Energy and Spin Dependence of Fission: ^{1}H and ^{4}He Emission from ^{194}Hg Compound Nuclei

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

We present here an initial report on the behavior of high-spin compound nuclei of mass number ≈ 200. In particular we focus on a phenomenological analysis of the measured cross sections for complete fusion, fission, and compound-nucleus evaporation of ^{1}H and ^{4}He. This study was undertaken to shed light on the very puzzling and apparently contradictory picture of fission-evaporation competition at high excitation and spin.[1-4] In addition, the information may contribute to an understanding of two processes which accompany the very inelastic reactions between very heavy nuclei: emission of light charged particles and fission.[5-7]

The strategy of the experiment has been previously described[8]; it depends upon forming a compound nucleus at a particular excitation energy through two different entrance channels with different distributions of angular momentum. In the present instance ^{194}Hg was formed via the entrance channels $^{12}C + {}^{182}W$ and $^{19}F + {}^{175}Lu$, and bombarding energies were selected to yield excitation energies of 98 and 142 MeV. Measurements were made of the energy and angular distributions of evaporation residues (ER), fission fragments, ^{1}H and ^{4}He produced in these reactions. By comparisons of the results for different entrance channels one may infer the cumulative decay fractions for these various modes of de-excitation from compound nuclei in several domains of energy and spin. We examine the separate dependence on energy and spin.

Statistical-model calculations for ^{194}Hg indicate that fission occurs mainly in the first few decay steps.[4] The major evaporation competition could be with either n, ^{1}H, or ^{4}He emission depending on the relative level densities of each daughter product and the saddle-point nucleus. It is often assumed that all daughter nuclei have similar level densities (i.e., those of a Fermi gas with $a = A/\text{const}$).[1] If so then fissionability will be mainly determined by competition with neutron emission, and charged-particle emission will not be prominent, especially early in the evaporation chain. This assumption has been made in Ref. 1 and followed to several important conclusions (e.g., fission barriers are found to be much smaller than those from the liquid-drop model).

TABLE I. Summary of results.

	The reaction systems			
Beam	^{12}C	^{19}F	^{12}C	^{19}F
Target	^{182}W	^{175}Lu	^{182}W	^{175}Lu
E_{lab} (MeV)	121	135	167	184
E^* (MeV)	98	98	142	142
	Cross sections (mb) and l_{crit}			
^{1}H [a]	266	214	544	490
^{4}He [a]	176	152 [b]	437	354
ER [a]	458	351	539	312
Fission [a]	607	780	1075	1066
Fusion	1065	1131	1614	1378
l_{crit} [c]	45	59	65	76
	Cumulative decay fractions [d]			
^{1}H	0.25	0.19	0.34	0.36
^{4}He	0.17	0.13	0.27	0.26
ER	0.43	0.31	0.33	0.23
Fission	0.57	0.69	0.67	0.77

[a]Estimated uncertainties are 20% absolute and 10% relative.

[b]For this datum only reproducibility was ± 25%.

[c]From the sharp-cutoff equation $\sigma_{fusion} = \pi\lambda\!\!\!^-{}^2(l_{crit} + 1)^2$.

[d]Estimated uncertainties are ± 17% for ^{1}H and ^{4}He, 10% for ER and 6% for fission.

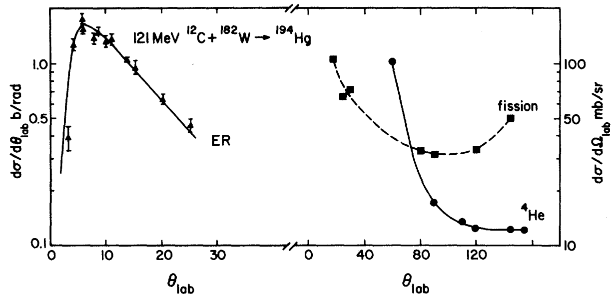

FIG. 1. Angular distributions for one case. Uncertainties shown are from statistics only.

Contrary to this assumption we show that ^{1}H and ^{4}He emission are very prominent indeed. Comparison of our cross sections (Table I) to statistical-model calculations in Ref. 4 indicates the need for different level-density parameters for n, H, and He daughter products. This effect demands a reassessment of the assumptions and conclusions of Ref. 1 and similar calculations. We have made even more extensive calculations than those in Ref. 4 (for higher energies and all steps in the evaporation chain) which substantiate this conclusion. Here we simply present important new experimental data and some strong inferences concerning the nature of the fission-evaporation competition.

Beams of ~1–100 nA of ^{12}C and ^{19}F were provided by the Lawrence Berkeley Laboratory 88-in. cyclotron. Self-supporting targets of ^{182}W (98%, 450 μg/cm^2) and ^{175}Lu (370 and 1420 μg/cm^2 for 135 and 184 MeV, respectively) were prepared by evaporation. Their thicknesses were measured by Rutherford scattering (both absolute and by reference to a weighed Au foil) and in some cases by weight. The beam intensity was monitored by a Faraday cup as well as by two Si detectors located in the reaction plane about 20° to the beam axis. ^{1}H and ^{4}He were observed with a three-member Si-detector telescope (45, 500, and 5000 μm), and fission products and heavy evaporation residues were measured with a Fowler-Jared gas telescope[9] (gas ionization counter at 10 or 40 Torr for ^{12}C or ^{19}F and 500-μm Si detector, $d\Omega \approx 0.1$ msr). Energy calibrations were made with ^{212}Pb (ThB) and ^{252}Cf sources. Most of the events recorded were for a single product in either telescope; some coincidence data were also obtained for H or He with a heavy reaction product.

In Fig. 1 are shown some typical observed angular distributions of several reaction products from the system of 121-MeV ^{12}C + ^{182}W. Our angular distributions for ^{1}H and ^{4}He are very similar to those of Britt and Quinton,[10] i.e., essentially independent of angle from ~120° to 160° c.m., but rapidly increasing forward. Also, the c.m. energy distributions for ^{4}He were very similar for angles greater than 100° and energies greater than 12.5 MeV. We have estimated the total compound-nucleus–derived ^{1}H and ^{4}He by integrating over energy ($\epsilon_{c.m.} \geq 12.5$ MeV for ^{4}He) and averaging the resulting value of $d\sigma/d\Omega$ for lab angles of 120° or more (i.e., we assumed that ^{1}H and ^{4}He evaporation was isotropic). That these ^{1}H and ^{4}He products were indeed associated with compound-nucleus evaporation and not fission-product evaporation was suggested by the following: For the reactions of 121-MeV ^{12}C and 135-MeV ^{19}F we have searched for coincident events between H or He and fission. These studies allow us to conclude that light-particle fission coincidences are very improbable ($\leq 5\%$).

Differential cross sections for fission ($d\sigma_f/d\Omega$) were measured at several angles for each reaction (and for 121-MeV ^{12}C + ^{197}Au to check consistency with Ref. 10). For 135-MeV ^{19}F the data were extensive enough to allow direct integration of the cross section in the lab system. For this case we found that the integrated fission cross section σ_f was related to the differential c.m. cross section at 90° as follows (with β equal to unity):

$$\sigma_f = \beta \int_{4\pi} (d\sigma_f/d\Omega)_{90^\circ\ \mathrm{c.m.}} (1/\sin\theta)_{\mathrm{c.m.}} d\Omega_{\mathrm{c.m.}}$$
$$= 2\pi^2 \beta (d\sigma_f/d\Omega)_{90^\circ\ \mathrm{c.m.}}.$$

For 184-MeV ^{19}F, we integrated with the assumption that the c.m. angular distribution was the same as at 135 MeV (i.e., $\beta = 1$). For ^{12}C reactions we integrated with the same assumptions (namely that the c.m. angular distributions are proportional to $1/\sin\theta_{\mathrm{c.m.}}$ and $\beta = 1$). This is supported by the recent measurements of Videbæk *et al.*[2] on similar systems, although Sikkeland *et al.*[11] preferred $\beta = 0.95$ for ^{12}C beams of energy ~10 MeV/amu. In view of this uncertainty, there may be up to a 5% error due to small deviations from $1/\sin\theta_{\mathrm{c.m.}}$ for both the ^{12}C- and ^{19}F-induced reactions. Our resulting fission cross sections are lower than those reported earlier[10,11] by ~15% for ^{12}C + ^{197}Au and by ~20% for ^{12}C + ^{182}W, both at 121 MeV lab.

The evaporation residues we have identified as the forward-peaked heavy residual nuclei.[12] For these angular distributions we have fitted $d\sigma/d\Omega$ to an exponential decrease for $\theta \geq 10°$, and the resulting angular distributions were integrated with the requirement of zero differential angular cross section ($d\sigma/d\theta$) at 0° lab. The possibility that a component of these products included heavy transfer products associated with the large cross sections for direct forward-peaked H and He cannot be experimentally ruled out. However, there is some indirect evidence that this is not a large effect: (1) For the ^{12}C-induced reactions, a forward-peaked high-energy ^{4}He would lead to a recoil energy for the heavy residual[10] which is reduced by a factor of ~2. This might very well drop it below our energy cutoff. (2) Many heavy residuals after ^{4}He evaporation should survive fission and reach our detectors. As the total residual-nucleus cross sections are comparable to the isotropic ^{4}He cross sections, we infer that residues of ^{4}He evaporation constitute most of σ_{ER} and that not much room is left for residues from direct reactions. (3) With increasing energy for ^{19}F + ^{175}Lu, the cross section for evaporation residues decreases while that for all direct reactions increases. It is true, nevertheless, that the integrated cross sections for forward-peaked H and He are quite large,[10,13] and in spite of the points made above we could conceivably have detected some residual nuclei from such reactions.

TABLE II. Cumulative decay fractions.

E^* (MeV)	98	98	142	142
J	0–45	45–59	0–65	65–76
^{1}H	0.25	0.11	0.34	0.41
^{4}He	0.17	0.09	0.27	0.22
ER	0.43	0.15	0.33	≈ 0
Fission	0.57	0.85	0.67	≈ 1

In Table I we give the measured cross sections and cumulative decay fractions for each channel. Fusion cross sections are the sum of those for fission and evaporation residues. The cumulative decay fractions are simply the individual cross sections divided by the fusion cross section. (These fractions need not sum to unity.) Values of l_{crit} were estimated from the sharp cutoff approximation; they are significantly smaller than $l_{\max}$.[14]

The dependence of the decay fractions on energy and spin can be made explicit by comparing results for the matched entrance channels. As described in Ref. 8 we use the independence hypothesis to subtract from the ^{19}F cross sections the contributions from $l < l_{\mathrm{crit}}$ for the ^{12}C reactions. Table II lists the resulting cumulative decay fractions for each energy and spin domain. As expected, the fission probability increases significantly with spin at each energy.[1,4,8,15] With increasing spin the ^{1}H and ^{4}He evaporation probability decreases (or remains constant) in contrast to an increase in the fission probability.[4]

A striking result is provided by comparison of columns 3 and 4 in Table I ($E^* = 98$ MeV, $l_{\mathrm{crit}} = 59$; $E^* = 142$ MeV, $l_{\mathrm{crit}} = 65$). Here we increase the initial excitation energy E^* by 44 MeV, while the spin domain is only slightly enlarged from 0–59 to 0–65. Even though the increased energy provides 3–5 more chances for fission along the evaporation chain, the cumulative fission fraction is not enhanced. (The sharp-cutoff equation applied to σ_{ER} even indicates an increase from ~31 to ~36 between 98 and 142 MeV of excitation.) In parallel we see a strong enhancement in particle evaporation from 0.19 to 0.34 for ^{1}H and 0.13 to 0.27 for ^{4}He. Since the ^{1}H and ^{4}He evaporation have increased but fission has not increased, we infer that these decay channels are bleeding charge from the compound nucleus and thus shielding it from fission. The importance of charged-particle evaporation is even more dramatic in the last two columns of Tables I and II. Here for 142-MeV initial excitation it appears that the probability for charged-particle emission greatly exceeds that for the survival of the compound-nucleus residue.

An understanding of reactions between heavy nuclei is clearly dependent on our factual knowledge of fissionability at high energy and spin.[5,6] Recently several calculations have been presented[1,4] in an attempt to approach a systematic parametrization of fission barriers and level densities. This Letter dramatizes a most important aspect of this problem: the competition between fission and light-charged-particle evaporation. Meaningful description of the fission-evaporation competition requires a more careful calibration of the associated level densities and transmission coefficients at high energies and spins.[1,4] Cross sections and energy spectra from this work will be compared to statistical-model calculations in a later paper.

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Breakup of ^{9}Be in the Coulomb Field of Heavy Nuclei

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Measured cross sections for the breakup of ^{9}Be ions in the Coulomb field are found to be in disagreement with calculations based on a model which describes well the Coulomb breakup of deuterons. A possible explanation for this discrepancy in terms of Coulomb excitation of the projectile is suggested.

The breakup of different particles in the field of nuclei for energies well below the Coulomb barrier can be calculated with a semiclassical model.[1] In the case of the breakup of the deuteron, the results of this approximation are in excellent agreement with quantal (distorted-wave Born approximation, DWBA) calculations and with measured cross sections.[2] The assumption for the semiclassical approximations are even better fulfilled in the case of heavy ions. In order to check the models for another system, we measured the Coulomb breakup of ^{9}Be into ^{8}Be

