PHYSICAL REVIEW C VOLUME 36, NUMBER 1 JULY 1987

Nuclear shape deformations in 485-MeV ^{56}Fe+^{197}Au reactions

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(Received 17 February 1987)

Detailed coincidence studies of light-charged-particle evaporation in 485-MeV ^{56}Fe+^{197}Au reactions have recently been used to probe the features of fusion-like fission and deeply inelastic reaction mechanisms. We summarize here the average statistical properties which characterize the several identified groups of hot nuclear emitters. These properties are derived from comparisons of observed ^{4}He/^{1}H energy spectra and angular distributions with model calculations. The results demonstrate remarkably low effective evaporation barriers for the very heavy composite system produced here, consistent with the trends found previously for much lighter systems.

Experimental measurements of ^{4}He and ^{1}H evaporation spectra have recently been reported[1] for reactions of 485-MeV ^{56}Fe+^{197}Au. Fusion-like fission reactions and deeply inelastic reactions were distinguished by heavy fragment coincidence techniques, and the light-charged-particles associated with each reaction type were analyzed in terms of appropriate emission sources. The Monte Carlo reacton simulation code GANES (Refs. 2 and 3) was employed to calculate the ^{4}He and ^{1}H evaporation spectra from the excited nuclear emitters, and the ^{4}He/^{1}H multiplicities were evaluated by fitting the calculations to the observed coincidence spectra.[1] Consistency between the several emitter multiplicities was established by using the results derived from the coincidence data to predict the inclusive ^{4}He and ^{1}H energy spectra and angular distributions, and verifying the excellent agreement with the corresponding singles data. This successful confluence of calculation and experiment not only supports the validity of the derived particle multiplicities, but also provides a direct route from the energy and angular distributions to the effective mean temperatures and evaporation barriers of the emitting nuclei. In this paper, we report these statistical properties, as extracted from the fits to the ^{4}He and ^{1}H coincidence data,[1] and explore the possible role of nuclear deformation in accounting for the characteristics of highly excited nuclei.

To obtain the best fits to the experimental data, within the GANES calculation framework for spherical emitters, it was necessary to employ an empirical set of effective ^{4}He/^{1}H evaporation barriers.[4] These barriers are based upon an extensive systematic analysis[4] of ^{4}He and ^{1}H evaporation data for a large body of reaction systems covering a wide Z range of highly excited nuclei. The analysis is similar in concept to that reported earlier[5] for ^{4}He, but makes more critical and extensive use of the particle spectra and treats ^{1}H data as well. The results from these analyses have clearly shown that barriers to ^{4}He/^{1}H evaporation are generally significantly lower than predicted from fusion cross sections[6] for the reverse processes. By use of the empirical barrier systematics for ^{4}He and ^{1}H, the GANES simulations for evaporation from spherical emitters can reproduce experimental spectra rather well, and such calculations have played an important role in the interpretation of charged particle spectra in several studies.[7–9]

We show in Table I the effective average spherical emitter properties derived by GANES fits (with empirical barriers) to the experimental ^{56}Fe+^{197}Au data.[1] For fusion-like fission reactions (spin zone 0–101$\hbar$ in the entrance channel[1]), the experimental data are well reproduced by considering evaporation from the composite system (CS) prior to scission, as well as evaporation from accelerated fission fragments (FF). For each of these emission sources, the derived barriers and temperatures for ^{4}He and ^{1}H evaporation are listed in the table, along with the root-mean-square spin of the emitter. The more peripheral collisions lead to deeply inelastic reactions (spin zone 101–220$\hbar$), for which projectile-like fragments (PLF) and target-like fragments (TLF) can account for the observed ^{4}He/^{1}H evaporation. The corresponding derived parameters for these emitters are also given in Table I.

It is noteworthy that the heavy emitters studied here (CS in fusion-like fission reactions and TLF in deeply inelastic reactions) exhibit very low effective evaporation barriers, in much the same way as found previously for ^{4}He/^{1}H emission from lighter systems.[5,9–11] The systematic lowering of ^{4}He/^{1}H evaporation barriers for highly excited nuclei has aroused much current interest,[9–14] and suggests that the hot emitting nuclei may be quite deformed from their near-spherical ground state shapes. To pursue the implications of this idea, we have carried out a series of calculations using an option in the code GANES which does not rely on evaporation from barrier-modified spheres. Rather, the code simulates particle evaporation from deformed emitters whose barriers are determined by the details and extent of deformation. A description of

TABLE I. Derived spherical emitter properties for ^{4}He and ^{1}H evaporation in 485-MeV ^{56}Fe+^{197}Au reactions.

Reaction type (spin zone)	Emitter[a]	J_{RMS}[b]	Derived properties $\langle T_\alpha \rangle$	B_α	$\langle T_p \rangle$	B_p
Fusion-like fission	CS	71	2.4	22.3	2.4	9.9
(0–101$\hbar$)	FF	5	2.9	12.3	2.9	4.8
Deeply inelastic	PLF	5	2.7	6.9	2.6	2.3
(101–220$\hbar$)	TLF	42	2.7	16.0	2.5	7.8

[a] The properties extracted for each emitter are: $\langle T_\alpha \rangle$ and $\langle T_p \rangle$, average nuclear temperature (MeV) following evaporation of ^{4}He and ^{1}H, respectively; B_α and B_p, effective s-wave emission barrier (MeV) for ^{4}He and ^{1}H, respectively. The estimated uncertainties are ±0.2 MeV in the temperatures and ±0.5 MeV in the barriers, exclusive of any model dependence.

[b] The root-mean-square spin of the emitter, derived from cross-section data (Ref. 1) and application of the sticking model.

the features of this computer program, and its application to several illustrative systems, has recently been published.[3] We outline our calculational procedure below.

We already have achieved excellent fits to the ^{4}He and ^{1}H evaporation spectra from 485-MeV ^{56}Fe+^{197}Au reactions, using a spherical model with empirical barriers. The derived parameters are given in Table I, and the fits were shown in Ref. 1. We now want to determine whether correspondingly good fits can be obtained by starting with barriers obtained from the inverse fusion cross-section data for ground state nuclei. The CS is then allowed to deform systematically, producing corresponding changes in the barriers and moments of inertia. The detailed calculations were performed for CS emission in fusion-like fission reactions, and the results are presented in Table II in terms of two parameters which characterize the shapes of the particle evaporation spectra—the average energy $\langle \epsilon \rangle$, and the width (standard deviation) of the energy distribution σ. (Although the spectral shapes are skewed, the skewness does not change appreciably from one spectrum to the next, and hence two parameters are sufficient for comparison purposes.) The first column in Table II lists several laboratory detection angles for ^{4}He/^{1}H, for which coincidence spectra were reported in Ref. 1. The next two columns give the $\langle \epsilon \rangle$ and σ values at each experimental lab angle, which result from GANES calculations for spherical CS emitters using the parameters in Table I. These values characterize "best fits" at each angle (see Ref. 1) and provide a benchmark for comparison to the effects of nuclear deformation. Columns 4 and 5 give results obtained for a spherical emitter, but with evaporation barriers determined from fusion reaction

TABLE II. Mean energies and widths of laboratory spectra for ^{4}He and ^{1}H evaporation from CS.

Detection angle[a] θ (Φ)	Spherical emitter[b,c] $\langle \epsilon \rangle$	σ	Spherical emitter[b,d] $\langle \epsilon \rangle$	σ	Deformed emitter ($b/a=1.7$)[b,e] $\langle \epsilon \rangle$	σ
			^{4}He			
10	41.4	5.2	44.3	5.2	41.5	5.1
70	29.7	4.6	32.3	4.6	29.9	4.5
70 (60)	27.2	4.0	28.7	4.0	28.1	4.0
140	16.9	3.4	18.8	3.5	17.0	3.4
160	15.5	3.3	17.3	3.3	15.6	3.2
			^{1}H			
10	19.6	4.4	23.0	4.4	21.6	4.3
70	15.7	4.0	18.8	4.0	17.6	4.0
70 (60)	14.6	3.8	17.6	3.7	17.5	4.0

[a] Detection angles θ and Φ denote in-plane and out-of-plane positions, respectively. All angles are expressed in degrees.

[b] All mean energies and widths are expressed in MeV. The width parameter σ is the standard deviation of the energy distribution. The estimated uncertainties are ±0.3 MeV in $\langle \epsilon \rangle$ and ±0.2 MeV in σ.

[c] Using barrier systematics from Ref. 4.

[d] Using barriers determined from fusion reaction systematics (Ref. 6), modified slightly to correct for the effects of thermal expansion (Ref. 15).

[e] GANES option for deformed emitter (prolate) with axis ratio $(b/a)=1.7$. A difference of ±0.2 in (b/a) would yield a distinct difference in the mean energies.

systematics,[6] modified slightly to correct for the effects of thermal expansion.[15] This situation corresponds to using the GANES option for deformed emitters, but with a major-to-minor axis ratio $(b/a)=1.0$. If the emitting nuclei were indeed spherical, we would expect these calculated values to agree with experiment.

The calculations were then repeated many times, gradually increasing the degree of prolate deformation with each execution of the code. With increasing deformation, the average energies of the evaporated particles decreased, yielding the results shown in the last two columns of Table II with $(b/a)=1.7$. For this deformation, Table II indicates that the average ^{4}He energies have been lowered sufficiently to match the experimental data at all angles. Thus if prolate deformation were solely responsible for the observed low evaporation barriers, we would infer that the CS in fusion-fission reactions of ^{56}Fe + ^{197}Au $(E^* \approx 180$ MeV) is prolate deformed with an axis ratio of approximately 1.7. This deformation is comparable to the saddle point shape calculated from the rotating-liquid-drop model.[16] Hence one may infer that the emitter is past the point of no return on its route toward scission, an inference consistent with the experimental knowledge that the transient nuclear system will eventually fission.

Examination of the ^{1}H results in Table II, however, suggests that deformation may be only one factor in the observed barrier reductions. For the same deformation which yields good fits for the ^{4}He data, the calculated average ^{1}H energies (Table II) have not been lowered nearly enough to agree with experiment. In fact, the amount of deformation required to reproduce the ^{1}H spectral energies was found to be unreasonably large $(b/a \gg 3)$. The dramatic barrier lowering for ^{1}H evaporation is very interesting indeed, as it implies that processes other than emitter deformation must be taken into consideration.[10] Suppose, for example, that the nucleon density within the hot, deformed nucleus exhibited a transient low-density tail in the matter distribution at larger distances. Then nucleon evaporation might take place from the fringes of the nucleus, while cluster particle evaporation, such as ^{4}He, might require the more nearly normal nucleon density at smaller distances from the charge center. This apparent difference between ^{1}H and ^{4}He evaporation is emerging as a general feature of highly excited nuclei, as indicated by the recent systematics of evaporation barriers[4] and results for other reacting systems over a broad mass range.[10,11]

This work has been supported by the Division of Nuclear Physics, Office of High Energy and Nuclear Physics, U. S. Department of Energy.

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