporation residues were measured with a Fowler-Jared gas telescope⁵ (gas ionization counter at 10-40 torr and 500 μm Si detector, $d\Omega \approx 0.1$ msr). Energy calibrations were made with ^{212}Pb (Th B) and ^{252}Cf sources. Most of the events recorded were for a single product in either telescope; some coincidence data were also obtained for H or He with a heavy reaction product.

In Fig. 12 are shown some typical observed angular distributions of several reaction products from the system of 121 MeV $^{12}\text{C} + ^{182}\text{W}$. Our angular distributions for ^1H and ^4He are very similar to those of reference 6, i.e., essentially independent of angle from ≈ 120 - $160^\circ_{\text{c.m.}}$, but rapidly increasing forward. Also, the c.m. energy distributions for ^4He were very similar for angles greater than 100° and energies greater than 12.5 MeV. We have estimated the total compound-nucleus derived ^1H and ^4He by integrating over energy ($\epsilon_{\text{c.m.}} \geq 12.5$ MeV for ^4He) and averaging the resulting value of $d\sigma/d\Omega$ for lab angles of 120° or more (i.e., we assumed that ^1H and ^4He evaporation was isotropic). That these ^1H and ^4He products were indeed associated with compound-nucleus evaporation and not fission product evaporation was suggested by the following: for the reactions of 121 MeV ^{12}C and 135 MeV ^{19}F we have searched for coincident events between H or He and fission. These studies allow us to conclude that light particle fission coincidences are very improbable ($\leq 5\%$).

Differential cross sections for fission ($d\sigma_f/d\Omega$) were measured at several angles for each reaction (and for 121 MeV $^{12}\text{C} + ^{197}\text{Au}$ to check consistency with Ref. 6). For 135 MeV ^{19}F the data were extensive enough to allow direct integration of the cross section in the lab system. For this case we found that the integrated fission cross section σ_f was related to the differential c.m. cross section at 90° as follows (with β equal to unity):

$$\sigma_f = \beta \int_0^\pi (d\sigma_f/d\Omega)_{90^\circ \text{ c.m.}} (1/\sin \theta)_{\text{c.m.}} d\Omega_{\text{c.m.}} = 2\pi^2 \beta (d\sigma_f/d\Omega)_{90^\circ \text{ c.m.}}$$

For 184 MeV ^{19}F , we integrated with the assumption that the c.m. angular distribution was the same as at 135 MeV, (i.e. $\beta = 1$). For ^{12}C reactions we integrated with the same assumptions used by Sikkeland et al.⁷ (namely that the c.m. angular distributions are proportional to $1/\sin \theta_{\text{c.m.}}$ for $60^\circ < \theta_{\text{c.m.}} < 120^\circ$ and β is 0.95 for ^{12}C beam energy of 10 MeV/amu). Our resulting fission cross sections are lower than those reported earlier^{6,7} by $\approx 15\%$ for $^{12}\text{C} + ^{197}\text{Au}$ and by $\approx 25\%$ for $^{12}\text{C} + ^{182}\text{W}$, both at 121 MeV lab.

The evaporation residues we have identified as the forward peaked heavy residual nuclei. For these angular distributions we have fitted $d\sigma/d\Omega$ to an exponential decrease for $\theta \geq 10^\circ$, and the resulting angular distributions were integrated with the requirement of zero differential angular cross section ($d\sigma/d\theta$) at 0° lab. The possibility that a component of these products included heavy transfer products associated with the large cross sections for direct forward-peaked H and He cannot be experimentally ruled out. However, there is some indirect evidence that this is not a large effect: (1) For the ^{12}C induced reactions a forward peaked ^4He would lead to a recoil energy for the heavy residual which is reduced by a factor of ≈ 2 . This might very well drop it below our energy cutoff. (2) Many heavy residuals after ^4He evaporation should survive fission and reach our detectors. As the residual-nucleus cross sections are comparable to the isotropic ^4He cross sections, we infer that not much room is left for direct-reaction contributions. (3) With increasing energy for $^{19}\text{F} + ^{175}\text{Lu}$, the cross section for evaporation residues decreases while that for all direct reactions increases. It is true, nevertheless, that the integrated cross sections for forward peaked H and He are quite large,^{6,11} and in spite of the points above we could conceivably have detected some residual nuclei from such reactions.

In Table II we give the measured cross sections and cumulative decay fractions for each channel. Fusion cross sections are the sum of those for fission and evaporation residues. The cumulative decay fractions are simply the individual cross sections divided by the fusion cross section. [These fractions need not sum to unity.] Values of ℓ_{crit} were estimated from the sharp cutoff approximation; they are significantly smaller than ℓ_{max} .⁹

The dependence of the decay fractions on energy and spin can be made explicit by comparing results for the matched entrance channels. As described in Ref. 4 we use the independence hypothesis to subtract from the ^{19}F cross sections the contributions from $\ell < \ell_{\text{crit}}$ for the ^{12}C reactions. Table III lists the resulting cumulative decay fractions for each energy and spin domain. As expected, the fission probability increases significantly with spin at each energy.^{1,2,4,10} With increasing spin the ^1H and ^4He evaporation probability decreases (or remains constant) in contrast to an increase in the fission probability.²

A striking result is provided by comparison of columns 3 and 4 in Table II. Here we increase the initial excitation energy by 44 MeV, while the spin domain is only slightly enlarged from 0-59 to 0-64. Even though the increased energy provides 3-5 more chances for fission along the evaporation chain, the cumulative fission fraction is not enhanced. [The sharp cutoff equation applied to σ_{ER} indicates an increase from ≈ 31 to ≈ 36 between 98 and 142 MeV of excitation]. In parallel we see a strong enhancement in particle evaporation from 0.19 to 0.35 for ^1H and 0.13 to 0.28 for ^4He . As the ^1H and ^4He evaporation have increased we infer that these decay channels are bleeding charge from the compound nucleus and thus shielding it from fission. The importance of charged particle evaporation is even more dramatic in the last two columns of Tables II and III. Here for 142 MeV initial excitation it appears that the probability

for charged particle emission greatly exceeds that for the survival of the compound-nucleus residue.

An understanding of reactions between heavy nuclei is clearly dependent on our factual knowledge of fissionability at high energy and spin.³ Recently several calculations have been presented^{1,2} in an attempt to approach a systematic parametrization of fission barriers and level densities. This letter dramatizes a most important aspect of this problem, the competition between fission and light charged particle evaporation. Meaningful description of the fission-evaporation competition requires a more careful calibration of the associated level densities and transmission coefficients at high energies and spins.^{1,2} Cross sections and energy spectra from this work will be compared to statistical-model calculations in a later paper.

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Table II. Summary of Results

<u>The reaction systems</u>				
Beam	^{12}C	^{19}F	^{12}C	^{19}F
Target	^{182}W	^{175}Lu	^{182}W	^{175}Lu
E_{lab}	121 MeV	135	167	184
E^*	98 MeV	98	142	142
<u>Cross sections (mb) and ℓ_{crit}</u>				
$^1\text{H}^a$	266	214	544	490
$^4\text{He}^a$	176	152 ^b	437	354
ER ^a	458	351	539	312
Fission ^a	577	780	1021	1066
Fusion	1035	1131	1560	1378
ℓ_{crit}^c	44	59	64	76
<u>Cumulative decay fractions^d</u>				
^1H	0.26	0.19	0.35	0.36
^4He	0.17	0.13	0.28	0.26
ER	0.44	0.31	0.35	0.23
Fission	0.56	0.69	0.65	0.77

^a Estimated uncertainties are 20% absolute and 10% relative.

^b For this datum only reproducibility was $\pm 25\%$

^c From the sharp cutoff equation $\sigma_{\text{fusion}} = \pi \lambda^2 (\ell_{\text{crit}} + 1)^2$.

^d Estimated uncertainties are $\pm 17\%$ for ^1H and ^4He , 10% for ER and 6% for fission.

Table III. Cumulative Decay Fractions

E^*	98 MeV	98	142	142
J	0-44	44-59	0-64	64-76
^1H	0.26	0.10	0.35	≈ 0.4
^4He	0.17	0.09	0.28	≈ 0.2
ER	0.44	0.14	0.35	≈ 0
Fission	0.56	0.86	0.65	≈ 1

Figure 12.

IV. RECOIL STUDIES OF HEAVY ION REACTIONS.

In a comparative study of entrance channel effects in heavy ion induced nuclear reactions, we are using thin-target stacked-foil techniques to measure excitation functions and recoil ranges of selected residual reaction products. From a series of range measurements at different incident projectile energies, and a knowledge of range-energy relationships for the reaction products in the stopping medium, it is possible to critically test the predictions of specific reaction mechanisms. The processes of particular interest in these experiments are those involving complete fusion of the beam projectile with the target nucleus, followed by the evaporation of a relatively large number of nucleons or small clusters. We have proposed the investigation of the two reactions

and

both of which lead to the same final product via significantly different entrance channels. Stacks of foils consisting of appropriately arranged targets and thin recoil catchers are irradiated by the required heavy ion beam and the reaction products of choice are analyzed off-line by radioactivity identification and measurement. The product nuclide ${}^{72}\text{Se}$ has a half-life of 8.5 d and decays exclusively by electron capture to the first excited state at 0.046 MeV in ${}^{72}\text{As}$. Detection of the 46-keV de-excitation gamma ray provides a direct measure of the ${}^{72}\text{Se}$ formation cross-section. Although the ${}^{72}\text{As}$ ground state is radioactive with a half-life of 26 h, and hence will be in equilibrium with ${}^{72}\text{Se}$, there is no significant interference in the spectral region of interest under the conditions we propose for counting.

In June of this year we carried out a successful experiment on the

$^{60}\text{Ni} + ^{20}\text{Ne}$ reaction using the 170-MeV ^{20}Ne beam of the LBL SuperHILAC accelerator. This run was carried out in the E71 beam line of the Users' cave and employed a modified targeting apparatus with effective water-cooling and beam monitoring arrangements. The target-catcher stack consisted of a total of 35 thin foils including 5 thin ^{60}Ni targets interspersed to span the range 170-60 MeV in projectile energy. After irradiation, the foils were separated and individually counted for ^{72}Se radioactivity using a high-resolution intrinsic Ge detector system in our laboratory at Carnegie-Mellon University. A typical gamma-ray spectrum recorded for one of the samples by this detector is shown in Fig. 13. It is readily apparent that the 46-keV gamma-ray from the decay of ^{72}Se stands out very clearly, and permits measurement of its intensity even at very low counting rates. The inset in Fig. 13 shows a measured decay curve for the 46-keV radioactivity in one of the samples. For each foil found to contain 46-keV radioactivity, the observed decay was in excellent agreement with the 8.5 d half-life of ^{72}Se .

The counting data were analyzed to obtain the average recoil range and range distribution of ^{72}Se from each ^{60}Ni target, and the radioactivity induced at each bombarding energy was summed to yield the ^{72}Se formation cross-section at that energy. The Ge detector efficiency was determined on an absolute basis using calibrated gamma-ray sources obtained from the National Bureau of Standards. The experimental results are shown in Fig. 14. At the top of the figure, we have plotted the observed average recoil ranges at each bombarding energy as a function of the calculated recoil energy, assuming full transfer of linear momentum in the initial impact and isotropic emission of evaporated particles in the subsequent de-excitation of the compound system. The solid line in this figure is the calculated range-energy relationship for ^{72}Se in Al as given by the stopping power data of Northcliffe and Schilling. The excellent agreement

Figure 13.

Figure 14.

provides strong support for a compound nucleus mechanism in this complex reaction in which the equivalent of 8 nucleons are emitted.

The lower part of Fig. 14 presents the cross-section results as a function of incident ^{20}Ne projectile energy. This excitation function has not yet been analyzed by any model calculations, however several interesting features can already be pointed out. The excitation function is quite broad and unlike that associated with typical (HI, xn) reactions for a single value of x . The vertical arrow at about 87 MeV in the figure indicates the threshold energy for the reaction

in which 4 protons and 4 neutrons are emitted from the compound system. Any other combination of 8 individual nucleons (followed by β -decay) would not change the threshold energy very much. Hence the fact that we find rather large cross-sections for ^{72}Se at and below the threshold energy requires that nucleon clusters must be emitted in the reaction, at least at the lower energies. Simple energetic calculations are quite convincing that at least one, and possibly two, alpha particles are evaporated from the compound nuclei in the de-excitation steps leading to ^{72}Se . Hence it is rather likely that the excitation function plotted in Fig. 14 is really a superposition of several excitation functions corresponding to different associations of the emitted particles in the final state.

These experiments are continuing and we hope to be able to study the $^{40}\text{Ar} + ^{40}\text{Ca}$ reaction for comparison in the near future.

V. ABSTRACTS OF PAPERS PRESENTED AT THE J. M. MILLER SYMPOSIUM,
 AMERICAN CHEMICAL SOCIETY NATIONAL MEETING,
 AUGUST 29 - SEPTEMBER 2, 1977, CHICAGO, ILLINOIS

1. CHARGED PARTICLES EMITTED IN REACTIONS OF 720 MeV ^{86}Kr WITH Au.
 J. Miller, D. Benson, G. Catchen, L. Kowalski, D. Logan, N. Lu, Columbia University, N. Y. N. Y. 10027; J. Alexander, T. Debiak, M. Rajagopalan, SUNY Stony Brook, N.Y. 11794; M. Kaplan, Carnegie-Mellon University, Pittsburgh, Pa. 15213; M. Zisman, Lawrence Berkeley Lab., Berkeley, Calif. 94720.

We have made a variety of measurements concerning charged particle emission from reactions of 720 MeV ^{86}Kr with Au: (1) integrated cross sections, angular and energy distributions for ^1H , ^2H , ^3H , ^4He and the heavy fragments; (2) maps of $d^3\sigma/d\Omega_1 d\Omega_2 d\epsilon$ for ^1H , ^4He in coincidence with heavy fragments at 36° and 41° ; (3) maps for heavy fragments in coincidence with other heavy fragments at 30° , 36° and 41° . The data will be discussed with respect to the possibility of distinguishing evaporated particles from those emitted prior to thermal equilibration. The coincidence efficiency for two heavy fragments gives information on the probability of two-body vs. multiple-body reactions, the simplest of which is sequential fission. Comparisons can be made to the decay properties of compound nuclei ^{75}Br and ^{194}Hg produced in other studies.

2. COINCIDENCE STUDIES FOR ^4He AND HEAVY PRODUCTS FROM REACTIONS OF 720 MeV ^{86}Kr WITH Au. J. Miller, G. Catchen, D. Logan, Columbia University, N. Y. N.Y. 10027; M. Rajagopalan, J. Alexander, SUNY Stony Brook, N. Y. 11794; M. Kaplan, Carnegie-Mellon University, Pittsburgh, Pa. 15213; M. Zisman, Lawrence Berkeley Lab., Berkeley, Calif. 94720.

The production of ^4He in coincidence with a heavy fragment has been studied with a solid state detector telescope and a Fowler-Jared gas telescope. For heavy fragments detected at 36° and 41° we have mapped the light fragment differential cross sections $d^3\sigma/d\Omega_1 d\Omega_2 d\epsilon$ from 81° through 340° . Measurements have been made in the reaction plane and for azimuthal angles up to 42° . The tests for equilibrium vs. pre-equilibrium emission are complex as one must consider energy and angular distributions in four separate frames of reference: (1) lab (2) center of mass (3) that of the detected heavy fragment (4) that of the undetected heavy fragment. The transformed differential cross sections will be presented and the resulting patterns will be discussed as they reflect the reaction mechanisms.

3. MONTE CARLO CALCULATIONS AS COMPARED TO EXPERIMENTS FOR ^4He EMISSION FROM REACTIONS OF 720 MeV ^{86}Kr WITH Au. J. M. Miller and D. Logan, Columbia University, N. Y., N. Y. 10027

Observations of light charged particles can provide a probe of the mechanisms of reactions between very heavy ions. Those evaporated from the heavy reaction products will depend on the temperatures, spins and coulomb barriers of those products. Those emitted at impact, prior to thermal equilibrium can possibly provide insight into the nature of the frictionally heated zone between the colliding nuclei. First, however, one must try to distinguish the pre-equilibrium emissions from equilibrium evaporation. We use experimental energy and angular distributions for heavy reaction products to provide a set of velocities for the moving nuclides capable of evaporating ^4He . We use measured emission probabilities and energy spectra for ^{75}Br and ^{194}Hg compound nuclei to simulate ^4He evaporation from the fully accelerated reaction products. The areas of agreement between calculation and experiment provide evidence for evaporation mechanisms; areas of disagreement suggest pre-equilibrium mechanisms.

4. COINCIDENCE STUDIES OF HEAVY FRAGMENTS FORMED IN REACTIONS OF 720 MeV ^{86}Kr WITH Au. J. Miller, D. Logan, L. Kowalski, G. Catchen, Columbia University, N. Y., N. Y. 10027; M. Rajagopalan, J. Alexander, SUNY Stony Brook, N. Y. 11794; M. Kaplan, Carnegie-Mellon University, Pittsburgh, Pa. 15213; M. Zisman, Lawrence Berkeley Lab., Berkeley, Calif. 94720.

Other workers have found for similar reactions strong evidence for a preponderance of reactions that obey two-body kinematics. Also, however, products have been observed that can be attributed to fission of the struck nucleus after a hard reactive collision. Such sequential fission would clearly give rise to three major products. We have initiated a study of the relative probability of two-body vs. multi-body reactions for 720 MeV $^{86}\text{Kr} + \text{Au}$. We have studied coincident production of two heavy fragments with two Fowler-Jared gas telescopes. The ratio of the number of coincident events to single events gives information on the probability for two-body reactions. If the bulk of the multi-body reactions are assumed to be sequential fission, then this fission probability can be determined as a function of Q for the reaction. Experimental results will be presented and comparisons made to fission of ^{194}Hg compound nuclei.

5. FORMATION AND DECAY OF ^{194}Hg AT HIGH EXCITATION ENERGY. J. Miller, D. Logan, G. Catchen, L. Kowalski, M. McMahan, Columbia University, N. Y., N. Y. 10027; M. Rajagopalan, J. Alexander, SUNY Stony Brook, Stony Brook, N. Y. 11794; M. Kaplan, J. Ball, Carnegie-Mellon University, Pittsburgh, Pa. 15213; M. Zisman, Lawrence Berkeley Lab., Berkeley, Calif. 94720.

We have studied the energy and spin dependence of the decay of the compound nucleus ^{194}Hg . This nucleus at initial excitations of 98 and 142 MeV has been produced by the reactions $^{12}\text{C} + ^{182}\text{W}$ and $^{19}\text{F} + ^{175}\text{Lu}$. Differential cross sections have been measured for H and He emission, fission products and evaporation residues. Integrated decay probabilities are reported as well as the detailed energy spectra for the evaporated particles. The fission probability clearly increases with angular momentum at fixed initial excitation energy, but it does not increase with energy between 98 and 142 MeV. The evaporation probability of ^4He increases strongly between 98 and 142 MeV and this bleeding of charge may well be shielding the system from fission. Comparisons of the experimental data will be made to statistical-model calculations via the Groggi II code.

6. EVAPORATION CALCULATIONS OF ^1H AND ^4He EMITTED FROM ^{75}Br AT HIGH EXCITATION ENERGIES. J. M. Miller and N. H. Lu, Columbia University, N. Y., NY 10027.

Nuclear evaporation processes have become very important for interpreting phenomena observed in reactions between very heavy nuclei. All too often, however, our knowledge of the statistical model parameters is not sufficient for systems at high excitation energy and spin. Information on these parameters can be obtained by careful comparison of evaporation calculations to decay properties of compound-nuclei. We have used the detailed statistical model code Groggi II to examine ^1H and ^4He spectra for ^{75}Br excited to 49 and 88 MeV. Comparisons of the calculations to the extensive data of Reedy et al. allow us to gain a consistent set of parameters. [R. C. Reedy, M. J. Fluss, C. F. Herzog, L. Kowalski and J. M. Miller, Phys. Rev. 188, 1771 (1969)].