MASTER

DOE/ER/13246-20

~~EOO-3246-20~~

NUCLEAR RESEARCH WITH HEAVY IONS

Annual Progress Report

For the Period January 1, 1980-December 31, 1980

Morton Kaplan
Principal Investigator

Department of Chemistry
Carnegie-Mellon University
Pittsburgh, Pennsylvania 15213

October 1980

PREPARED FOR THE
U. S. DEPARTMENT OF ENERGY
UNDER CONTRACT NO. DE-AC02-76ER13246

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Department of Energy, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product or process disclosed or represents that its use would not infringe privately owned rights.

NUCLEAR RESEARCH WITH HEAVY IONS

CONTRACT DE-AC02-76ER13246

ABSTRACT

The program of research is oriented towards experimental studies of the interactions between heavy ions and complex nuclei. We probe these interactions by detailed measurements of light-charged-particle emission using counter telescopes for atomic number and mass number identification. Singles measurements of the charged-particle energy spectra and angular distributions, together with coincidence correlations with heavy nuclear-reaction fragments, provide insight into the contributing reaction mechanisms. The application of the statistical model to the appropriate experimental data allows the determination of parameters necessary to calibrate the theory, and gives indications of dynamical control vs. equilibrium in the several degrees of freedom associated with the nuclear collisions. A large body of data are presented and discussed for ^{40}Ar reactions with ^{116}Sn , ^{154}Sm , ^{164}Dy , and ^{197}Au targets. Complete results are also given for twelve reactions which produce ^{194}Hg compound nuclei at several excitation energies.

DISCLAIMER

This book was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Morton Kaplan
Principal Investigator

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

MGW

TABLE OF CONTENTS

I.	Introduction.....	I-1
II.	Light Charged Particle Emission in ^{40}Ar Induced Reactions: A Probe of the Very Early Evolution of the Collisions.....	II-1
III.	Charged Particle Emission from ^{194}Hg Compound Nuclei: Energy and Spin Dependence of Fission-Evaporation Competition.....	III-1
IV.	Publications.....	IV-1
V.	Papers in Preparation.....	V-1

CONTRACT DE-AC02-76ER13246(U. S. Department of Energy--Carnegie-Mellon University)Annual Report: October 1980

INTRODUCTION

The experimental research program is primarily concerned with the nuclear reactions induced by collisions between heavy-ion projectiles and complex target nuclei, the dynamics and thermodynamics associated with such collisions, and the relationships of the observables to the equilibrium and non-equilibrium properties of nuclear matter. Most of the experiments are carried out at the SuperHILAC and 88" Cyclotron accelerators of the Lawrence Berkeley Laboratory in close collaboration with Professor J. M. Alexander's group from the State University of New York at Stony Brook. Several years ago we jointly developed a long range plan of heavy ion research involving studies of deeply inelastic reactions of very heavy ions and measurements of compound nuclear formation and decay characteristics. This plan has proved to be very productive and successful, and we have been following along its basic course as our knowledge and techniques have continued to evolve. We feel we have achieved a powerful mix of experimental approaches and calculational reinforcement and anticipate further growth and development of our ideas and methods as the program progresses.

During the past contract year we have completed several experimental projects and carried others forward. The Program Advisory Committees of the SuperHILAC and 88" Cyclotron accelerators have passed favorably on our proposed experiments, and accelerator time has been allocated for carrying them out. This past year we have used a total of 79 shifts at the two accelerators, as indicated by the summary in Table I. Examination of this table should give

Table I. Experiment Summary 1979-1980

Date	Facility	Systems Studied	E(Lab) (MeV)	Measurements
November 1979	SuperHILAC 35 shifts	$^{40}\text{Ar} + ^{116}\text{Sn} \rightarrow ^{156}\text{Er}$	201,	Charged particles; fission; ER's, Li-O; forward angle charged particles and out-of-plane correlations at 340.
		$^{40}\text{Ar} + ^{154}\text{Sm} \rightarrow ^{194}\text{Hg}$		
		$^{40}\text{Ar} + ^{164}\text{Dy} \rightarrow ^{204}\text{Po}$		
		$^{40}\text{Ar} + ^{197}\text{Au} \rightarrow ^{237}\text{Bk}$		
		$^{20}\text{Ne} + ^{174}\text{Yb} \rightarrow ^{194}\text{Hg}$	125	Charged particles, fission.
April 1980	88" Cyclo- tron 21 shifts	$^{16}\text{O} + ^{181}\text{Ta}$	215	Charged particles; fission; coincidences between H/He and fission and between H/He and H/He.
		$^{16}\text{O} + ^{208}\text{Pb}$		
		$^{16}\text{O} + ^{238}\text{U}$		
		$^{16}\text{O} + ^{12}\text{C}$		
August 1980	SuperHILAC 23 shifts	$^{40}\text{Ar} + \text{Ag}$	200,	Charged particles; fission; Li-O at back angles; particle-fission coincidences and particle-particle coincidences at 340.
		$^{40}\text{Ar} + ^{154}\text{Sm}$		
		$^{40}\text{Ar} + ^{197}\text{Au}$		
		$^{40}\text{Ar} + ^{12}\text{C}$	340	

an overview of our more recent undertakings, which are being pursued in combination with the data workup and analyses of ^{86}Kr and ^{136}Xe experiments performed earlier (see particularly C00-3246-18 and C00-3246-19, Annual Reports for 1978 and 1979). The later sections of this report describe in detail several studies which have reached the manuscript stage, and we also give a listing of current publications and papers in progress.

The Lawrence Berkeley Laboratory accelerators have continued to perform very well and have been of utmost importance in the success of our program. We are pleased to acknowledge the hospitality and support of the many LBL staff personnel who make it all possible. The principal investigator on this research project, Professor Morton Kaplan, devoted one-half time to the program during the academic year and full time for 2 1/2 summer months. Dr. Douglas Logan was a full time senior research associate in our group this year and Dr. Ludwik Kowalski from Montclair State College participated with us during the summer. Dr. Mehmet Kildir, on leave from the Middle East Technical University in Ankara, Turkey, arrived in August as a Visiting Professor and will be with our group full time for the next two years. A new graduate student has also joined us and will become involved in the program as his work progresses. Our direct collaborations this year were with Professor J. M. Alexander, Dr. M. F. Rivet, Dr. L. Vaz, Dr. D. Guerreau, and E. Duek from Stony Brook; Dr. H. Delagrange from Bordeaux; Dr. J. W. Ball from MIT, and Dr. M. S. Zisman from LBL.

LIGHT CHARGED PARTICLE EMISSION IN ^{40}Ar INDUCED REACTIONS:

A PROBE OF THE VERY EARLY EVOLUTION OF THE COLLISIONS

D. Logan

Department of Chemistry, Carnegie-Mellon University
Pittsburgh, Pennsylvania 15213

H. Delagrange^a, M. F. Rivet^b, M. Rajagopalan, John M. Alexander
Department of Chemistry
State University of New York at Stony Brook
Stony Brook, New York 11794

Morton Kaplan

Department of Chemistry, Carnegie-Mellon University
Pittsburgh, Pennsylvania 15213

M. S. Zisman

Lawrence Berkeley Laboratory
Berkeley, California 94720

and

E. Duek

Department of Chemistry
State University of New York at Stony Brook
Stony Brook, New York 11794

Abstract

Charged particle emission was studied for the reactions 222, 274 and 340 MeV $^{40}\text{Ar} + ^{116}\text{Sn}$, ^{154}Sm , ^{164}Dy and ^{197}Au . Energy and angular distributions were measured for H and He and angular distributions for Li, Be, B, C, N and O, fission-like fragments and evaporation residues (ER). For H and He the data are consistent with a low-temperature evaporative component and a high-temperature forward peaked component. For Li through O the forward-peaked emission was studied for 340 MeV ^{40}Ar only. The ER cross sections decrease strongly with increasing Z reflecting the increasing fissionability. However the cross sections for ^1H and ^4He in coincidence with fission are essentially constant with Z. Coincidence measurements, energy spectra and $^4\text{He}/^1\text{H}$ ratios indicate that most H/He evaporation precedes fission. This implies that the energy thermalization is very rapid indeed and that the light particle spectra can probe the very early history of the composite systems.

Nuclear Reactions: ^{116}Sn , ^{154}Sm , ^{164}Dy , ^{197}Au (^{40}Ar ; H/He, fission and evaporation residues), $E = 222, 274$ and 340 MeV, measured energy and angular distributions in singles mode. For $E = 340$ MeV, coincidence measurements between H/He and one fission-like fragment, and angular distributions for Li, Be, B, C, N and O in the singles mode.

I Introduction

This paper is one of a series in which we study heavy-ion reactions by measurements of the light charged particles (H/He) along with the heavier fragments such as evaporation residues (ER) and fission fragments.¹⁻⁴ Our emphasis here is on the attempt to form various compound nuclei $^{156}_{68}\text{Er}$, $^{194}_{80}\text{Hg}$, $^{204}_{84}\text{Po}$ and $^{237}_{97}\text{Bk}$ at excitation energies up to 200 MeV and spins of a hundred or so. At these very high energies the concept of "fusion" is complicated by the occurrence of complete and partial or incomplete fusion and by the similarities of "true fission" and "fission-like" reactions.^{2,3} These complications impinge on the utility of the oft-used sharp cutoff approximation for ℓ_{crit} , the critical ℓ value for fusion. Nevertheless we try to extract fusion cross sections, ℓ_{crit} values and the temperatures of the composite nuclei. The thermometer we use is the high energy part of the H/He spectra at backward angles.^{5,6} Evidence is presented that much H/He evaporation precedes fission; therefore, the maximum and the low-energy part of the evaporation spectra reflect the coulomb barriers of the newly born composite nuclei and thus give some ideas on their shapes or identities.⁷ The competition between fission and particle evaporation is reflected by the relative cross sections for H/He, ER and fission. The importance and the nature of direct H/He emission is viewed by the angular and energy distributions, particularly at forward angles.^{5,6} In other papers^{1,4} we have explored in a similar manner the energy and spin dependence of deexcitation of ^{194}Hg and ^{156}Er . Also, we have presented in Ref. 2 a somewhat more detailed study of one reaction, 340 MeV $^{40}\text{Ar} + ^{197}\text{Au}$.

In 1961 Britt and Quinton showed that both direct and evaporative components could be identified in H/He spectra from reactions between complex nuclei.⁵ Galin et al.⁸ demonstrated for the composite system ^{117}Te that the direct components were much less important for ^{40}Ar than for ^{14}N induced reactions (excitations of 71 and 107 MeV), and this suggested ^{40}Ar (or similar projectiles)

as particularly useful for producing compound nuclei after complete fusion. The preponderance of deeply inelastic collisions for even heavier projectiles, for example ^{86}Kr , also argues for ^{40}Ar as a good choice of projectile for systematic studies of compound nuclei.⁹

Fusion cross section measurements at low energies make it possible to estimate the fusion barriers.¹⁰⁻¹⁴ These barriers and semiempirical theories allow estimates of the critical l values for fusion. Recently the evidence has been mounting that forward peaked ^4He emission is often correlated with partial fusion reactions^{2, 15-19} rather than projectile breakup,⁵ and thus the notion of straight forward identification of "evaporation residues" after truly complete fusion has been put in question.³ One of our objectives in this study is to determine the magnitude of such forward-peaked H/He particles and therefore their possible influence on the concept of complete fusion and l_{crit} .²⁰ A preliminary discussion of this question has already been published.³

To the extent that "complete (and incomplete) fusion" can be identified, we seek its dependence on target and energy. Particle evaporation has been shown to precede fission in substantial amounts² for 340 MeV $^{40}\text{Ar} + ^{197}\text{Au}$. Here we seek the Z dependence of this fission-evaporation competition. Standard parametrizations of the statistical model indicate that with increasing energy, charge and spin, fission should increasingly dominate H/He emission from an equilibrated system.²¹ The experimental data seem to be inconsistent with this prediction of the equilibrium statistical model. Thus we feel that the whole question of energy equilibration and the power of "available phase space" as a driving force must be studied by systematic experimentation for nuclei at high excitation and spin.

In Section II we sketch the experimental techniques and in Section III we present the results. Some of the relationships to earlier experiments and simple reaction models are discussed along with the data presentation. In Section IV we set some time limits on the decay of composite systems prior to equilibration. We discuss the spin zones for fission and evaporation and some misleading features of "sharp-cutoff" thinking. Evidence is presented for the breakdown of phase-space equations for fission-evaporation competition in reactions of 340 MeV ^{40}Ar . Finally a flow chart of the cross sections and mean spins is presented along with some suggestions for future experimentation.

II. Experimental arrangement

Beams of ^{40}Ar were provided by the SuperHILAC at the Lawrence Berkeley Laboratory. They were defined by two four-jaw collimators upstream of the 75 cm. diameter scattering chamber. Self-supporting targets were used of ^{116}Sn , ^{154}Sm , ^{164}Dy and ^{197}Au (0.85, 0.67, 1.00, and 1.25 mg/cm² respectively); each contained >95% of the isotope indicated. The thickness of the Au target was measured by weight and the other target thicknesses were determined relative to it by elastic scattering. The mean charge states of the beam were taken to be 16.3, 15.3 and 15.0 at 340, 274 and 222 MeV respectively.²² These values are consistent with the assumption of Rutherford scattering from Au at small angles. The beam intensity was limited by the dead time of the system ($\approx$ 10-20%). Elimination of the buncher was found to allow a significant increase in beam intensity, and the introduction of a new and faster ADC and multiplexer system allowed significantly higher counting rates for the last run (some of the 340 MeV data). Dead time was measured by a pulser triggered by one of two beam monitors and passed through the test input of selected preamplifiers.

The basic detection scheme has been described elsewhere:^{1,2,4} gas ionization telescope (GT) ($\approx$ 20 torr of methane and 300 μm Si stopping detector)²³ for ER and fission products, solid state telescope (SST) (45 μm , 500 μm , 5mm Si detectors for light charged particles (H, He, Li ... O) and in some cases fission products.

For the SST, cover foils of either 10 or 50-70 mg/cm² Pb were used (the latter was chosen to stop completely the elastically scattered ⁴⁰Ar at the more forward angles). Normally an SST was mounted such that $\Delta\Omega \approx 8$ msr which allowed approach to about 20° from the beam axis. For the 340 MeV experiment, one SST was mounted at a much lower geometry ($\Delta\Omega \approx 0.8$ msr) which allowed measurements to be made as close as 5° to the beam. Energy calibrations and pulse height defects for the GT were made by the elastically scattered beam and by a source of ²⁵²Cf; for the SST, sources of Th B were used. For light charged particles that barely enter the third member of the SST, a small experimental problem arises. If less than ≈ 0.5 MeV is deposited in this third detector, then the processing of this pulse is non linear. At worst this results in the assignment of an apparent energy for this particle from only the first two members of the SST. This effect can be seen as an apparent discontinuity in the ⁴He spectra in Figs. 1 and 2 ($\theta_{cm} = 6^\circ$ and 18°). A correction could be applied by averaging the one high point for $\epsilon_{cm} \approx 24$ MeV with the one low point for $\epsilon_{cm} \approx 25$ MeV. We have no reason to believe that the spectra are distorted outside this very narrow zone.

One set of measurements was made for coincidence between fission and H/He (emitted in the backward direction) from 340 MeV ⁴⁰Ar + ¹¹⁶Sn, ¹⁵⁴Sm and ¹⁶⁴Dy. Similar measurements had already been made² for ¹⁹⁷Au. Fission fragments were recorded in the GT at $\Delta\Omega \approx 1$ msr and $\theta_{lab} \approx 55^\circ$ ($\theta_{c.m.} \approx 90^\circ$); and H/He were recorded at θ_{lab} of 79°, 104° and 129° ($\theta_{c.m.} \approx 90^\circ$, 120° and 140°) in the reaction plane. A time to amplitude converter (TAC) was used to record the spectrum of time delays between pulses from the GT and SST. This spectrum gave a true coincidence peak of about 30 nsec. width and a small flat tail indicating a negligible rate of random coincidences. Single events were prescaled by a factor of 100 and recorded simultaneously with the coincident events. One set of measurements was also made (340 MeV ⁴⁰Ar beam) of Li, Be, B, C, N and O at lab angles from 6-40°. Energy thresholds for these particles of Z(3-8) were rather high and thus we could observe them only at forward angles.

III. Experimental Results

A. Qualitative features

The overall features of the energy and angular distributions in the singles mode are illustrated in Figs. 1 - 4 and in Table I. For $\theta_{c.m.} \gtrsim 40^\circ$ the spectra exhibit one broad peak and an exponential high-energy tail that depends on angle (Fig. 1). For the smallest angles the spectra often break into two components. The low energy peak is of similar energy to that observed at large angles while the high energy component is much broader as shown in Fig. 2. If one assumes that an evaporative component is present then it can be identified with the observed spectra at backward angles. The subtraction of this component from the observed spectra at forward angles can expose the spectrum from direct processes (see Fig. 2);⁶ they are very broad with no obvious connection to the beam velocity. The energies and the cross sections decrease rapidly with increasing angle as shown in Figs. 1 and 3. The characteristics of this direct component will be discussed later in Section IV and in more detail in future publications.

In Table I we characterize the shapes of these c.m. spectra by three parameters, the full width at half maximum (FWHM), the mid point of this width (ϵ_{mp}), and the temperature (T). The latter is obtained by fitting to the function

$$P(\epsilon) \propto (\epsilon - B) \exp(-\epsilon/T) \quad (1)$$

with the value of the barrier parameter B taken from Ref. 7. The T parameter obtained at backward angles may be taken as a crude approximation to the nuclear temperature. For forward angles the T parameter simply gives a description of the spectral shape and has no obvious physical interpretation. The values of ϵ_{mp} , FWHM and T are given for typical forward and backward angles of each set in Table I.

For all targets and ⁴⁰Ar beams of 270 and 340 MeV (Fig. 3) the spectra at back angles relax to a constant temperature with angular distribution consistent with evaporative decay (flat or slowly rising toward 180°). The magnitude

and shape of the evaporative components were determined from the angular distributions for $\theta_{\text{c.m.}} > 120^\circ$ with the assumption that the direct component vanishes beyond this angle. The energy spectra were totally relaxed in this region, and thus we have used a fitting function from the equilibrium statistical model:^{24,25}

$$W(\theta_{\text{c.m.}}) = W_0 \exp [-(\beta_2/2) \sin^2 \theta_{\text{c.m.}}] I_0 [(\beta_2/2) \sin^2 \theta_{\text{c.m.}}] \quad (2)$$

where W_0 and β_2 are free parameters and I_0 is the zeroth order ^{modified} Bessel function. The fit was made by a least squares technique using the code MINUIT. The anisotropy parameter β_2 will be related to the spins of the emitters in section C. After subtraction of this evaporative component (symmetric about 90°) the remaining forward-peaked (direct) component was fit to the function

$$W(\theta) = A \exp (-b\theta - c\theta^2) \quad (3)$$

The total "evaporative" and "direct" components were determined by integration of these functions. The smooth curves in Fig. 3 show the results of the fits, and the integrated cross sections are summarized in Table II. For 222 MeV ^{40}Ar reactions with Sm, Dy and Au the temperature seems relaxed but the angular distributions never decisively lose their preference for more forward angles (for the angular range of this study). For these cases the evaporative component was assumed to be isotropic and $d\sigma/d\Omega$ was identified with the smallest measured value. Therefore these cross sections should be taken as upper limits for evaporation. By contrast, for the Sn target the evaporative component is considerably larger than the direct component. Apparently this trend continues for the even lighter target ^{77}Se as Galin et al.⁸ observed essentially pure evaporative emission for this case. Note, however, that angles smaller than $\approx 20^\circ$ were not explored for excitations of ≈ 140 MeV in either this work or in Ref. 8.

We were able to make some initial observations of Li, Be, B, C, N and O products with the same SST and absorber foils used primarily for H/He measurement. As the energy thresholds were rather high we did not study the possibility of emission at back

angles. Nevertheless these products were clearly identified at forward angles and their angular distributions and integrated cross sections are given in Fig. 4 and Table II. We have not made a serious attempt to measure the isotope distributions at each angle as this would require considerably more beam time. Nevertheless one can get a feeling for these distributions from the results shown in Fig. 5.

The fission-like products as identified by the GT could include contributions from deeply inelastic collisions and non-equilibrium fission as well as from equilibrium fission.²⁶ It has often been said that for the higher energies and the lower Z targets, this distinction is particularly difficult.²⁷ In Fig. 4 we show the angular distributions of gross fission-like products (ER and quasi-elastic products excluded) transformed to c.m. with the assumption that all fragments have the average c.m. velocity of a symmetric fission product.²⁸ These angular distributions seem to become more asymmetric with increasing beam energy and decreasing Z of target. At forward angles it is especially difficult to distinguish fission products from target-like products of lower Z and the projectile-like products of higher Z. In addition, at back angles the heavier fission products are easily lost below the energy threshold due to the large velocity of the center of mass. However at c.m. angles of $\approx 90^\circ$ the energy distributions have a clear valley between broad peaks that one can identify with deeply inelastic and fission reactions. Thus we estimate the fission cross sections to be $2\pi^2 (d\sigma/d\Omega)_{90^\circ \text{ c.m.}}$ (assuming an angular distribution of $1/\sin\theta_{\text{c.m.}}$) as given in Table III.

Measurements of evaporation residue cross sections were made relative to elastic scattering as they were simultaneously observed in the same GT. The "true" direction of the beam axis was determined by observations of elastic scattering to the right and left sides successively. Rutherford scattering formulas were used for elastic

scattering as the angles where ER's were measured are well below the grazing or quarter-point angle. As the recoil energies of heavy residual nuclei after massive transfer are also well above the threshold for GT detection, we would probably include products from most such incomplete fusion reactions as well as those from complete fusion. Therefore the values of ER and fusion cross sections (and the associated values of l_{ER} and l_{crit}) in Table III should be interpreted as representing complete plus incomplete fusion.²⁰ As discussed previously³ the contribution from incomplete fusion could be very large for reactions induced by 340 MeV ^{40}Ar .

B. Magnitudes of the cross sections

The fusion cross sections of 0.5 to 1.6 barns follow the trends of other published data for similar reactions.^{3,20,27,29} They imply that very large entrance-channel l -waves are involved in the fusing collisions; l_{crit} values range from 68 to 145 (Table III). However the large cross sections for forward-peaked, light charged particles (Table II and Fig. 3) also imply significant mixing of complete and incomplete fusion.^{2,15-19} Thus the energy and spin values of many heavy nuclei after the fast impact part of the collision may be reduced by several tens of MeV and tens of $\hbar$ units compared to that which would have resulted from complete fusion. Cross sections for the less abundant light charged particles ^2H , ^3H , Li, Be, B, C, N and O are also reported in Table II for the 340 MeV ^{40}Ar reactions. As these cross sections are rather small these products probably do not play a major role in the overall mass or energy balance for the reactions. But they may turn out to be useful probes of the role of clustering phenomena in the evolution of the composite system.

The major competitors for the exit channels after equilibration are fission and emission of neutrons, ^1H , and ^4He . As the evaporative $^1\text{H}/^4\text{He}$

cross sections and decay fractions (Tables II and III) seem quite large, it is natural to explore the possibility of evaporation both before and after scission. In another paper² we have presented strong arguments against α -evaporation from fission fragments for 340 MeV $^{40}\text{Ar} + ^{197}\text{Au}$.

Briefly the arguments presented there are as follows: (1) The observed singles spectra are not as wide as those from kinematic simulations of post fission evaporation (2) The mean energies and the cross sections of ^4He are nearly identical in singles and in coincidence at several angles with respect to the fragments (3) The observed cross section ratios for ^4He to ^1H are much larger than those expected for evaporation from fission fragments. Each of these arguments also applied for the evaporative ^1H , but with much less force. Therefore the possibility remained for some significant evaporation of ^1H from the fission fragments.

In this study we have measured the spectra of ^1H and ^4He in coincidence with one fission product for three geometrical configurations. The shapes of some of these spectra for the ^{154}Sm and ^{116}Sn targets are given in Fig. 6 in comparison to a kinematic calculation. The results for ^{164}Dy are very similar to those for ^{154}Sm . The calculation was made to simulate evaporation from fission fragments with an angular distribution of $1/\sin \theta_{\text{c.m.}}$. The assumed mass, charge, and kinetic energy distributions of the fragments were taken from empirical systematics.²⁸ All fission fragments were assigned the same multiplicity for light charged particle emission (taken to be isotropic).⁵⁴

The evaporation spectrum was assumed to follow Eq. 1 with $T = 2.0$ MeV and barrier parameters from Ref. 7. The energy spectrum for ^4He observed in the singles mode is much more narrow than the calculated one. Also the observed spectra for ^4He in coincidence

are very similar to those in singles and do not exhibit the high-energy peak expected for evaporation from the moving fragments. We conclude that ${}^4\text{He}$ evaporation from the fragments is rare for ${}^{154}\text{Sm}$ and ${}^{164}\text{Dy}$. The data for ${}^{116}\text{Sn}$ (Fig. 6B) allow more room for post fission evaporation, but this is surely not the preferred mechanism. The calculated and observed spectra for ${}^1\text{H}$ in singles at $\theta_{\text{c.m.}} \approx 115^\circ$ differ only in some details of their shape. However, the observed coincidence spectra exhibit a single peak again very similar to the singles spectrum and qualitatively different from the double-peaked curve expected from two separate fission fragments. We conclude that ${}^1\text{H}$ evaporation from the fission fragments is also rare for ${}^{154}\text{Sm}$ and ${}^{164}\text{Dy}$; similarly for ${}^{116}\text{Sn}$ this seems not to be the preferred mechanism.

The ratios of evaporative ${}^4\text{He}$ to ${}^1\text{H}$ also provide a test for the extent of post scission emission. This point is discussed more fully in Refs. 2 and 25 so we only mention it here. Examination of Table III shows that the measured ratios of ${}^4\text{He}$ to ${}^1\text{H}$ are all greater than 0.5. (Neglect the data for 222 MeV ${}^{40}\text{Ar} + \text{Sm, Dy}$ and Au as large uncertainties result from the dominance of the direct component.) Comparison of these ratios to those for the compound nuclei ${}^{75}\text{Br}^*$ or ${}^{117}\text{Te}^*$ would imply implausibly large spins for the fission fragments if they were to be the emission sources.^{2,25}

What about evaporation from the fragments after deeply inelastic reactions?³⁰⁻³⁴ The H or He evaporated from the rapidly moving and forward-peaked projectile-like product would be included in the group that we call direct. The kinematics are such that H or He evaporated from the slowly moving target-like product could possibly be included with those we assign to the evaporative component. For the similar reaction 373 MeV ${}^{32}\text{S} + {}^{197}\text{Au}$, Gamp et al. have made a detailed study of ${}^4\text{He}$ emission in coincidence with projectile-like fragments.³⁰ They find integrated ${}^4\text{He}$ production in coincidence to be less than 5% of the inclusive cross section. In addition they can exclude emission from the target-like fragment as a prominent mechanism. For 222 and 274 MeV ${}^{40}\text{Ar}$ reactions the excitation of this target-like fragment is expected to be too low for

it to dominate the evaporative H/He. For 340 MeV $^{40}\text{Ar} + ^{154}\text{Sm}$, ^{164}Dy and ^{197}Au the coincidence data (in Ref. 2 and in this work) indicate that the major (but not exclusive) correlation of coincident events is with fission rather than deeply inelastic reactions. For 340 MeV $^{40}\text{Ar} + ^{116}\text{Sn}$ the evaporative $^1\text{H}/^4\text{He}$ cross sections (singles) are so large that contributions are rather likely from several sources: the evaporation residues, the target-like fragments and the composite systems prior to scission. We will discuss this in connection with Table V later.

C. Anisotropies for H/He and coincidence between fission and ^1H and ^4He .

From Fig. 3 we see that the cross sections for $^1\text{H}/^4\text{He}$ at back angles increase strongly with incident energy. Also an increase of $d\sigma/d\Omega$ toward 180° becomes apparent at 340 MeV for both ^4He and ^1H . This back-angle anisotropy is also measurable for ^4He for 274 MeV incident energy and for the ^{116}Sn target even at 222 MeV. Anisotropies for the evaporative components are very useful as they can provide information on the root mean square spins of the emitters, $J_{\text{rms}}^{24,25,35}$. The values of J_{rms} for all fusion reactions is expected to increase with incident energy over the fusion barrier. However the particular nuclei that evaporate H or He could have J_{rms} values very different from those for all fusion reactions; for example, they could be heavily selected by competition with fission. We have assigned values to the anisotropy parameters β_2 from the fits of Eq. 2 to the data at backward angles (Fig. 3); then we have estimated J_{rms} from these values of β_2 .

Catchen et. al.²⁵ have discussed the equations from the statistical model that relate these β_2 parameters to the spins of the emitters:^{24,35}

$$\beta_2 = \frac{\hbar^2 (J_0 + 1/2)^2}{2 J_T} \frac{\mu R^2}{J_\perp} \quad (4)$$

where J_0 is the spin of the emitting nucleus, $\mathcal{J}$ and T are the moment of inertia and temperature that characterize the level density of the residual nucleus. The exit channel ℓ values are controlled by the centrifugal barrier for particle emission of reduced mass μ (centrifugal barrier $= \hbar^2 \ell(\ell+1)/\mu R^2$). The symbol $\mathcal{J}_1$ represents $\mathcal{J} + \mu R^2$. Refs. 7, 10 and 25 use experimental data on fusion and evaporation to examine the choice of parameters $\mathcal{J}$, T and μR^2 necessary for estimation of $(J_0 + 1/2)^2$ from β_2 . Values of β_2 and the associated rms spin [$\langle (J_0 + 1/2)^2 \rangle^{1/2} = J_{\text{rms}}$] deduced by their method are also listed in Table IV. See the appendix for details.

One usually assumes that fission from high-spin nuclei occurs predominantly perpendicular to the spin axis ($K \ll J$).³⁶ Thus the detection of a fission fragment establishes a reaction plane approximately normal to the spin axis of the fissile nucleus. Particles evaporated prior to fission are expected to have an angular correlation with the spin axis $W(\varphi)$,^{24,25}

$$W_{J_0, \mathcal{J}T}(\varphi) = \exp(\beta_2 \sin^2 \varphi) \quad (5)$$

The determination of β_2 from the angular distribution in singles along with the differential cross section for coincidence between fission and evaporative ^1H or ^4He ($d^2\sigma/d\Omega_G d\Omega_S$) permits one to integrate and obtain the total cross section for such coincident events.²⁵ The last two columns in Table IV give the measured differential cross sections and the integrated coincident cross section (σ_{coinc}). The integrated coincident cross sections have uncertainties of $\approx 35\%$ due to the statistical significance of the coincidence data and uncertainties in the values of β_2 . Nevertheless these estimates can be quite informative as discussed later with Table V. (See the appendix and Ref. 25 for details of the integration to give σ_{coinc} .)

IV. Discussion

A. Some simple estimates of the time scales

One of the primary aspects of any reaction mechanism is the relative time scale for the chain of events. Here we consider four kinds of happenings (1) emission of forward peaked particles H/He etc. (2) fusion (complete or incomplete) (3) emission of H/He into the backward angles and (4) fission. The first two must occur in times considerably smaller than a rotation period for the composite system. The latter two are usually thought to require something akin to half a rotation period or even much more. We must resort to some kind of reaction model if we are to set any more stringent limits on these times.

For the forward peaked H/He we could envisage their prompt ejection after one or a few collisions in much the same picture as the nucleon-nucleon collision model of Serber.³⁷ Then a typical time would be $\approx R/v$ where a nuclear radius R is taken as a typical traversal distance and v the mean velocity during the traversal. For nucleons one would estimate v to be of the order of the Fermi velocity; for heavier particles (^4He etc.) the whole notion of the Serber model seems rather unnatural. Nevertheless such a picture should lead to $\approx 1 \times 10^{-22}$ sec for a nuclear traversal time in a collision cascade model.

One might argue that the colliding nuclei must move toward one another for some significant distance (e.g. $\frac{1}{2} R$) in order to provide the initial collisions needed to cut away the light charged particles from their brothers and sisters.³⁸ Hence another $2 - 3 \times 10^{-22}$ sec would be a reasonable mean induction time for a collision cascade model.

The hot spot model provides another simple means to estimate an upper limit for the mean decay time.^{6, 39} One can visualize a small hot zone on the nuclear surface that emits a narrow beam of particles. Then the mean decay time is given by the mean decay angle divided by the angular velocity ω . The former can be taken from the data in Fig. 3 (for T vs $\theta_{c.m.}$) after subtracting an assumed symmetric component. The angular velocity can be obtained if one can estimate a mean l value and a moment of inertia. From reactions induced by lighter projectiles, gamma ray data in coincidence with forward-peaked ⁴He seem to indicate that the value of l_{crit} is probably near to the relevant mean l value.¹⁶⁻¹⁹ A configuration of two touching spheres probably provides a reasonable estimate of the relevant moment of inertia (possibly this should be considered as an upper limit). Mean decay times so estimated are $\approx 3 - 8 \times 10^{-22}$ sec. The precision of the data in Fig. 3 and the crudely estimated values of J and ω preclude any discussion of Z or energy dependence of these times. The important point is simply their very small values $5 \pm 3 \times 10^{-22}$ sec. (These times may even be overestimated by our parameter choices and the model of a narrow emission cone from the hot spot zone. For example a smaller moment of inertia would give even shorter times.)

It is interesting that the mean times from the hot-spot and traversal models are so similar. The implication is that the emissions occur so rapidly that rather little rotation of the composite system occurs; hence an essential distinction between the two models is nearly removed for the forward-peaked component. Also interesting is the implication that these forward peaked particles are ejected so rapidly that the fusion decision is yet to be made.³ For entrance channel l values near to or less than l_{crit} most fusion

models¹⁰⁻¹⁴ visualize the partners approaching one another with a very small radial velocity. Thus the traversal of the real potential barrier toward fusion is explored with this slow radial motion, and the time for the double nuclear system to rotate ≈ 1 radian may give a rough estimate of the time to decide for or against fusion. For these systems rotation through 1 radian (for touching spheres at l_{crit}) requires $6 - 20 \times 10^{-22}$ sec. We conclude that the ejection of forward-peaked H/He (for $l \approx l_{\text{crit}}$) probably occurs concurrently with or prior to the fusion decision and should be allowed for in a useful reaction model.³ This point is addressed in an extension of the sharp cutoff classification by Siwek-Wilczyńska *et al.*,¹⁸ but not in the models that focus on an a priori potential.¹⁰⁻¹⁴

The apparently slower decay modes, H/He evaporation and fission, also provide an interesting insight into the relative decay times. The values of l_{crit} for 340 MeV ⁴⁰Ar reactions (109 - 145 Å) are considerably larger than the calculated stability limits in the liquid drop model (≈ 80 Å). Several authors have proposed the transient stability of a double-nucleus system for $\approx 1 \times 10^{-21}$ sec.²⁶ Such an entity could indeed be responsible for the large observed values of l_{crit} . It is especially interesting that evaporative H/He emission precedes the scission of even such short lived species. Extensive energy mixing and evaporative decay must occur on a time scale comparable to scission. This implication of extremely rapid energy thermalization is encouraging for diffusion models that have assumed thermal equilibration at each step in deeply inelastic reactions.⁴⁰

B. The charge and energy dependence of various processes

In Fig. 7 we show the Z dependence of the cross sections for each process we study at three excitation energies for the compound nucleus. The fusion cross sections are rather insensitive to Z for each energy; by contrast the fraction of ER decreases by more than tenfold from Z = 68 to 84 and by much more from Z = 84 to 97. This decrease is gener-

ally attributed to a decreasing fission barrier⁴¹ which rapidly increases the number of available channels to fission. As the direct H and He are expected to be emitted before equilibration they should not be affected by the number of available fission channels and indeed they are relatively constant with Z (e.g. ~ 100 mb at $E^* = 100$ MeV, 100 - 250 mb at 140 MeV and 150 - 500 mb at 190 MeV.)

On the other hand if the low-temperature H and He are evaporated from a completely equilibrated compound nucleus, then their abundance (Fig. 7) and the values of J_{rms} for the emitters (Table IV) should reflect the Z and J dependence of the fission barrier. The expected decrease in cross section is indeed observed from Z = 52 to 68 to 80. However for Z = 80 to 84 and even 97 there is scarcely any change. (Recall that in Section III-B we showed that there is very little H/He emission from fragments after scission.) These low temperature H/He emissions seem to precede scission and are characterized by $J_{rms} \sim 50 - 100 \hbar$ (or $\sim \ell_{crit}/\sqrt{2}$) regardless of Z and the number of open fission channels. The rapid increase of these evaporative emissions with energy (Fig. 7 and the cumulative decay fractions in Table III) suggests that they become exit channels of major importance. This is not easy to rationalize with a standard statistical model that utilizes similar energy dependence for the level density of saddle-point and evaporation daughter nuclei.²¹ We conclude that the dynamics or the intrinsic rates of the emission processes control their abundance relative to fission rather than the available phase space. The scission time has been estimated to be $\sim 3 \times 10^{-21}$ sec⁴² whereas the time for thermal equilibration and subsequent evaporation⁴³ seems to be even shorter (or at least comparable). This we feel, is a very important result as it implies that the H/He spectra might give a running record of the extent of the thermalization processes before scission. It also implies that

the sharp cutoff approximation for fission evaporation competition ($\Gamma_f/\Gamma_{\text{tot}} \rightarrow 1$ for $J > J_f$ where $B_f(J_f) = B_n$) is simply not valid for high excitation energies.⁴⁴ We discuss this point more fully in Ref. 4.

There are several additional important implications of a shift from control by phase space to control by dynamics. Our equations based on equilibrium statistical mechanics surely lose their generality, and the regal position of the fission saddle point is threatened. Evaporation of H or He could conceivably occur either before or after traversal of the saddle point as discussed above. But also the fissile system may not have enough time to explore all its K states as assumed in an equilibrium model.³⁶ Such a situation would severely shake the foundations used for exploring angular momentum transfer via sequential fission studies.^{45,46} Recent results from the Heidelberg group⁴⁶ do indeed suggest the demise of equilibrium theory for the angular correlations observed for sequential fission in the reactions $^{238}\text{U} + ^{238}\text{U}$ and $^{238}\text{U} + ^{248}\text{Cm}$.

An additional consequence of a shift to dynamic control is the possibility of invalidation of the Bohr independence hypothesis for the excited "compound" nuclei.⁴⁷ "Fission" probability could depend on mass asymmetry of the collision partners in addition to spin and excitation energy.^{26,48} As the limits for complete equilibrium are approached and passed it is likely that some decay modes will retain the features of equilibration longer than others.⁴⁹ The angular distributions and temperatures shown in Fig. 3 suggest that H and He emission at backward angles may be clinging tenaciously to their evaporative character. However, the collective motion toward fission may well be too slow to explore all the open channels that are available.

The forward-peaked emission of the various light particles clearly does not originate from evaporation. From Table II we see that there is relatively little dependence of these cross sections on target Z. Also it is interesting that one observes so much of the loosely bound ^2H and ^3H and even the more complex ions Li, Be, B, C, N and O. It would seem likely that such particles would be ejected either at impact or at scission.⁵⁰ The similarity of their angular distributions to those for protons could be said to suggest similarity in their mechanistic origin. This reasoning argues against reaction models which employ long mean free paths inside the nucleus.^{11,51}

C. A Flow chart to summarize our findings for 340 MeV $^{40}\text{Ar} + ^{116}\text{Sn}$, ^{154}Sm , ^{164}Dy and ^{197}Au .

In Table V we present a summary of many of the cross sections and spin values that we have taken from experimental observations or systematics. Let us follow down the column for the target ^{116}Sn . From systematics of elastic scattering data one estimates a reaction cross section (σ_R) of 2483 mb and $\ell_{\text{max}} = 168$.⁵² Subtraction of the measured fission and ER cross section leads to 1436 mb for quasi elastic and deeply inelastic reactions ($\sigma_{\text{QE}} + \sigma_{\text{DI}}$). Direct (or forward peaked) emission of light charged particles gives a comparable sum, some of which surely accompanies the so called "fusion" cross section (σ_{CF}) and complicates its common designation "complete fusion". The evaporative cross sections for ^4He and ^1H are as large or larger than the fusion cross sections and values of J_{rms} (from the angular distributions) are very similar to $\ell_{\text{crit}}/\sqrt{2}$. This result is consistent with a constant probability of emission from entrance channel waves of $0 < \ell \lesssim \ell_{\text{crit}}$. Normally one expects fission competition to eliminate the evaporative emission from the higher spin states. For the Sn target about one fourth of the evaporative ^4He and ^1H (232 and 356

mb) are found in coincidence with fission. Presumably most of the rest (926 mb ^4He and 1341 mb ^1H) comes from the ER products. The implied charge loss for the ER products ($\Delta Z \approx 7$ units) is consistent with that observed by other workers.⁴⁴ The observed cross sections for evaporative ^4He and ^1H in coincidence with fission are about the same for all targets in spite of the very large difference in fissionabilities. One possible interpretation of this result is that the time for motion to the scission point is sufficiently long to allow essentially complete energy thermalization and a rate determined evaporation probability of $\approx 1/3$ to $1/2$ for ^1H or ^4He . By contrast, the evaporative ^4He not in coincidence with fission decreases rapidly with Z following the decrease in evaporation residues. Possibly this result reflects rather constant values of Γ_α/Γ_n for each of the evaporation chains. The corresponding Z dependence for evaporative ^1H not in coincidence with fission is not as strong with apparently ≈ 200 mb remaining even for Dy and Au targets. Presumably these protons were evaporated from target-like products after deeply inelastic reactions. More extensive coincidence measurements are required to explore this point.

D. Suggestions for further experimentation

It is very interesting that the direct component of the charged particle emission seems to be emitted so rapidly that very little rotation of the composite system can occur. If a "hot spot" is formed³⁹ and emission occurs at the touching points one would expect a decided energy dependence of the angular distribution. At near barrier energies one would expect the grazing angle to move aft, and along with it the direct emission of H/He to move away from zero degrees. Such a change is not apparent in Fig. 3, but one should make measurements at still lower energies to force a large increase in the angle for the grazing collisions. If the direct emission becomes more forward peaked at near barrier energies than at higher energies one might infer that high velocity particles traverse the nucleus similar to the "promptly emitted particle" mechanism.⁵¹ In that case the source of cluster emission (e.g. ^2H , ^3H , ^4He ...) is both very puzzling and interesting. The similarity

of the angular distributions for protons and all the other light charged particles is consistent with a single mechanism for their production.

For the evaporative H/He emission it would be very interesting to obtain more extensive coincidence data (with fission,^{1,2} deeply inelastic reactions³⁰⁻³⁴ and with specific residual nuclei¹⁹ after evaporation). This could allow much more detail in the discussion of the angular momentum deposition for individual exit channels. Experimentation in both of these directions has been undertaken.

V. Summary

We have presented a systematic pattern for light charged particle emission, fission and ER production in several ^{40}Ar reactions. The spectra and angular distributions of H/He are consistent with a low-temperature evaporative component at back angles and a high-temperature direct component at forward angles. Forward-peaked emission of Li, Be, B, C, N, and O was also observed for 340 MeV ^{40}Ar . Fission-like products were observed with a gas ionization detector; their angular distributions approach $1/\sin \theta_{\text{c.m.}}$ for the ^{197}Au target, but become forward-peaked for lighter targets. Energy spectra and cross sections measured in both singles and coincidence modes indicate H/He emission prior to scission.² From the anisotropies in the backward hemisphere one can estimate the rms spin of the emitting nuclei to be ≈ 50 -100. Coincidence measurements for 340 MeV ^{40}Ar show that 200-400 mb of evaporative ^1H and ^4He are emitted in coincidence with fission for all four targets. The large amount of evaporation in competition with fission is difficult to explain with phase space models. The large amount of forward-peaked light charged particles implies significant energy dissipation concurrent with the fast impact period of $\approx 5 \times 10^{-22}$ sec. The presence of a significant number of complex particles ^2H , ^3H , Li ... provides a probe of nucleonic clustering in the very early life of the composite nucleus.

Appendix

In order to obtain an integrated cross section σ_{coinc} for a light particle (L) in coincidence with a heavy fission fragment (H) we must adopt a reaction model and its associated angular distributions. We use the equilibrium statistical model for evaporation of the light charged particle²⁴ followed by that of fission in a plane perpendicular to the spin vector. Our detection of the fission fragment then fixes a reaction plane and the spin of the composite system perpendicular to it. In Ref. 25 the expected angular correlations with respect to the spin vectors were discussed. Here we restate the equation used and the choice of parameters as taken from that study.²⁵ The angular correlation of particle L with respect to this spin vector is $W_{J_0, J_T}(\varphi)$ as given by Eq. 5. Its integration over the directions of the light particle gives $(d\sigma_L/d\Omega_H)$

$$d\sigma_L/d\Omega_H = 4\pi \int_0^{\pi/2} W(\varphi) \sin \varphi d\varphi$$

(6)

$$= 2\pi W(90^\circ) (\pi/\beta_2)^{1/2} \text{erf}(\beta_2^{1/2})$$

where $W(90^\circ)$ is the in plane coincidence cross section $d\sigma_L^2/d\Omega_L d\Omega_H$. Then the integration over all fission fragment directions is made with the assumption of c.m. angular distribution proportional to $1/\sin \theta_H$. We have used values of β_2 determined by fits to the angular distribution as measured in singles (see Table IV). To the extent that fission selects a high-spin fraction of these events we underestimate β_2 . To the extent that our model ignores misalignment of the spin vector from the normal to the reaction plane,³⁶ we overestimate the effective value of β_2 .

From Eq. 4 it is clear that if one seeks to estimate $\langle (J_0 + 1/2)^2 \rangle^{1/2}$ from the measured value of β_2 then he must assign numerical values to J , T , and μR^2 . We have taken the value of μR^2 from empirical studies⁷ of fusion of ^4He and ^1H .

$$\mu R^2 = \mu (1.42 A^{1/3} + R_p \text{ or } R_\alpha)^2 \quad (7)$$

with $R_p = 1.44$ fm and $R_\alpha = 2.53$ fm. The moment of inertia $\mathcal{J}$ was taken to be that of a rigid sphere of radius $1.20A^{1/3}$ fm. The temperature is related to the average energy available for thermal excitation:

$$U = aT^2 \quad (8)$$

with "a" = $(A/10) \text{ MeV}^{-1}$ and

$$U = E^* - \langle \epsilon \rangle - S - E_{\text{rot}} \quad (9)$$

The separation energy of the emitted particle is S and its average kinetic energy is $\langle \epsilon \rangle$

$$\langle \epsilon \rangle \sim B + 2T \quad (10)$$

In Ref. 25 a detailed comparison is made of measured values of β_2 to values calculated by this parametrization, using available data for $^{75}\text{Br}^*$ and $^{117}\text{Te}^*$.^{8,53}

Acknowledgements

This work was supported in part by the Division of Nuclear Physics of the U. S. Department of Energy and by CNRS of France. The staff of the SuperHILAC accelerator at the Lawrence Berkeley Laboratory has been very helpful. We have especially appreciated the data acquisition program written by Creve Maples and the consideration extended to us by R. Stevenson.

- ^a Permanent address: Centre d'Etudes Nucléaires de Bordeaux-
Gradignan, Laboratoire de Chimie Nucléaire
ERA No. 144, Le Haut Vigneau,
33170 Gradignan, France
- ^b Permanent address: Laboratoire de Chimie Nucléaire, Institut
de Physique Nucléaire, B.P. No. 1,
91406 Orsay, France

References

1. J. M. Miller, D. Logan, G. L. Catchen, M. Rajagopalan, J. M. Alexander, M. Kaplan, J. W. Ball, M. S. Zisman and L. Kowalski, Phys. Rev. Lett. 40, 1074 (1978).
2. D. Logan, M. Rajagopalan, M. S. Zisman, J. M. Alexander, M. Kaplan and L. Kowalski, Phys. Rev. C22, 104 (1980).
3. H. Delagrange, D. Logan, M. F. Rivet, M. Rajagopalan, J. M. Alexander, M. S. Zisman, M. Kaplan and J. W. Ball, Phys. Rev. Lett. 43, 1490 (1979).
4. M. Rajagopalan, D. Logan, J. W. Ball, M. Kaplan, H. Delagrange, M. F. Rivet, J. M. Alexander and M. S. Zisman (preprint 1979).
5. H. C. Britt and A. R. Quinton, Phys. Rev. 124, 877 (1961).
6. T. Nomura, H. Utsunomiya, T. Motobayashi, T. Inamura and M. Yanokura, Phys. Rev. Lett. 40, 694 (1978).
7. M. A. McMahan and J. M. Alexander, Phys. Rev. C. 21, 1261 (1980).
8. J. Galin, B. Gatty, D. Guerreau, C. Rousset, U. C. Schlotthauer-Voos and X. Tarrago, Phys. Rev. C9, 1113, 1126 (1974); *ibid* C10, 638 (1974).
9. U. Schröder and J. R. Huizenga, Ann. Rev. Nucl. Sci. 27, 465 (1977).
10. L. C. Vaz and J. M. Alexander, Phys. Rev. C18, 2152 (1978) and (preprint, 1979).
11. J. R. Birkelund and J. R. Huizenga, in Proceedings of the Symposium on Heavy-Ion Elastic Scattering, Rochester, N.Y. 1977 (unpublished); J. R. Birkelund, J. R. Huizenga, J. N. De and D. Sperber, Phys. Rev. Lett. 40, 1123 (1978); J. R. Birkelund, L. E. Tubbs, J. R. Huizenga, J. N. De and D. Sperber, Phys. Rep. 56, 107 (1979).
12. J. Galin, D. Guerreau, M. Lefort and X. Tarrago, Phys. Rev. C9, 1018 (1974); C. Ngô, B. Tamain, J. Galin, M. Beiner, R. J. Lombard, Nucl. Phys. A240, 353 (1975).
13. K. Siwek-Wilczyńska and J. Wilczyński, Phys. Lett. 74B, 313 (1978).
14. B. Sikora, M. Blann, W. Scobel, J. Bisplinghoff and M. Beckerman, Phys. Rev. C. 21, 614 (1980).

15. R. Bimbot, D. Gardès and M. F. Rivet, Nucl. Phys. A189, 193 (1972).
16. T. Inamura, M. Ishihara, T. Fukuda and T. Shimoda, Phys. Lett. 68B, 51 (1977).
17. D. R. Zolnowski, H. Yamada, S. E. Cala, A. C. Kahler and T. T. Sugihara, Phys. Rev. Lett. 41, 92 (1978); H. Yamada, D. R. Zolnowski, S. E. Cala, A. C. Kahler, J. Pierce and T. T. Sugihara, Phys. Rev. Lett. 43, 605 (1979).
18. K. Siwek-Wilczyńska, E. H. duMarchie van Voorthuysen, J. Van Popta, R. H. Siemssen and J. Wilczyński, Phys. Rev. Lett. 42, 1599 (1979).
19. D. G. Sarantities, L. Westerberg, M. L. Halbert, R. A. Dayras, D. C. Hensley and J. H. Barker, Phys. Rev. C18, 774 (1978); K. A. Geoffroy, D. G. Sarantities, M. L. Halbert, D. C. Hensley, R. A. Dayras and J. H. Barker, Phys. Rev. Lett. 43, 1303 (1979).
20. See for example, M. Lefort, J. Physique C5, 57 (1976).
21. H. Delagrangé, A. Fleury and J. M. Alexander, Phys. Rev. C16, 706 (1977).
22. E. Baron, Ph.D Thesis, University of Paris, Orsay, France (1975); E. Baron and B. Delaunay, Phys. Rev. A12, 40 (1975).
23. M. M. Fowler and R. C. Jared, Nucl. Instr. Meth., 124, 341 (1975).
24. T. Døssing, Preprint, 1978.
25. G. L. Catchen, M. Kaplan, J. M. Alexander, and M. F. Rivet, Phys. Rev. C., 21, 940, (1980).
26. W. Norenberg and C. Riedel, Z. Physik A290, 335 (1979); G. J. Mathews and L. G. Moretto, Phys. Lett. 87B, 331 (1979); C. Grégoire, R. Lucas, C. Ngô and B. Schürmann, Saclay Report DPH - N/MF/79/33 (1979) (unpublished).
27. See for example, H. C. Britt, B. H. Erkkila, R. H. Stokes, H. H. Gutbrod, F. Plasil, R. L. Ferguson and M. Blann, Phys. Rev. C13, 1483 (1976).
28. E. K. Hyde, The Nuclear Properties of the Heavy Elements III, Fission Phenomena (Prentice-Hall, Englewood Cliffs, N.J., 1964); V. E. Viola, Nucl. Data A1, 391 (1966).
29. S. Della Negra, H. Gauvin, H. Jungclas, Y. Le Beyec and M. Lefort, Z. Physik A282, 65 (1977); N. H. Lu, D. Logan, J. M. Miller, T. W. Debiak and L. Kowalski, Phys. Rev. C13, 1496 (1976); W. Scobel, H. H. Gutbrod, M. Blann and

- and A. Mignerey, Phys. Rev. C14, 1808 (1976); H. Gauvin, D. Guerreau, Y. Le Beyec, M. Lefort, F. Plasil and X. Tarrago, Phys. Lett. 58B, 163 (1975); B. Tamain, C. Ngô, J. Peter and F. Hanappe, Nucl. Phys. A252, 415 (1978); C. Ngô, J. Peter, B. Tamain, M. Berlander and F. Hanappe, Z. Physik A283, 161 (1977).
30. A. Gamp, J. C. Jacmart, N. Poffé, H. Doubre, J. C. Roynette, and J. Wilczyński, Phys. Lett. 74B, 215 (1978); A. Gamp, H. L. Harney, J. C. Roynette, E. Plagnol, H. Fuchs, H. Doubre, J. C. Jacmart and N. Poffé, Z. Physik A291, 347 (1979).
 31. J. M. Miller, G. L. Catchen, D. Logan, M. Rajagopalan, J. M. Alexander, M. Kaplan and M. S. Zisman, Phys. Rev. Lett. 40, 100 (1978). G. L. Catchen, D. Logan, J. M. Miller, D. Benson, N. H. Lu, T. W. Debiak, M. Rajagopalan, J. M. Alexander, M. Kaplan and M. S. Zisman, Preprint (1979).
 32. J. W. Harris, T. M. Cormier, D. F. Geesaman, L. L. Lee, Jr., R. L. McGrath and J. P. Wurm, Phys. Rev. Lett. 38, 1460 (1977).
 33. R. Albrecht, W. Dünneberger, G. Graw, H. Ho, S. G. Steadman and J. P. Wurm, Phys. Rev. Lett. 34, 1400 (1975); H. Ho, R. Albrecht, W. Dünneberger, G. Graw, S. G. Steadman, J. P. Wurm, D. Disdier, V. Rauch and F. Scheibling, Z. Physik A283, 235 (1977).
 34. G. K. Gelbke, M. Bini, C. Olmer, D. L. Hendrie, J. L. Laville, J. Mahoney, M. K. Mermaz, D. K. Scott and H. H. Wieman, Phys. Lett. 71B, 83 (1977).
 35. T. Ericson and V. Strutinski, Nucl. Phys. 8, 284 (1958); *ibid* 9, 689 (1959).
 36. R. Vandenbosch and J. R. Huizenga, Nuclear Fission, Academic Press, New York (1973).
 37. R. Serber, Phys. Rev. 72, 1114 (1947), and Y. Yariv and Z. Fraenkel, Phys. Rev. C20, 2227 (1979).
 38. M. Blann, Nucl. Phys. A235, 211 (1974). M. Blann, A. Mignerey and W. Scobel, Nukleonika 21, 335 (1976).

39. R. M. Weiner and M. Weström, Phys. Rev. Lett. 34, 1523 (1975).
40. The importance of the various relevant time scales is discussed by D. Agassi, C. H. Ko and H. A. Weidenmüller, Ann. of Phys. 107, 140 (1977) and in press.
41. S. Cohen, F. Plasil and W. J. Swiatecki, Annals. of Physics (N.Y.) 82, 557 (1974).
42. J. R. Nix, Argonne Nat'l. Lab. Rep. ANL/PHY/76-2, Vol. I, (1976).
43. A. Fleury, H. Delagrange and J. P. Dufour, Phys. Rev. C16, 1396 (1977).
44. The sharp cutoff approximation is often used as a guide. See for example Ref. 22 and H. C. Britt, B. H. Erkkila, P. D. Goldstone, R. H. Stokes, B. B. Back, F. Folkmann, O. Christensen, D. Fernandez, J. D. Garrett, G. D. Hagemann, B. Herskind, D. L. Hillis, F. Plasil, R. L. Ferguson, M. Blann and H. H. Gutbrod, Phys. Rev. Lett. 39, 1458 (1977); A. Gavron, Phys. Rev. C21, 230 (1980).
45. P. Dyer, R. J. Puigh, R. Vandenbosch, T. D. Thomas and M. S. Zisman, Phys. Rev. Lett. 39, 392 (1977).
46. D. V. Harrach, P. Glässel, Y. Civelekoglu, R. Männer and H. J. Specht, Phys. Rev. Lett. 42, 1728 (1979) and D. V. Harrach, P. Glässel, Y. Civelekoglu, R. Männer, H. J. Specht, J. B. Wilhelmy, H. Freiesleben and K. D. Hildenbrand, International Symposium on Physics and Chemistry of Fission Julich Germany, May 1979, (paper IAEA-SM-241/D4).
47. N. Bohr, Science 86, 161 (1937).
48. S. Agarwal, Ph.D Thesis, University of Paris, Orsay, France 1980.
49. L. G. Moretto, J. Galin, R. Babinet, Z. Fraenkel, R. Schmitt, R. Jared and S. G. Thompson, Nucl. Phys. A259, 173 (1976).
50. I. Halpern. Ann. Rev. Nucl. Sci. 21, 245 (1971).
51. J. P. Bondorf, J. N. De, A. O. T. Karvinen, G. Fai and B. Jakobsson, Phys. Lett. 84B, 162 (1979).

52. L. C. Vaz and J. M. Alexander, Phys. Rev. C. 18, 833 (1978); J. M. Alexander, H. Delagrange and A. Fleury, Phys. Rev. C12, 149 (1975).
53. R. C. Reedy, M. J. Fluss, G. F. Herzog, L. Kowalski and J. M. Miller, Phys. Rev. 188, 1771 (1969).
54. Recently γ ray multiplicities have been measured for several fission reactions induced by heavy ions e.g. $^{16}\text{O} + ^{208}\text{Pb}$ and ^{181}Ta , J. W. Ball, A. F. Dalmanian, S. Gazes, A. P. Smith, S. G. Steadman, F. Videback, G. R. Young, Private Communication and Bull APS 24, 696 (1979). Typically the γ ray multiplicities are ≈ 8 per fission event which indicates that only a small fraction of the spin of the fissile nucleus is converted into the spins of the fission fragments. The oft-used sticking model also implies only small spins on the fission fragments. With these considerations we feel that isotropy is a good approximation to the angular distribution expected for H/He evaporation from fission fragments.

Table I

Parameters that describe the energy spectra for ^1H and ^4He

E_{lab} (MeV)	Target	^4He				^1H			
		$\theta_{\text{c.m.}}$ (deg)	ϵ_{mp}^a (MeV)	FWHM ^a (MeV)	T (MeV)	$\theta_{\text{c.m.}}$ (deg)	ϵ_{mp}^a (MeV)	FWHM ^a (MeV)	T (MeV)
220		142	-	-	2.09 ± 0.05	134	$8.5 \pm 1.$	$9.2 \pm 2.$	1.77 ± 0.02
		31	$19.9 \pm 1.$	$12.8 \pm 2.$	$3.76 \pm .3$	44	$8.2 \pm 1.$	$7.6 \pm 2.$	$1.85 \pm .08$
271	^{116}Sn	147	$20.3 \pm 1.$	$10 \pm 2.$	$2.76 \pm .05$	163	$9.3 \pm 1.$	8.9 ± 2	$2.03 \pm .05$
		32	$20.2 \pm 1.$	$13.3 \pm 2.$	$5.63 \pm .19$	30.5	$8.8 \pm 1.$	$11.5 \pm 2.$	$3.31 \pm .28$
339		155	$19.5 \pm 1.$	$9. \pm 1.$	$3.04 \pm .11$	153	9.4 ± 0.5	8.8 ± 0.5	$2.18 \pm .03$
		19	$27.2 \pm 1.$	$30. \pm 1.$	6.45 ± 0.3	18	$11.4 \pm 1.$	$12.2 \pm 1.$	4.0 ± 0.1
		6.5	$27.5 \pm 1.$	$31 \pm 1.$	7.0 ± 0.2	6	11.2 ± 0.5	$12.6 \pm 1.$	3.56 ± 0.15
221		135	$19. \pm 1$	10.3 ± 2	2.29 ± 0.30	132.5	$9.3 \pm 1.$	$9.6 \pm 2.$	1.75 ± 0.30
		30	23.5 ± 1	15.2 ± 2	6.00 ± 0.50	29	9.3 ± 1	9.6 ± 2	3.41 ± 0.50
272	^{154}Sm	163	20.7 ± 1	11.7 ± 2	2.69 ± 0.30	162	9.8 ± 1	10.8 ± 2	2.2 ± 0.3
		30	23.5 ± 1	16.6 ± 2	5.61 ± 0.5	29	10.3 ± 1	10.4 ± 2	4.0 ± 0.5
340		153.5	$20.35 \pm .5$	$9.3 \pm 1.$	$2.86 \pm .11$	151	$10.5 \pm .5$	$9.8 \pm 1.$	$2.21 \pm .05$
		18	$29.8 \pm 1.$	$29.6 \pm 1.$	7.0 ± 0.3	18	$13.6 \pm 1.$	$13.3 \pm 1.$	3.8 ± 0.5
		6	$32.5 \pm 1.$	$35.0 \pm 1.$	6.68 ± 0.25	6	14.1 ± 0.5	$13.8 \pm 1.$	4.1 ± 0.2
221		134	19.3 ± 1	11.4 ± 2	$2.12 \pm .10$	133	-	-	$1.57 \pm .11$
		29	25.2 ± 1	16.2 ± 2	$5.41 \pm .16$	28	10.3 ± 1	11.4 ± 2	$3.31 \pm .29$
272	^{164}Dy	152	21.9 ± 1	12.2 ± 2	$2.70 \pm .10$	142	9.8 ± 1	11 ± 2	$2.04 \pm .10$
		30	25.6 ± 1	16.8 ± 2	$5.66 \pm .30$	42.8	9.1 ± 1	12.2 ± 2	$3.13 \pm .36$
339		153	21.2 ± 0.5	$10. \pm 1.$	$2.57 \pm .10$	151	9.5 ± 0.5	$10.2 \pm .5$	$2.37 \pm .06$
		49	19.6 ± 0.5	$16.5 \pm 1.$	4.64 ± 0.14	46.	$10.2 \pm 1.$	$11.3 \pm 1.$	2.47 ± 0.09
219		138	21.2 ± 1	15.8 ± 2	-	137	-	-	2.29 ± 0.30
		29	27.2 ± 1	16.7 ± 2	$5.78 \pm .22$	27	$11.1 \pm 1.$	12.6 ± 2	$3.93 \pm .48$
270	^{197}Au	162	22.6 ± 1	14.5 ± 2	$2.87 \pm .23$	161	-	-	$1.87 \pm .10$
		29	27.3 ± 1	16.4 ± 2	$6.91 \pm .38$	28.	11.2 ± 2	12.5 ± 3	$4.05 \pm .22$
339		150	$23.0 \pm 1.$	$11. \pm 2.$	$2.4 \pm .2$	150	$12. \pm 1.$	$12. \pm 2$	$2.5 \pm .2$
		18	$27.4 \pm 1.$	$21.9 \pm 2.$	6.4 ± 0.5	17	13.6 ± 0.5	$12.7 \pm 1.$	3.4 ± 0.3
		6	$25.4 \pm 1.$	$18.6 \pm 1.$	8.5 ± 0.5	6	12.8 ± 0.5	$13.8 \pm 1.$	3.55 ± 0.11

^a The full width at half maximum is FWHM and its midpoint is ϵ_{mp} . For those cases with no entry the spectrum did not fall to half height at low energies and therefore FWHM could not be fixed.

Table II

Integrated charged particle cross sections (mb)

E _{lab} (MeV)	Target	Symmetric				Forward peaked			
		⁴ He	¹ H	² H	³ H	⁴ He	¹ H	² H	³ H
185	¹¹⁶ Sn	194	453	9.1	2.5				
220		315	628	19.7	3.7	93 ^a	31	7.1	2.1
271		555	956	57.4	17.7	228 ^a	155	21.6	7.6
339		1158	1697	155	56.6	495 ^a	466	75	21.6
221	¹⁵⁴ Sm	77	73.5	6.7	2.9	83 ^a	90	8	2.3
272		232	242	31.4	15.6	195 ^a	123	18.3	7.3
340		624	703	108	66	566 ^a	392	77	36
221	¹⁶⁴ Dy	56.4	91.4	4.8	2.1	151 ^a	151	14.3	3.3
272		176	205	24.7	13.7	235 ^a	190	21.8	9.5
340		478	553	83	46.5	386 ^a	251	45	26.5
219	¹⁹⁷ Au	18.8	31.7	1.7	0.90	58 ^a	54	6.6	1.4
270		96	106	11.8	7.7	122 ^a	83	10.5	3.9
339 ^c		359	386	50	33	204 ^a	127	29	13
Detection threshold (MeV, lab)		8	2	3	3	14-18 ^b	3-5 ^b	5-6 ^b	6-7 ^b
Forward peaked									
		Li	Be	B	C	N	O		
339	¹¹⁶ Sn	7.2	2.8	2.4	2.1	0.45	0.19		
	¹⁵⁴ Sm	11.6	2.9	4.1	4.1	1.1	0.4		
	¹⁶⁴ Dy	7.5	2.8	2.5	2.7	0.47	0.18		
	¹⁹⁷ Au	3.2	1.1	0.94	1.11	0.21	0.17		
Detection threshold (MeV, lab)		36	57	78	105	125	160		

^a c.m. energy > 10 MeV for Sn and > 12 MeV for Sm, Dy and Au. Substantial emission was also observed at lower energies for $40^\circ \lesssim \theta_{\text{c.m.}} \lesssim 90^\circ$

^b The variation is due to the different beam stopping foils used

^c Data from Ref. 2 were used along with new data from this work

Table III

Summary of ER and fusion cross sections and evaporative decay fractions

E_{lab} (MeV)	Target [Cnd. sys.]	E^* ^a (MeV)	σ_{ER} ^b (mb)		l_{ER} (ℓ)	$\sigma_{fission}$ ^c (mb)		σ_{fusion} (mb)	l_{crit} ^d (ℓ)	Cumulative decay fractions ^e					
										¹ Li	² Li	³ Li	⁴ He	ER	Fission
185	¹¹⁶ Sn [¹⁵⁶ Er]	75	538	+ 50	57 + 3	162 + 20	700 + 70	65 + 3	0.65	0.013	0.004	0.28	0.77	0.23	
220		102	423	+ 42	55 + 3	406 + 41	529 + 83	77 + 5	0.76	0.024	0.0045	0.38	0.51	0.49	
271		141	335	+ 28	54 + 2	503 + 74	538 + 102	86 + 6	1.14	0.068	0.021	0.66	0.40	0.60	
339	¹⁵⁴ Sm [¹⁹⁴ Hg]	190	416	+ 38	68 + 3	707 + 61	1423 + 100	112 + 5	1.51	0.14	0.050	1.03	0.37	0.63	
221		101	86.3	+ 27	26 + 1.5	754 + 64	840 + 74	83 + 4	0.087	0.008	0.0035	0.092	0.10	0.90	
272		142	79	+ 18	28 + 1	919 + 92	998 + 102	101 + 6	0.24	0.031	0.016	0.23	0.08	0.92	
340	¹⁶⁴ Dy [²⁰⁴ Po]	195	124	+ 16	39 + 2.5	1439 + 307	1563 + 323	142 + 15	0.45	0.069	0.042	0.40	0.08	0.92	
221		96	13.2	+ 4.2	10 + 1.6	852 + 75	875 + 80	86 + 4	0.10	0.0055	0.0024	0.064	0.015	0.985	
272		137	18.7	+ 6	13 + 2	949 + 71	968 + 77	101 + 4	0.21	0.025	0.014	0.18	0.019	0.98	
339	¹⁹⁷ Au [²³⁷ Bk]	190	31	+ 6	19 + 2	1194 + 207	1225 + 215	127 + 11	0.45	0.068	0.038	0.39	0.025	0.975	
219		64	-	-	-	518 + 46	518 + 46	68 + 4	0.061	0.0033	0.0017	0.036	-	1.0	
270		107	-	-	-	794 + 142	794 + 142	94 + 8	0.13	0.015	0.0097	0.12	-	1.0	
339		161	-	-	-	1577 + 208	1577 + 208	149 + 10	0.24	0.031	0.021	0.23	-	1.0	

^a Excitation of hypothetical compound nucleus with no rotational energy^b From the equation $\sigma_{ER} = \pi \lambda^2 (l_{ER} + 1)^2$ ^c Estimated as described in the discussion of Fig. 4^d From the equation $\sigma_{fusion} = \pi \lambda^2 (l_{crit} + 1)^2$ ^e Evaporative H or He or ER or fission cross section divided by the fusion cross section

Table IV

Summary of anisotropy parameters, J_{rms} for the emitters
and integrated coincidence cross sections

E_{lab} (MeV)	Target	β_2^a	J_{rms}^b ($\hbar$)	$d^2\sigma/d\Omega_C d\Omega_S^c$ (mb/Sr ²)	σ_{coinc}^d (mb)	
^4He						
220	^{116}Sn	1.49 ± 0.57^e	52 ± 12^e			
271		1.98 ± 1.03	65 ± 17			
339		1.70 ± 0.70	66 ± 13	3.50	232	$\pm 82^f$
272	^{154}Sm	1.58 ± 0.84	74 ± 17			
340		1.89 ± 0.55	89 ± 13	4.3	287	± 94
272	^{164}Dy	1.33 ± 0.62	73 ± 16			
339		1.05 ± 0.57	72 ± 27	4.4	406	± 48
270	^{197}Au	0.28 ± 0.28	38 ± 19			
339		1.11 ± 0.58	82 ± 20	2.8^g	252^g	
^1H						
339	^{116}Sn	0.95 ± 0.82	97 ± 40	4.4	356	± 85
340	^{154}Sm	0.78 ± 0.39	115 ± 20	4.0	348	± 49
272	^{164}Dy	0.19 ± 0.19	60 ± 30			
339		-	60	3.0	346	± 39
339	^{197}Au	0.98 ± 0.69	140 ± 40	1.6^g	145^g	
^2H						
220	^{116}Sn	1.48 ± 0.65	67 ± 14			
271		1.89 ± 1.11	82 ± 20			
339		2.50	-	0.55	34	± 17
340	^{154}Sm	1.04 ± 0.42	92 ± 18	0.85	71	± 20
339	^{164}Dy	0.50 ± 0.45	70 ± 31	0.54	53	± 24
339	^{197}Au	1.49 ± 1.00	124 ± 35			
^3H						
339	^{116}Sn	2.88	-	0.20	11.3	± 2.3
272	^{154}Sm	0.76 ± 0.51	55 ± 18			
340		0.97 ± 0.42	68 ± 14	0.28	24	± 16
339	^{164}Dy	0.75 ± 0.51	64 ± 20	0.32	29	± 25
339	^{197}Au	0.76 ± 0.76	72 ± 36			

^a From fits of Eq. 2 to data in Fig. 3

^b See discussion of Eq. 4 and Ref. 25 for tests of the parameters used

^c The average of the c.m. cross section observed for the three configurations in Fig. 6

^d From the integration of Eq. 5 as described in the appendix and in Ref. 25

^e Uncertainties estimated from maximum and minimum values of β_2 that give an acceptable fit (by eye) to the data in Fig. 3

^f Uncertainty from reproducibility of $d^2\sigma/d\Omega_C d\Omega_S$ only

^g Data from Ref. 2, normalized to singles data from this work by the factor 0.71

Table V

Flow chart for singles and coincidence cross sections (mb)

for 340 MeV $^{40}\text{Ar} + \text{X}^a$

	^{116}Sn		^{154}Sm		^{164}Dy		^{197}Au	
$\sigma_R (L_{\text{max}})$	2483	(168)	2565	(180)	2530	(179)	2407	(180)
$\sigma_{QE} + \sigma_{DI}$	1360		1002		1305		830	
Direct	{ 495 (^4He) 97 ($^{2,3}\text{H}$)	466 (^1H)	566 (^4He)	392 (^1H)	386 (^4He)	251 (^1H)	204 (^4He)	127 (^1H)
		15 (L1-0)	113 ($^{2,3}\text{H}$)	24 (L1-0)	71 ($^{2,3}\text{He}$)	16 (L1-0)	42 ($^{2,3}\text{H}$)	7 (L1-0)
$\sigma_{CF} (L_{\text{crit}})$	1123	(112)	1163	(142)	1225	(127)	1577	(149)
Evaporative (J _{rms})	1158 (^4He) (66)	1697 (^1H) (100)	624 (^4He) (29)	703 (^1H) (115)	478 (^4He) (72)	553 (^1H)	359 (^4He) (82)	386 (^1H) (140)
Evaporative in coincidence with fission	{ 232 (^4He)	356 (^1H)	287 (^4He)	348 (^1H)	406 (^4He)	346 (^1H)	252 ^a (^4He)	145 ^a (^1H)
Fission	707		1439		1194		1577	
Evaporative but not in coincidence with fission	{ 924 (^4He)	1341 (^1H)	337 (^4He)	355 (^1H)	72 (^4He)	207 (^1H)	107 ^a (^4He)	241 ^a (^1H)
$\sigma_{ER} (L_{2R})$	416	(68)	124	(39)	31	(19)	0	(0)

^a These results include additional and updated results compared to those reported at the International Conference on Continuum Spectra, San Antonio, Texas, 1979

Figure Captions

- Fig. 1 - Singles energy spectra (c.m.) for ^4He and ^1H at various angles. The average c.m. angle is indicated and the corresponding multiplier is on the same horizontal line. Parameters describing the spectra are given in Table I, and one indication is shown for ϵ_{mp} .
- Fig. 2 - Spectra for ^4He at a forward and a backward angle and their difference.
- Fig. 3 - Measured angular dependence of $(d\sigma/d\Omega)$ and T for ^4He and ^1H . The incident energies are indicated at the upper left. Different symbols are for different experiments; filled triangles are from Ref. 2. See Table II and its footnotes.
- Fig. 4 - Angular distributions for the fission-like products (upper) and for Li, Be, B, C, N, O (lower). Energy thresholds and integrated cross sections are given in Table II.
- Fig. 5 - Example of an isotope distribution of the particles with $3 < Z < 8$. The number of events is plotted versus the value of the "particle identifier function", PI: $PI = [(E_2 + E_1)^{1.73} - E_2^{1.73}] / e_1$. (E_1 and E_2 are the energies deposited in the first and second members of the SST; e_1 is the thickness, in μm , of the first detector.) Mass number and percentage occurrence are indicated for each species.
- Fig. 6 - Spectra for ^4He and ^1H in singles and in coincidence with one heavy fragment (with the laboratory configuration as shown). The smooth curves were calculated by a Monte Carlo kinematic simulation for evaporation for the fission fragments. (A) $^{40}\text{Ar} + ^{154}\text{Sm}$. (B) $^{40}\text{Ar} + ^{116}\text{Sn}$.
- Fig. 7 - Integrated cross sections at three excitation energies for fusion, fission, ^4He , ^1H and ER vs charge of the composite nucleus, Z_{CN} . Data for a target of ^{77}Se are from Ref. 8. Data for ^{116}Sn , ^{154}Sm and ^{164}Dy were taken directly from the measurements; those for ^{197}Au were interpolated and extrapolated to the indicated excitation energies (see Table III).

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6A

Fig. 6B

Fig. 7

CHARGED PARTICLE EMISSION FROM ^{194}Hg COMPOUND NUCLEI:
ENERGY AND SPIN DEPENDENCE OF FISSION-EVAPORATION COMPETITION

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

D. Logan, Jane W. Ball and Morton Kaplan
Department of Chemistry
Carnegie-Mellon University
Pittsburgh, Pennsylvania 15213

Hugues Delagrangé,^a M. F. Rivet,^b John M. Alexander and Louis C. Vaz
Department of Chemistry
State University of New York at Stony Brook
Stony Brook, New York 11794

and

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

Abstract

Twelve reactions have been studied that produce the compound system $^{194}\text{Hg}^*$ over the excitation energy range 57-195 MeV. Beams of ^{12}C , ^{19}F , ^{20}Ne and ^{40}Ar ions in conjunction with appropriate targets have been used to measure cross sections for evaporative H/He, fission and evaporation residues (ER). Most ^1H and ^4He seem to be evaporated prior to fission or instead of fission and very little if any from the fission fragments. The probability of H/He evaporation increases dramatically with excitation energy and extends to very large spins ($\geq 60 \hbar$). The fission competition becomes decidedly weaker for excitation ≥ 100 MeV, and a connection with charged particle evaporation is suggested. The dimensionless cross section for ER ($\sigma_{\text{ER}}/\pi\chi^2$) depends on both the entrance channel and on energy, indicating that non-equilibrium mechanisms must play an important role. Heretofore ER production has been usually thought to arise from the lower partial waves while direct reactions are dominant only for the higher partial waves.

I. Introduction

Reactions between complex nuclei often give rise to intermediate transient systems with very high spins and excitation energies. Their subsequent deexcitation involves competition between fission and evaporation of neutrons, protons, alpha particles, etc. and finally γ -ray emission.¹⁻³ In order to probe the mechanisms of mass, energy, and angular momentum transfer in deeply inelastic reactions, measurements have been and are being made of the energy and angular distributions of these emitted nucleons, particles and γ -rays.⁴ The interpretation of such measurements requires a great deal of information about the statistical properties of excited nuclei.⁵ Systematic studies of reactions that proceed via the complete-fusion mechanism are the primary sources of this information. Projectiles of intermediate mass (e.g. ^{12}C , ^{40}Ar etc.) have been shown to be most effective for forming the equilibrated compound systems that are needed.

Our group has made a series of studies⁶⁻⁹ of the reactions of Au with ^{40}Ar , ^{86}Kr and ^{136}Xe . Often highly excited target-like fragments Au^* have been formed and their decay observed via H/He emission or sequential fission. In order to better understand these observations we have embarked on a parallel series of studies of fission-evaporation competition in compound-nucleus reactions by measuring cross sections for fission, H/He emission, and evaporation residues.^{10,11} We have selected the compound system $^{194}\text{Hg}^*$ as typical of Au^* and easily produced by many target-projectile combinations. In this paper we follow up an earlier letter¹⁰ with a phenomenological analysis of the cross-section data. In a separate communication¹¹ we

discussed, for the ^{40}Ar reactions, the more extensive pattern of the fusion cross sections and the direct emission of H/He. Also separately we will present information on the energy spectra observed in the various reactions and make comparisons to statistical-model calculations.

We have followed the established strategy of forming the same compound nucleus through several entrance channels.¹² As we determine the cross sections for fusion (evaporation residues plus fission) along with those for evaporative H/He emission, we obtain a pattern of the cumulative decay fractions (CDF) for $^{194}\text{Hg}^*$ vs the initial excitation energy and average spin. This pattern has intrinsic value for improving our understanding of nuclear deexcitation, testing the applicability of equilibrium theory at high energies and a particular supplementary value for assisting in the interpretation of studies of deeply inelastic reactions.

II. Experimental arrangements

Beams of ^{12}C , ^{19}F and ^{20}Ne have been provided by the 88-inch cyclotron and ^{20}Ne and ^{40}Ar by the SuperHILAC at the Lawrence Berkeley Laboratory. Self supporting targets of ^{182}W , ^{175}Lu , ^{174}Yb and ^{154}Sm were used and their thicknesses measured by comparison of the elastic scattering with that from an Au target of known thickness (determined by weight and alpha-particle energy-loss measurements). Fission and evaporation residue (ER) products were measured by a gas-ionization telescope¹³ (GT) (≈ 20 torr of methane and 300 μm Si stopping detector) and H/He by a solid state telescope (SST) (45 μm , 500 μm , 5 mm Si detectors). The GT (solid angle 0.1 to 0.2 msr) could

be used at angles as small as 3° to the beam for ER measurements. Often a second GT (1 - 2 msr) was used for fission product measurements. For measurements of H/He in the SST (3 - 10 msr) the back angles were emphasized to test for evaporative decay. For angles larger than the grazing angle only thin cover foils (0.2 - 10 mg/cm² Au or Pb) were used for the SST, and the laboratory energy thresholds were ≈ 2 and ≈ 8 MeV for ^1H and ^4He respectively.

In the more recent experiments (^{40}Ar and ^{20}Ne beams) we mounted two GT's and two to four SST's in the reaction chamber together and recorded data from four or five of these simultaneously. Irradiation times and intensities were planned primarily for measurements in the singles mode (several hundred ER events per run, hundreds to thousands of fission events per run, three to twenty thousand H and He per run). Often coincidences between fission and H/He were also recorded and provided some crude limits on the abundance of evaporation-fission cascades.

III. Experimental Results

The general features of the observed energy and angular distributions for H/He have been given elsewhere.^{8-12,14,15} Very similar behavior has been observed for all the reactions studied; namely there is strong forward peaking and enhancement of high energy emissions at the forward angles, and at backward angles the angular distributions become flat or slightly backward peaked. In Fig. 1 some energy spectra are shown for ^{12}C and ^{19}F reactions, and in Refs. 9 and 11 some results are shown for ^{40}Ar reactions. Comparisons of these spectra show that for a given reaction their shapes are essentially independent of angle (for $\theta_{\text{c.m.}} > 100^\circ$). Also the spectral

shapes are almost independent of target projectile combinations for a given excitation energy of the compound nucleus. These features indicate that these H/He emissions are from essentially equilibrated systems. Therefore we assume complete equilibration and fit the back-angle differential cross sections to an equation from the statistical model.¹⁶

$$W(\theta_{c.m.}) = W_0 \exp[(\beta_2/2) \sin^2(\theta_{c.m.})] I_0 [(\beta_2/2) \sin^2(\theta_{c.m.})] \quad (1)$$

where W_0 and β_2 are free parameters and I_0 is the zeroth order modified Bessel function. Only for some of the ^{40}Ar reactions was the anisotropy parameter β_2 determined well enough to warrant any discussion.¹¹ In this work we have sought only the angle and energy integrated evaporative component. For ^{40}Ar induced reactions the large c.m. velocity, along with the detection threshold, cut off the low-energy part of the spectra for $\approx 140^\circ - 160^\circ$. We have estimated a correction for this effect from the more completely measured spectra at $\approx 120^\circ$; this correction was never more than 10%. In Table I the H/He cross sections represent the evaporative components only, as obtained by integration of Eq. (1) after fitting to our experimental data. The major source of uncertainty in these evaporative cross sections for ^4He and ^1H is attributable to the assignment and separation of the evaporative component. This uncertainty is largely systematic in its nature and is thus difficult to assign. Our best guesses are given in footnotes to Table I. Associated uncertainties in the ratios of ^4He to ^1H and the cumulative decay fractions are probably significantly smaller due to various error

cancelations.

For reactions induced by ^{12}C , ^{19}F and ^{20}Ne , the fission component was easily identified on a contour plot (GT) of ΔE vs E . For ^{40}Ar beams these contour plots are known to be complicated by projectile-like fragments and target-like fragments from deeply inelastic reactions.¹⁷ Nevertheless we have assigned a zone on the $\Delta E - E$ maps to fission-like fragments; this zone clearly excludes ER and quasi elastic reaction products, but could include some deeply inelastic reaction products. In Ref. 11 we show angular distributions for these fission-like events from ^{40}Ar induced reactions. Presumably the inclusion of some deeply inelastic reactions leads to the observed increase of the values of $d\sigma/d\theta$ at small angles. For $\langle\theta_{\text{c.m.}}\rangle \approx 90^\circ$ one finds many fewer products similar to the projectile and the singles energy spectra of heavy fragments clearly resolve into two components.¹¹ The low-energy target-like products are well separated in energy from a broad peak for products of intermediate mass. In this angular region we feel that fission can be more easily identified and we have therefore estimated the fission cross section consistently for all the reactions by interpolating $d\sigma/d\Omega$ to $\langle\theta_{\text{c.m.}}\rangle = 90^\circ$ and multiplying by $2\pi^2$ (i.e. we assume $d\sigma/d\Omega \propto 1/\sin\theta_{\text{c.m.}}$).⁹⁻¹¹

Our raw experimental data for the determination of ER cross sections are much the same as those reported by many other workers who have used gas telescopes. (See Ref. 18 for an extensive set of original references.) An extrapolation (comprising 20 - 40% of the cross section) had to be made from 3° or 4° to 0° . This extrapolation and other random experimental errors lead to absolute uncertainties of $\approx 25\%$ for the integrated ER cross sections. The relative uncertainties are of course, much smaller. For the ^{12}C reactions the recoil energies for the ER products approach the energy threshold for the GT and any incomplete

fusion would probably not be included.^{8,10} We will discuss this point more fully in the next section. For the two lowest energy ^{40}Ar reactions the ER locus comes very close to that for the slit scattering of low-energy ^{40}Ar . For these cases there is a possibility that some of the ER products were obscured and omitted from the cross sections we report. This is an important experimental point to try to clarify as will become clear in the next section. At somewhat lower energies Stokstad et al.¹⁹ report much larger ER cross sections than we find for $^{40}\text{Ar} + ^{154}\text{Sm}$.

Table I presents a summary of the cross sections for evaporation residues, fission, and evaporative H and He. Some of these results were presented earlier^{10,11} and a few have been modified slightly by averaging with more recent determinations. Fusion cross sections are taken as the sum of fission and evaporation residues. The cumulative decay fraction (CDF) for each product is simply its cross section divided by the fusion cross section (σ_{cf}). The values of the critical l for fusion (l_{crit}) and for evaporation residues (l_{ER}) were obtained from the sharp cutoff equations

$$\sigma_{cf} = \pi \lambda^2 (l_{crit} + 1)^2 \quad (2)$$

and

$$\sigma_{ER} = \pi \lambda^2 (l_{ER} + 1)^2, \quad (3)$$

Energy and spin dependence of these quantities is discussed in the next section. The values of σ_{cf} or σ_{ER} divided by $\pi \lambda^2$ can, of course, be considered as dimensionless cross sections with much greater significance than implied by the term "sharp cutoff model." One might say

that l_{crit} (or l_{ER}) represents the effective number of partial waves that must be involved in fusion (or ER) reactions, with the understanding that higher partial waves may also be involved but with decreasing probability.

As mentioned before and in Ref. 10, our coincidence data are of limited statistical significance. Nevertheless we are able to set an upper limit of $\sim 5\%$ on the fraction of fission in coincidence with H/He for 121 MeV ^{12}C and 135 MeV ^{19}F . This upper limit precludes a significant contribution from H/He evaporation before fission or from the fission fragments for these cases. For the higher energies, however, a significant fraction of the H/He evaporation can be accompanied by fission. For example, for 340 MeV $^{40}\text{Ar} + ^{154}\text{Sm}$ more than half the evaporated ^1H and ^4He are found to be in coincidence with fission.¹¹ It is important to establish whether these emissions occur from the fission fragments or from the reaction complex prior to scission. There are three pieces of evidence that indicate the heavy predominance of pre-scission H/He evaporation.^{9,11} (1) The energy spectra for ^1H and ^4He in coincidence with a fission product do not exhibit the kinematic shifts expected for evaporation from moving fission fragments. Instead they are very similar to the spectra in the singles mode. (See Fig. 6 in Ref. 11). (2) The ratios of ^4He to ^1H are very large (> 0.6) for all the reactions leading to $^{194}\text{Hg}^*$. Such ratios would imply unreasonably large spins if emission was from a fission fragment (see the discussion of Fig. 4 later). (3) The shapes of the observed singles spectra, especially for ^4He , are quite different from those calculated from a kinematic simulation of evaporation from fission fragments. Fig. 2 shows

the comparison for one case. The smooth curves for the kinematic simulations are invariably broader than the measured spectra and are steeper at high energies. This is a general result of the random vector additions of the velocities of fission fragment and evaporated particle. All the measured singles spectra have shapes typical of evaporation from a compound nucleus as shown in Fig. 1 and Refs. 9 and 11. These shapes cannot be reconciled with evaporation from the moving fragments. Even though we do not have coincidence data for all the reactions studied here, arguments (2) and (3) above convince us that in general H/He emission from the composite system $^{194}\text{Hg}^*$ predominates over emission from fission fragments.

IV. Discussion

A. Some comparisons to other work

In Fig. 3 we show excitation functions for the various observed products for one reaction system, $^{12}\text{C} + ^{182}\text{W}$. Our lowest incident energy, 77 MeV, is well above the barrier so the fusion cross section mounts relatively slowly with increasing energy.¹⁸ The balance between fission and ER formation is, however, very strongly energy dependent. Our fission cross sections near 120 MeV are $\approx$ 20% smaller than the previous measurements of Sikkeland et al.²⁰; near 80 MeV we are in reasonable agreement with both Ref. 20 and with recent data from Chalk River.²¹ Excitation functions for fission of $^{194}\text{Hg}^*$ and some lighter compound systems have been analyzed previously by use of the equilibrium statistical model.²²⁻²⁵ Our addition of data for evaporation residues and light charged particle evaporation brings some interesting new constraints for such an analysis. We will

make some comments on these constraints later but first let us consider the phenomenology of fusion and the spin and energy dependence of the cross sections.

B. Complete and incomplete fusion and the postulate of a critical distance.

In Refs. 8 and 11 we have discussed the conceptual problems that may result from the combined presence of complete and incomplete fusion reactions. For the data given in Table I, the values of σ_{CF} probably include both these processes for ^{19}F , ^{20}Ne and ^{40}Ar induced reactions¹¹ and probably exclude most incomplete fusion for 77 - 121 MeV ^{12}C .¹⁰ Therefore, it is not evident what constitutes a meaningful comparison of our apparent fusion cross sections to the available semiempirical correlations. Nevertheless in Table II we do make the comparison of the measured fusion cross sections to those calculated by the critical distance postulate.²⁶⁻²⁹ The calculated cross sections all employ a critical radius of $1.00 (A_t^{1/3} + A_p^{1/3})$ fm and a point charge coulomb potential. There is rather little dependence of the calculated values on the choice of nuclear potential used or (for the proximity potential) on its empirical adjustments (see footnote to Table II). The measurements for ^{19}F , ^{20}Ne and ^{40}Ar projectiles are all rather close to the calculated values. However for ^{12}C the measured cross sections, especially at the lower energies, are much smaller than those calculated. The recoil energies for the heavy residuals are lowest for the ^{12}C induced reactions, and thus they would be most easily cut out by the detection threshold. Any forward-peaked light particle accompanying a partial

fusion reaction could easily take away enough momentum to exclude the heavy recoil from detection. The heavier projectiles (^{19}F , ^{20}Ne and ^{40}Ar) have considerably greater momenta and such momentum leaks would have much less chance of eliminating their associated incomplete fusion residues from detection.^{8,10}

Our inference from these considerations is that, for ^{19}F , ^{20}Ne and ^{40}Ar induced reactions, we detect complete plus incomplete fusion and that for ^{12}C we omit the latter. Correspondingly the empirical r_{crit} value of 1.0 fm has probably been established by data that include both complete and incomplete fusion.²⁶ Therefore this postulate predicts our results rather well for all but ^{12}C reactions where the measurements may well eliminate the incomplete fusion. This is a point of some significance for the use of the critical distance idea to estimate critical angular momenta (ℓ_{crit}) or cross sections for fusion.

C. Procedure for obtaining decay fractions for high-spin domains

In Ref. 12 it has been shown that the Bohr independence hypothesis allows one to separate the cross sections or decay fractions into their parts from various spin domains. With their notation we denote two entrance channels as x and y that lead to $^{194}\text{Hg}^*$ at the same excitation energy. Then let $\sigma_i'(x)$ represent the cross sections for process i (e.g. fission or ^1H or ^4He emission) divided by $\pi\lambda_x^2$ and $T_J(x)$ the transmission coefficient for forming a compound-nucleus of spin J by entrance channel x. Then we have

$$\frac{\sigma_i'(x) - \sigma_i'(y)}{\sigma_{\text{cf}}'(x) - \sigma_{\text{cf}}'(y)} = \frac{\sum_{J=0}^{\infty} (2J+1) W_1(J) [T_J(x) - T_J(y)]}{\sum_{J=0}^{\infty} (2J+1) [T_J(x) - T_J(y)]} = \langle W_1(J) \rangle_{x-y}$$

where the symbol $W_i(J)$ denotes the decay probability for spin J to exit channel i and $\langle W_i(J) \rangle_{x-y}$ is its average value over the region of J for which $T_J(x) - T_J(y) \neq 0$. These cumulative decay fractions or values of $\langle W_i(J) \rangle_{x-y}$ for each high-spin domain are given in Table III. From the sharp-cutoff values of ℓ_{crit} we can approximate the domain of spins for which $T_J(y) < T_J(x)$ and estimate average values $\langle J \rangle$ for each domain (values are given in Table III).

D. The ratio of evaporative ^4He to ^1H

In Fig. 4 we show the observed ratios of evaporative ^4He to ^1H as a function of ℓ_{crit} for $^{194}\text{Hg}^*$ as compared to data for other reaction systems. The results for $^{194}\text{Hg}^*$ and the other rather heavy composite systems ($^{204}\text{Po}^*$ and $^{237}\text{Bk}^*$) are quite different from those for the lighter systems $^{75}\text{Br}^*$ and $^{117}\text{Te}^*$.^{12,15,16} The heavy systems have $^4\text{He}/^1\text{H}$ ratios that are large (>0.5) and only slowly varying with ℓ_{crit} . The lighter ones have $^4\text{He}/^1\text{H}$ ratios that change by twofold as ℓ_{crit} is increased by ≈ 30 n. The system $^{156}\text{Er}^*$ is of intermediate character. We have used these differences as the basis for an argument against H/He emission from fission fragments^{9,11} that we expect to be similar to $^{75}\text{Br}^*$ and $^{117}\text{Te}^*$. This argument assumes that these ratios do not change drastically from the neutron deficient Br and Te systems to the more neutron rich fission products.^{2,9,30} Similarity in the mass dependence for ^1H and ^4He separation energies provide the basis for this assumption.⁹ It should, of course, be tested by experimental measurements.

It is interesting to try to extend the analysis further by using the $^4\text{He}/^1\text{H}$ ratios obtained for the more restricted spin zones (Table III). As these values are derived by taking differences, their un-

certainties are not easy to assign but are surely large. Nevertheless these ratios for $^{194}\text{Hg}^*$ at different excitation energies are for the most part very similar to those measured directly. There is however a weak suggestion of a rapid rise near $\langle J \rangle \sim 70$ for $E^* = 98$ MeV and near $\langle J \rangle \sim 90$ for $E^* = 142$ MeV. The experimental uncertainties do not allow us to be sure that these apparent increases are real. But as they could be a signature of near yrast behavior we mention them as an interesting area for possible future investigation (see Fig 3 in Ref. 30).

E. Evaporation spectra

By the procedure just described one can also attempt to identify the part of the evaporative energy spectrum for ^4He that derives from the emitters of high spin. Recently Blann³¹ has reemphasized that the liquid drop model (RLDM)²⁴ predicts large changes in the equilibrium shapes for very high-spin nuclei. Presumably such changes would be reflected in exit barrier alterations that would lead to substantial changes in the evaporation spectra.³² Also several papers have suggested metastability of a double nuclear complex for entrance channel spins $\gtrsim 80$; such highly deformed systems would also have exit barriers for H/He that would be strongly altered from near spherical compound nuclei.³³ In Fig. 5 we show energy spectra $(d^2\sigma/d\Omega d\epsilon) \cdot (1/\pi\chi^2)$ at back angles for two reactions with a large difference in ℓ_{crit} value. For $E^* = 80$ MeV, both the shapes and magnitudes of the measured spectra are very similar. For $E^* = 194$ MeV the magnitudes are quite different but the shapes are so similar that the shape of the difference spectrum cannot be distinguished from those observed directly. It is possible that compensating changes in the coulomb

barriers and centrifugal spinoff energies could have left the emission spectra unaltered. Superficially this would seem unlikely but a detailed analysis should be performed.

F. Energy and spin dependence of CDF

In Fig. 6 we have plotted the cumulative decay fractions vs average spin $\langle J \rangle$ for ER formation and for ^4He evaporation. The patterns for these two exit channels are very different and are very revealing about the qualitative aspects of fission-evaporation competition. Fig. 7 shows the same data for σ_{ER} plotted in a different way and compared to similar data from other studies.^{17,34-36}

Before addressing these figures directly let us review the oversimplified qualitative statistical model used by many for a first orientation to such data.³⁷ One writes a Boltzmann expression for the width (or decay probability) ratio $\Gamma_f/\Gamma_n \approx \exp[-(B_f(J) - B_n)/T]$ where B_f is the fission barrier and B_n the neutron binding energy and $\Gamma_n \gg \Gamma_p$ or Γ_α . Thus one expects a sharp change in Γ_n/Γ_f at the spin J where $B_f(J) \approx B_n$. Increasing excitation energy E^* raises T (as $E^* \approx a T^2$) and broadens the transition region of spins where fission and evaporation have comparable widths. The liquid drop model (RLDM)²⁴ can be used to estimate $B_f(J)$ (for $^{194}\text{Hg}^*$ RLDM gives $B_f(J=0) \approx 15$ MeV and $J \approx 40$ for $B_f(J) = B_n$). Thus one expects fission to remove the high-spin compound nuclei before any particle evaporation. For the survivors of lower spin the RLDM predicts that B_f decreases as Z^2/A increases, and therefore along a neutron-evaporation cascade the fission barrier will be slightly decreased after each step and fission will slightly deplete the surviving population of evaporation residues.

References 23 and 37 have used this simple, qualitative picture to discuss data on fission and evaporation residues for compound nuclei of $A \approx 150$. The qualitative pattern of the data for their cases and for this $^{194}\text{Hg}^*$ study is quite similar. At first glance the values of l_{ER} (see Table I) seem to vary only slowly with excitation energy or l_{crit} (for entrance channels with $l_{\text{crit}} > l_{\text{ER}}$). The hypothesis of Britt et al.³⁷ was that there must be a very abrupt increase in fission probability for the spin where $B_f(J) = B_n$. Even for the first step of fission-evaporation competition many of the high spin compound nuclei are expected to be removed by fission. Successive steps in the competitive decay also lead to losses to fission of remaining nuclei that are characterised by the highest spins. The low-spin fraction of evaporating nuclei is not expected to be reduced appreciably by the successive fission-evaporation competition, and thus $\sigma_{\text{ER}}/\pi\chi^2$ or l_{ER} should be almost energy independent. This is a very different situation from that for actinide fission where $B_f(J=0) \approx B_n$, and the residual-nucleus population for the whole range of spins is heavily reduced by fission competition at each step.³⁸ Such a reduction in the fission survival population would lead to a steady decrease of σ_{ER} (and the inferred values of l_{ER}) with increasing E^* .

The observed values of σ_{ER} for $^{194}\text{Hg}^*$ present a much more complicated picture from that described above as we can see from the plots in Figs. 6(a) and 7(a). The lower envelope of the data points for σ_{ER} for $^{194}\text{Hg}^*$ in Figs. 6 and 7 is consistent with an energy independent value of l_{ER} for the initial spin for $^{194}\text{Hg}^*$ ($l_{\text{ER}} = 27$). By the above argument fission dominates the decay for initial spins > 27 . However, there are five data points for which the observed ER cross sections are too

large to be reconciled with this idea and an l_{ER} value of 27 (see particularly Fig. 7). For initial excitation of 98 MeV the value of σ_{ER} for 135 MeV ^{19}F seems abnormally large while the 121 MeV ^{12}C and 221 MeV ^{40}Ar reactions seem "normal". For $E^* = 142$ MeV the 272 MeV ^{40}Ar induced reaction seems normal but σ_{ER} or l_{ER} values for 167 MeV ^{12}C and 184 MeV ^{19}F are much larger. For $E^* = 194$ MeV both the ^{20}Ne and the ^{40}Ar reactions give values of σ_{ER} or l_{ER} that seem decidedly large compared to the trend from lower energies (i.e. $l_{ER} = 27$).

It is important to recognize that the variation in these values of l_{ER} or $\sigma_{ER}/\pi\chi^2$ (for fixed E^*) cannot be ascribed to a simple failure of the sharp cutoff approximation. Even if the fission survival probability $P_{ER}(J, E^*)$ is a slowly varying function of spin, we expect $\sigma_{ER}/\pi\chi^2$ to be essentially independent of entrance channel. This expectation follows from the assumption that $P_{ER}(J, E^*)$ is a property of the equilibrated compound nucleus with only small values at high spin but dominant at low spin (e.g. $J < 27$). The fact that $\sigma_{ER}/\pi\chi^2$ (for $E^* = 142$ MeV) is not constant demands that $P_{ER}(J, E^*)$ differ for each entrance channel and that therefore the intermediate transition complex is not fully equilibrated. The two obvious mechanisms that could contribute are as follows: (a) Incomplete fusion reactions may contribute more to ER for ^{12}C and ^{19}F than for ^{40}Ar . (b) Deeply inelastic fission-like reactions may compete with ER production more for ^{40}Ar than for ^{19}F or ^{12}C .³⁹ These possibilities cannot be distinguished, but in any case the results require some mechanism that does not involve complete equilibration, between excitation modes that lead to fission-like decay and those leading to ER production (presumably particle emission).

What about the two high values of $\sigma_{ER}/\pi\lambda^2$ for $E^* = 194$ MeV?

As they are nearly equal, they can be explained by a function $P_{ER}(J, E^*)$ that derives from a fully equilibrated reaction intermediate.

However, it is interesting that λ_{ER} for $E^* = 194$ MeV is significantly larger than most values at lower energies. Here the large evaporation probabilities for H/He may be playing a role. In this situation one might infer that part of the enhancement of σ_{ER} could derive from the large pre-scission and apparently evaporative H/He deexcitation as shown in Fig. 6(b). If the H/He evaporation competes more favorably with fission at high energy, then possibly the fission fraction could be reduced for both ^{20}Ne and ^{40}Ar reactions for $E^* = 194$ MeV.

Assume for the moment that part of this decrease in fissility with increasing λ_{crit} is indeed correlated with the evaporative H/He. Then return to Fig. 6 and compare the λ_{crit} dependence of the cumulative decay fractions (CDF) for ER's to those for ^4He . The values of CDF for ^4He are strongly dependent on both E^* and J . The decrease with increasing spin presumably reflects more extensive fission competition with increasing J . However the mild slope $(d(\text{CDF}_\alpha)/dJ)$ does not reflect an abrupt fission competition and seems too small to be driven by the Boltzmann equation with a spin-dependent fission barrier predicted by the rotating liquid drop model,

$$\Gamma_\alpha/\Gamma_f \sim \exp[-(B'_\alpha - B_f(J))/T] \quad (5)$$

where B'_α is the sum of the binding energy and coulomb barrier energy. For example, CDF_α for $E^* = 142$ MeV falls by only about 20% between spin ≈ 40 and ≈ 80 . For $^{194}\text{Hg}^*$ the RLDM predicts a zero fission barrier for $J = 80$ and thus a very small evaporation probability for any particle.²⁴

The cumulative decay fractions for ^4He increase very rapidly with

increasing excitation energy. One could assume that the pattern of Fig 6(b) is typical of all members of the decay chain (e.g. $^{194}\text{Hg} \rightarrow ^{193}\text{Hg} \rightarrow ^{192}\text{Hg} \rightarrow \text{etc.}$). Presumably, most evaporative decays are via neutron emission with occasional emission of a light charged particle. If we assume that the branching ratios for charged particle evaporation are rather uniformly distributed along each cascade then we can roughly follow the α decay probability for each evaporation step. The nearly vertical series of arrows in Fig. 6 shows a crude estimate of the average α decay fractions (P_α) for each deexcitation step between 194 and 57 MeV. Starting with $E^* = 194$ MeV and $J = 56$ one might assume $\Delta E^* \approx 12$ MeV and $\Delta J \approx 2$ for each emitted particle. Then the values of $\langle P_\alpha \rangle$ are ≈ 0.14 [$\langle P_\alpha \rangle \approx (0.81 - 0.25)/4$] between 194 and 142 MeV, ≈ 0.05 between 142 and 98 MeV, ≈ 0.04 between 98 and 80 MeV and ≈ 0.01 between 80 and zero MeV. For protons all the corresponding numbers are very similar (but somewhat larger).

This strong increase of the H/He evaporation fractions with energy [Fig. 6(b)] may well be correlated with the increase of $\sigma_{\text{ER}}/\pi\lambda^2$ with λ_{crit} and with E^* as shown in Figs. 6(a) and 7. Note that the data used are essentially independent; Figs. 6(a) and 7 use only the fission and ER measurements while 6(b) is mainly based on the ^4He cross sections (albeit normalized by σ_{CF}). Clearly coincidence studies can provide information needed to establish or refute such a suspected correlation. We have not measured coincidences between H/He and ER's, but some data are given in Ref. 11 for coincidences between H/He and fission. For 340 MeV $^{40}\text{Ar} + ^{154}\text{Sm}$ there are ≈ 1300 mb of evaporated $^1\text{H}/^4\text{He}$, more than half of which is in coincidence with fission. The rest of the H/He evaporation could well have provided much of the charge, energy,

and angular momentum loss needed to enhance the survival of these ER products with respect to fission. Possibly a more straightforward test for this effect could be made by measurement of the Z distribution for these ER products.

For whatever reasons, it is clear from Fig. 7 that the values of $\sigma_{ER}/\pi\lambda^2$ are not constant but increase with increasing ℓ_{crit} . Although the absolute uncertainties are $\approx 25\%$ for the values of σ_{ER} , only the relative errors are important to establish the variation of $\sigma_{ER}/\pi\lambda^2$ with ℓ_{crit} . Our data for $^{194}\text{Hg}^*$ (Fig. 7(a)) indicate that a large increase in $\sigma_{ER}/\pi\lambda^2$ occurs for ^{40}Ar at $\ell_{crit} \approx 110$; for $^{19}\text{F}/^{20}\text{Ne}$ at $\ell_{crit} \approx 50$; for ^{12}C at $\ell_{crit} \approx 40$. For comparison we have plotted data for several other reactions in the same way (see Figs. 7(b) and 7(c)). For $^{40}\text{Ar} + ^{110}\text{Pd}/^{109}\text{Ag}$ there appears to be a narrow plateau for $\sigma_{ER}/\pi\lambda^2 \approx 4000$ for $60 \lesssim \ell_{crit} \lesssim 90$; then a decided increase. A very similar composite system is formed by $^{86}\text{Kr} + ^{65}\text{Cu}$; the abrupt increase here occurs for $\ell_{crit} \approx 150$. Each of the other ^{40}Ar reactions seems to show a break for $\ell_{crit} \approx 80$. In sum, all the results point to a distinct rise in $\sigma_{ER}/\pi\lambda^2$ for large values of ℓ_{crit} (and/or E^*). The value of ℓ_{crit} for this breakaway changes with the target-projectile combination from ≈ 40 for ^{12}C to $\approx 80 - 110$ for ^{40}Ar to ≈ 150 for $^{86}\text{Kr} + ^{65}\text{Cu}$.

G. General relationship to the statistical model

Can we reconcile this pattern of observations with the qualitative statistical picture described earlier? The answer can be affirmative only if extensive modifications are made. First we must invoke extensive non-equilibrating mechanisms related to the ER production for ^{19}F ($E^* = 98$ MeV) and both ^{12}C and ^{19}F ($E^* = 142$ MeV). Next we must invoke, for $E^* = 194$ MeV, either extensive preequilibrium paths or extensive H/He evaporation to inhibit fission and enhance ER. Finally we must give up the simplest Boltzmann equation and invoke separate level density parameterizations for each exit channel to provide the rapid increase of CDF_α with E^* and its rather slow decrease with ℓ_{crit} . With all these modifications the statistical model will require careful and fine tuning of its level density parameters and the simple features often invoked will be largely eradicated.

To illustrate the delicacy required let us examine three field maps in the $E^* - J$ plane for the decay probability resulting from several parametrizations of first step evaporative decay from $^{194}\text{Hg}^*$. (We use the code EMIK, a modification of GROGIF,⁴⁰ designed to provide emission probabilities and lifetimes by the methods originally described by Grover and Gilat and used by other authors.^{22,41}) In Fig. 8 we show calculated probability contours for three different parametrizations of the fission barrier (B_f) and level densities (through the level density parameter, "a"). First in Fig. 8(a) results are given for a fission barrier 1 MeV smaller than that from RLDM and identical values of "a" (i.e. $a_f = a_n = a_p = a_\alpha$). For this case neutron emission dominates except for $J > 50$ and $E^* < 150$ MeV;

clearly there is not enough ${}^1\text{H}/{}^4\text{He}$ to explain Fig. 6 and Table I. Next in Fig. 8(b) we raise the values of a_p and a_α by 3% which does indeed enhance ${}^1\text{H}/{}^4\text{He}$ emission decidedly without major change in the fission. From this kind of tuning of a_p/a_n and a_α/a_n it might well be possible to get enough H/He emission as called for by the data in Fig. 6, namely a rapid increase in ${}^1\text{H}/{}^4\text{He}$ emission with increasing E^* and a slow decrease of ${}^1\text{H}/{}^4\text{He}$ emission with J.

In Fig. 8(c) emission probabilities are shown for a parametrization with $a_f/a_n = 1.185$, $a_p/a_n = a_\alpha/a_n = 1.03$ and $B_f = 17.5$ MeV. Here the fission is much more important even at low J for high excitation energy. Clearly this parametrization cannot give enough ${}^1\text{H}/{}^4\text{He}$ emission at high E^* and J to satisfy Fig. 6. Parameters similar to these were selected by Delagrange et al.²² to fit the steep fission excitation function for ${}^{12}\text{C} + {}^{182}\text{W}$ ($50 < E^* < 100$ MeV). Parameters similar to those in 8(a) were chosen by Beckerman and Blann²³ to fit the ratios of ER to fission (for lighter nuclei) with emphasis on the higher excitations where the fission excitation function is rather flat. These authors have used a fission barrier much smaller than the RLDM prediction ($B_f(J=0) = 0.6 B_f^{\text{RLDM}}(J=0)$). Although we have not attempted to get an overall fit for ${}^{194}\text{Hg}^*$ it would appear that within the statistical model a transition is called for from the larger value of a_f/a_n compared to unity at low energies to a much smaller one at very high energy. A shell-model level density calculation may provide a physical basis for such an energy dependence of the "a" values as suggested by Cârjan et al.⁴² Even with such a model of energy-dependent level density parameters the large calculated number of decay channels for fission may be

irreconcilable with the experimental observations of a large $^1\text{H}/^4\text{He}$ evaporation probability at high E^* and J . The very interesting fission studies obtained by the "blocking technique" may also be relevant here.²¹ Apparently a large fraction of the fission events often occur after essentially complete evaporative cooling of the compound nucleus.

It is possible that we are witnessing the gradual decline of the equilibrium statistical model for very highly excited nuclei. The calculated absolute lifetimes drop well below 10^{-21} sec for a wide region in $E^* - J$ space. ($E^* - J$ maps are shown in Fig. 9 for the parametrizations used in Fig. 8). A calculation of absolute decay lifetimes⁴¹ is much more subject to error than that for relative decay probabilities as one must use the level density of the emitter as well as its daughters. Nevertheless these very short times (much shorter than the scission time of $\sim 2 \times 10^{-21}$ sec³³) may signal an inability of the system to count its available phase space.⁵ Such a situation might be very similar in its consequences to a level density function with the value of a_f decreasing with E^* . It could also correspond to a shift from phase space to dynamic control of the fission-evaporation branching. This situation might be expected to change with the entrance channel masses so as to favor fission and disfavor ER formation for the more mass symmetric entrance channels.³⁹ Such favoring is indeed exhibited by the different dependence on ℓ_{crit} of $\sigma_{\text{ER}}/\pi\lambda^2$ for each projectile in Fig. 7 (a), but, of course, other non-equilibrium processes could also provide an explanation.

In sum, predictions of the statistical model for decay at high energy and spin are tremendously sensitive to even the fine details of the level density parameters. If we are to develop any predictive power in this framework we will need much more extensive and focused experimental data to test and/or calibrate the model. Similarly we must have reliable energy spectra for $^1\text{H}/^4\text{He}$ and a sophisticated model for penetration of barriers encountered at these energies and spins. Even with such sophisticated models we may be pushed beyond the limits of control by pure phase space considerations.

V. Summary

Twelve reaction systems have been studied that give the composite/compound nucleus $^{194}\text{Hg}^*$. Cross sections are presented for the production of evaporative H/He, fission and evaporation residues. The energy spectra and angular distributions of H/He at backward angles have been used to identify H/He emission after thermal equilibration. Several arguments based on our data rule out evaporation from the fission fragments as an important deexcitation mechanism. Systematic behavior of the ER cross sections reveals two interesting features:

- (1) Non-equilibrium mechanisms affect the ER production: Either incomplete fusion directly feeds the ER's or non-equilibrium fission competes with ER formation. Our expectation was that such fast non-equilibrium reactions would be localized on partial waves near l_{crit} (or ~ 59) and would not affect ER production from much smaller l waves.

(2) Fission in competition with evaporation becomes weaker for excitation energies > 100 MeV. The systematic behavior of the cumulative decay fraction for H/He evaporation reveals a rapid increase with E^* and a slow decrease with spin extending to $\langle J \rangle$ well over 60 for $E^* > 100$ MeV. Conventional statistical-model calculations of the fission-evaporation competition at these high energies are hypersensitive to relative values of the level density parameters. Careful adjustment of the level densities as well as the emission barriers is required if one is to try to account for these processes within the framework of existing statistical model codes and their built in approximations. Alternatively, the results can be said to suggest that the competition between evaporation and fission evolves away from the pure phase space arguments of the current models at lower energies to mechanisms that call for the inclusion of reaction dynamics at high excitation energies.

Acknowledgments

This project was supported in part by the Division of Nuclear Physics of the U.S. Department of Energy and by CNRS of France. The staffs of the SuperHILAC and 88 inch Cyclotron at the Lawrence Berkeley Laboratory have been very helpful. We are grateful to E. Duek, L. Kowalski, Y. LeBeyec and A. Fleury for helpful discussions and assistance in many ways.

References

- ^a Permanent address: Centre d'Etudes Nucléaires de Bordeaux-Gradignan Laboratoire de Chimie Nucléaire ER4 No. 144, Le Haut Vigneau, 33170 Gradignan, France.
- ^b Permanent address: Laboratoire de Chimie Nucléaire, Institut de Physique Nucléaire, B.P. No. 1, 91406 Orsay, France.
1. D. Bodansky, Ann. Rev. Nucl. Sci. 12, 107 (1962).
 2. T. D. Thomas, Ann. Rev. Nucl. Sci. 18, 343 (1968).
 3. A. Fleury and J. M. Alexander, Ann. Rev. Nucl. Sci. 24, 279 (1974).
 4. U. Schröder and J. R. Huizenga, Ann. Rev. Nucl. Sci. 27, 465 (1977), J. Galin, D. Guerreau and R. Babinet, J. Phys. Soc. Japan 44, 683 (1978), V. V. Volkov, Phys. Rep. C44, 93 (1978).
 5. T. Ericson, Adv. Phys. 9, 423 (1960).
 6. J. M. Miller, G. L. Catchen, D. Logan, M. Rajagopalan, J. M. Alexander, M. Kaplan and M. S. Zisman, Phys. Rev. Lett. 40, 100 (1978).
 7. M. Rajagopalan, L. Kowalski, D. Logan, M. Kaplan, J. M. Alexander, M. S. Zisman and J. M. Miller, Phys. Rev. C19, 54 (1979).
 8. H. Delagrangé, D. Logan, M. F. Rivet, M. Rajagopalan, J. M. Alexander, M. S. Zisman, M. Kaplan and J. W. Ball, Phys. Rev. Lett. 43, 1490 (1979).
 9. D. Logan, M. Rajagopalan, M. S. Zisman, J. M. Alexander, M. Kaplan and L. Kowalski, Phys. Rev. C22, 104 (1980).
 10. J. M. Miller, D. Logan, G. L. Catchen, M. Rajagopalan, J. M. Alexander, M. Kaplan, J. W. Ball, M. S. Zisman and L. Kowalski, Phys. Rev. Lett. 40, 1074 (1978).
 11. D. Logan, H. Delagrangé, M. F. Rivet, M. Rajagopalan, J. M. Alexander, M. Kaplan, M. S. Zisman and E. Duek, Phys. Rev. C. (in press, 1980).
 12. See for example, R. C. Reedy, M. J. Fluss, G. F. Herzog, L. Kowalski and J. M. Miller, Phys. Rev. 188, 1771 (1969); A. M. Zebelman, L. Kowalski, J. M. Miller, K. Beg, Y. Eyal, G. Yaffe, A. Kandil and D. Logan, Phys.

Rev. C10, 200 (1974).

13. M. M. Fowler and R. C. Jared, Nucl. Instrum. Methods 124, 341 (1975).
14. See particularly H. C. Britt and A. R. Quinton, Phys. Rev. 124, 877 (1961).
15. J. Galin, B. Gatty, D. Guerreau, C. Rousset, U. C. Schlotthauer-Voos and X. Tarrago, Phys. Rev. C9, 1113, 1126 (1974); *ibid* C10, 638 (1974).
16. T. Døssing, Private communication 1978 and G. L. Catchen, M. Kaplan, J. M. Alexander and M. F. Rivet, Phys. Rev. C21, 940 (1980).
17. See for example, H. C. Britt, B. H. Erkkila, R. H. Stokes, H. H. Gutbrod, F. Plasil, R. L. Ferguson and M. Blann, Phys. Rev. C13, 1483 (1976).
18. L. C. Vaz and J. M. Alexander, Phys. Rev. C18, 2152 (1978) and L. C. Vaz, J. M. Alexander and G. R. Satchler, submitted to Phys. Rep. C.
19. R. G. Stokstad, W. Reisdorf, K. D. Hildenbrand, J. V. Kratz, G. Wirth, R. Lucas and J. Poitou, Z. Physik A295, 269 (1980).
20. T. Sikkeland, J. E. Clarkson, N. H. Steiger-Shafir and V. E. Viola, Phys. Rev. C3, 329 (1971); T. Sikkeland, Phys. Rev. 135, B669 (1964).
21. J. U. Anderson, A. S. Jensen, K. Jorgensen, E. Laegsguard, K. O. Nielsen, J. S. Förster, I. V. Mitchell, D. Ward, W. M. Gibson and J. J. Cuomo, Kgl. Danske Mat-fys Med. 40:7 (1980) and IAEA -SM/241-C7 (1979 IAEA, Julich).
22. H. Delagrange, A. Fleury and J. M. Alexander, Phys. Rev. C16, 706 (1977).
23. M. Beckerman and M. Blann, Phys. Rev. Lett. 38, 272 (1977); Phys. Lett. 68B, 31 (1977); Phys. Rev. C17, 1615 (1978).
24. S. Cohen, F. Plasil and W. J. Swiatecki, Ann. Phys. (N.Y.) 82, 557 (1974).
25. W. Myers and W. F. Swiatecki, Nucl. Phys. 81, 1 (1966).
26. C. Ngô, B. Tamain, M. Reiner, R. J. Lombard, D. Mas and H. H. Dcubler, Nucl. Phys. A252, 237 (1975); K. A. Bruekner, J. R. Buchler and M. Kelly, Phys. Rev. 173, 944 (1968).
27. H. Ngô and C. Ngô, Orsay Report I.P.N.P./TH 80-20 (1980).
28. K. Siwek-Wilczyńska and J. Wilczyński, Phys. Lett 74B, 313 (1978).

29. J. Blocki, J. Randrup, W. J. Swiatecki and C. F. Tsang, Ann. Phys. (N.Y.) 105, 427 (1977).
30. J. Gilat and J. R. Gover, Phys. Rev. C3, 734 (1971).
31. M. Blann, Phys. Rev. C21, 1770 (1980).
32. M. A. McMahan and J. M. Alexander, Phys. Rev. C21, 1261 (1980).
33. W. Norenberg and C. Riedel, Z. Physik A290, 335 (1979); C. Grégoire, R. Lucas, C. Ngô and B. Schürmann, Saclay Report DPH - N/MF/79/33 (1979) (unpublished).
34. S. Della Negra, H. Gauvin, H. Jungclas, Y. LeBeyec and M. Lefort, Z. Physik A282, 65 (1977); C. Cabot et al. Strasburg (1980).
35. B. Tamain, C. Ngô, J. Peter and F. Hanappe, Nucl. Phys. 252, 187 (1975).
36. H. Gauvin, D. Guerreau, Y. LeBeyec, M. Lefort, F. Plasil and X. Tarrago, Phys. Lett. 58B, 163 (1975).
37. The sharp cutoff approximation is often used as a guide, See for example Ref. 17 and H. C. Britt, B. H. Erkkila, P. D. Goldstone, R. H. Stokes, B. B. Back, F. Folkmann, O. Christensen, B. Fernandez, J. D. Garrett, G. B. Hagemann, B. Herskind, D. L. Hillis, F. Plasil, R. L. Ferguson, M. Blann and H. H. Cutbrod, Phys. Rev. Lett, 39, 1458 (1977); More detailed calculations are discussed similarly by A. Gavron, Phys. Rev, C21, 230 (1980).
38. E. K. Hyde, The Nuclear Properties of the Heavy Elements III, Fission Phenomena (Prentice-Hall, Englewood Cliffs, N.J., 1964).
39. S. Agarwal, Ph.D thesis, University of Paris, Orsay, France, 1980.
40. J. R. Grover and J. Gilat, Phys. Rev. 157, 802 (1967); J. R. Grover and J. Gilat, Phys. Rev. 157, 823 (1967); J. Gilat, Brookhaven National Laboratory Report No. BNL 50246, 1970 (unpublished).

41. A. Fleury, H. Delagrangé and J. P. Dufour, Phys. Rev. C16, 1396 (1977).
42. N. Cârjan, A. Fleury and H. Delagrangé, Phys. Rev. C19, 2267 (1979).

Table I. Experimental Results for ^{194}Hg Compound Nuclei

Beam	The Reaction Systems											
	^{12}C	^{12}C	^{20}Ne	^{40}Ar	^{12}C	^{19}F	^{40}Ar	^{12}C	^{19}F	^{40}Ar	^{20}Ne	^{40}Ar
Target	^{182}W	^{182}W	^{174}Yb	^{154}Sm	^{182}W	^{175}Lu	^{154}Sm	^{182}W	^{175}Lu	^{154}Sm	^{174}Yb	^{154}Sm
E_{lab} (MeV)	77	104	125	196	121	135	221	167	184	272	252	340
E^* (MeV) ^a	57	82	80	80	98	98	100	142	142	141	194	195
Cross Sections ^b (mb), $^4\text{He}/^1\text{H}$ Ratio, ℓ_{cr} and ℓ_{ER}												
^1H	-	204	114	55^+	266	214	73.5^+	544	490	242	1189	703
^2H	-	27	6.0	2.8^+	24	25	6.7	65	87	31.4	189	108
^3H	-	9	2.4	1.09^+	11	10	2.9	32	51	15.6	104	66
^4He	31	124	73	37	176	152	77	387	354	232	984	624
ER	545	475	291	94	458	351	86	539	312	79	225	124
Fission	23	330	663	500^c	607	780	754	861	1066	919	985	1439
Fusion	568	805	954	594	1065	1131	840	1400	1378	998	1210	1563
$^4\text{He}/^1\text{H}$	-	0.61	0.64	0.67	0.66	0.71	1.05	0.71	0.72	0.96	0.83	0.89
ℓ_{cr}	25.5	36	53	66	45	59	83	65	76	101	85	142
ℓ_{ER}	25	27	29	26	29	32	26	37	36	28	36	39
Cumulative Decay Fractions (CDF) ^d												
^1H	-	0.25	0.12	0.093	0.25	0.19	0.087	0.34	0.36	0.24	0.98	0.45
^2H	-	0.034	0.006	0.005	0.02	0.022	0.008	0.04	0.063	0.03	0.16	0.07
^3H	-	0.011	0.003	0.002	0.01	0.009	0.003	0.02	0.037	0.016	0.09	0.04
^4He	0.055	0.15	0.076	0.062	0.17	0.13	0.092	0.24	0.26	0.23	0.81	0.40
ER	0.96	0.59	0.305	0.16	0.43	0.31	0.10	0.38	0.23	0.08	0.186	0.08
Fission	0.04	0.41	0.695	0.84	0.57	0.69	0.90	0.62	0.77	0.92	0.81	0.92

Footnotes

to

Table I

⁺ Upper limit.

^a Q-values were taken from A. H. Wapstra and N. B. Gove, Nucl. Data A9, 265 (1971).

^b Cross sections for ^1H , ^2H , ^3H and ^4He emission have been integrated for the evaporative component only as described in the text. See Refs. 10 and 11 for a discussion of their uncertainties; for ^{12}C and ^{19}F reactions they are $\pm 20\%$ absolute and $\pm 10\%$ relative; for ^{20}Ne and ^{40}Ar reactions they are $\pm 15\%$ absolute and $\pm 8\%$ relative. Cross sections for ER and fission products have comparable uncertainties. See text for discussion of possible interferences of (a) slit scattering on ER determinations for 196 and 221 MeV ^{40}Ar and (b) the possibility of some deeply inelastic reactions being included with fission for 340 MeV ^{40}Ar .

^c This value was not measured; it was interpolated from our data and those in Ref. 19.

^d $\text{CDF}_i = \sigma_i / \sigma_{\text{cf}}$.

Table II

Experimental and calculated^a fusion cross sections, σ_{cf} (mb)

E_{lab} (MeV)	σ_{cf}^{expt} (mb)	(Ref. 26)	(Ref. 27)	Calculated (Ref. 28)	(Ref. 29)	(Ref. 18)
$^{12}_C + ^{182}_W$						
77	568	941		871	802	983
104	805	1348	1330	1273	1201	1331
121	1065	1438	1422	1373	1312	1424
167	1400	1590	1578	1543	1499	1580
$^{19}_F + ^{175}_{Lu}$						
135	1131	1138	1159	1201	1057	1121
184	1378	1406	1421	1452	1347	1393
$^{20}_{Ne} + ^{174}_{Yb}$						
125	954	876	944	963	794	856
252	1210	1525	1558	1568	1484	1515
$^{40}_{Ar} + ^{154}_{Sm}$						
196	594	548	626	836	545	519
221	840	760	829	1015	757	734
272	998	1072	1128	1279	1069	1051
340	1563	1342	1387	1508	1340	1325

Footnotes

to

Table II.

^a Calculations of σ_{cf} made with the code FRANPIE described in Ref. 18 with the choice of nuclear potential indicated. The critical distance hypothesis was used with $R_{crit} = 1.0 (A_{tgt}^{1/3} + A_{proj}^{1/3})$ fm for energies above the transition energy [$E_{c.m.} = V(R_{crit})$] for each potential [$\sigma_{cf} = \pi R_{crit}^2 (1 - V(R_{crit})/E_{c.m.})$]. For the cases denoted by an asterisk the incident energy is less than the transition energy and the partial wave summation was made $\sigma_{cf} = \pi \lambda^2 \sum (2l + 1) T_l$ as described in Ref. 18.

^b Tabulated proximity potential empirically adjusted to match fusion barriers by using Eq. (11) of Ref. 18.

Table III

Cumulative decay fractions for high spin zones ^a

* (MeV)	80	80	80	98	98	98	142	142	142	194
J Zone	36-53	36-66	53-66	45-59	45-83	59-83	60-76	60-101	76-101	85-142
<J> ^c	47	56	62	54	70	75	71	87	93	123
¹ H	0.005	0.023	0.042	0.11	0.02	b	0.30	0.16	0.09	0.14
⁴ He	0.010	0.023	0.035	0.09	0.06	0.05	0.22	0.20	0.20	0.16
He/ ¹ H	2.04	0.98	0.85	0.86	2.93	b	0.75	1.30	2.20	1.13
ER	0.06	b	b	0.15	b	b	b	b	b	0.02

Footnotes

to

Table III

- ^a Calculated from Eq. (4) and data in Table I.
- ^b The missing entries are for cases in which Eq. (4) gives a negative value for CDF. For ¹H presumably this is due to experimental uncertainties. For ER's this can be related to non-equilibrium mechanisms as discussed in the text.
- ^c Taken from the sharp cutoff approximation $\langle J \rangle = l_{cr} + (2/3)(l_{cr} - l_{cr})$ where subscripts 1 and 2 refer to the two different reactions.

Figure Captions

Fig. 1. Energy spectra at back angles for ${}^4\text{He}$ produced by two different entrance channels (squares, ${}^{12}\text{C} + {}^{182}\text{W}$; circles, ${}^{19}\text{F} + {}^{175}\text{Lu}$). The two lower data sets for 167 MeV ${}^{12}\text{C} + {}^{182}\text{W}$ have been multiplied by the factors shown in parenthesis. Arrows denote the FWHM and the cross shows its midpoint for each spectrum.

Fig. 2. Typical energy spectra for ${}^1\text{H}$ and ${}^4\text{He}$ from the reaction 340 MeV ${}^{40}\text{Ar} + {}^{154}\text{Sm}$. Experimental points are compared to smooth curves calculated by a Monte Carlo simulation of evaporation from fission fragments. Gaussian distributions were assumed for the mass and total energy distributions in fission with standard deviations of 24 mass units and 12 MeV, respectively. Angular distributions for each fission product were taken to be $1/\sin \theta_{\text{c.m.}}$ and isotropic for H/He. The evaporation spectra were taken as $P(\epsilon) \propto (\epsilon - B) \exp(-\epsilon/T)$ with barrier parameter B from Ref. 32 and T from Ref. 11.

Fig. 3. Excitation functions for fusion, +; fission, $\diamond$; ${}^1\text{H}$, O, ${}^4\text{He}$, Δ ; ${}^2\text{H}$, V; ${}^3\text{H}$, X; and evaporation residues ER, $\square$ for the reaction system ${}^{12}\text{C} + {}^{182}\text{W}$.

Fig. 4. Ratio of evaporative ${}^4\text{He}$ to ${}^1\text{H}$ from direct observation as given in Table I. (Data from this work and Refs. 11, 12 and 15). Comparison can also be made to the results in Table III for the high-spin zones.

Fig. 5. Evaporation spectra for ${}^4\text{He}$ from two reactions. No significant difference in shape is apparent for the data and thus for the different spin domains.

Fig. 6. Cumulative decay fractions for evaporation residues (a) and ${}^4\text{He}$ (b) vs average spin. The letters represent points from Table I from the various reactions as shown in Fig. 7. The high-spin zones as given in Table III: O, 80 MeV; Δ , 98 MeV; $\square$, 142 MeV; $\diamond$, 194 MeV. The nearly vertical arrows for ${}^4\text{He}$ crudely represent evaporation probabilities for each separate step in the evaporation cascade. For ${}^{194}\text{Hg}^*$, $E^* = 194$ MeV, $J = 56$, one might guess for the first four evaporation steps that $\Delta J \approx 2$ and $\Delta E^* \approx 12$ for the neutron emission that is expected to dominate. Therefore the summed ${}^4\text{He}$ evaporation probability is $\approx 0.81 - 0.25 = 0.56$ or for each individual step $P_\alpha \approx 0.14$.

Fig. 7. The dimensionless evaporation residue cross section $\sigma_{\text{ER}}/\pi\lambda^2$ vs ℓ_{crit} for several reactions as indicated. (a) Data from this work. Excitation energies are noted for reactions leading to ${}^{194}\text{Hg}^*$. (b) Data from Refs. 11, 35 and 36 (c) Data from Refs. 17 and 34.

Fig. 8. $E^* - J$ field maps for evaporation probability contours calculated with the indicated parameters: (a) parameters chosen similar to those in Ref. 23. (b) Same as in (a) but with slight increase in a_p and a_α to enhance ${}^1\text{H}/{}^4\text{He}$ evaporation (c) parameters chosen similar to those in Ref. 22.

Fig. 9. Lifetimes for decay of an equilibrated nucleus $^{194}\text{Hg}^*$ as calculated from the phase space equations. The level density parameters used correspond to those in Figs. 8(a), 8(b) and 8(c), respectively.

III - 38,

Blank

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 7

FIRST STEP DECAY FRACTIONS (%)

Fig. 8

CALCULATED LIFETIME

Fig. 9

PUBLICATIONS

1. Fusion and Emission of ^1H and ^4He in Reactions Between Complex Nuclei at High Energies. H. Delagrange, D. Logan, M. F. Rivet, M. Rajagopalan, J. M. Alexander, M. S. Zisman, M. Kaplan, and J. W. Ball, Phys. Rev. Letters 43, 1490 (1979).
2. Semiempirical Methods for Estimating Fragment Spins from Studies of ^4He and ^1H Emission. G. L. Catchen, M. Kaplan, J. M. Alexander, and M. F. Rivet, Phys. Rev. C21, 940 (1980).
3. Rapid Energy Equilibration and Emission of H and He in the Reaction of 340 MeV ^{40}Ar with ^{197}Au . D. Logan, M. Rajagopalan, M. S. Zisman, J. M. Alexander, M. Kaplan, and L. Kowalski, Phys. Rev. C22, 104 (1980).
4. Light Charged Particle Emission in ^{40}Ar Induced Reactions: A Probe of the Very Early Evolution of the Collisions. D. Logan, H. Delagrange, M. F. Rivet, M. Rajagopalan, J. M. Alexander, M. Kaplan, M. S. Zisman, and E. Duek, Phys. Rev. C22, 1080 (1980).
5. Charged Particle Emission from ^{194}Hg Compound Nuclei: Energy and Spin Dependence of Fission-Evaporation Competition. M. Rajagopalan, D. Logan, J. W. Ball, M. Kaplan, H. Delagrange, M. F. Rivet, J. M. Alexander, L. C. Vaz, and M. S. Zisman, Phys. Rev. C (submitted).

PAPERS IN PREPARATION

1. Emission of ^4He in Deeply Inelastic Reactions of 700 MeV ^{86}Kr with Au.
D. R. Logan, M. Kaplan, G. L. Catchen, M. Rajagopalan, J. M. Alexander, T. W. Debiak, E. Duek, M. S. Zisman, J. M. Miller, D. Benson, and N. H. Lu.
2. Emission of ^1H , ^2H , and ^3H in Reactions of 700 MeV ^{86}Kr with Au.
D. R. Logan, M. Kaplan, G. L. Catchen, J. M. Alexander, M. Rajagopalan, E. Duek, and M. S. Zisman.
3. Emission of H and He in Reactions of 1064 MeV ^{136}Xe with Au.
H. Delagrange, M. Rajagopalan, J. M. Alexander, D. Logan, M. Kaplan, M. S. Zisman, and L. Kowalski.
4. Coincidence Studies of Momentum Transfer in Reactions of 8.5 MeV/A ^{40}Ar and ^{20}Ne with ^{197}Au . L. Kowalski, E. Duek, M. Rajagopalan, J. M. Alexander, D. Logan, M. Kaplan, and M. S. Zisman.
5. Tests of Energy Equilibration in ^{40}Ar Reactions: Correlations Between Evaporative ^1H , ^4He and Fission. M. F. Rivet, D. Logan, J. M. Alexander, E. Duek, M. S. Zisman, and M. Kaplan.
6. Quadrupole Interactions in DNA at Hf and Ag sites Studied by Perturbed Angular Correlations. J. W. Ball and M. Kaplan.
7. Search for Enhanced ^{12}B Formation from the Reaction $^{65}\text{Cu}(^{12}\text{C}, ^{12}\text{B})^{65}\text{Zn}$.
A. A. Caretto, Jr., M. Kaplan, R. J. Spector, M. V. Yester, and R. L. Ferguson.