New Mechanism of α-Particle Production in Heavy-Ion–Induced Fission

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Detailed studies have been made of the multiplicity, energy, and angular distributions of α particles emitted in coincidence with fission fragments from the ^{165}Ho + ^{56}Fe ($E_{\rm lab}$ = 465 MeV) reaction. Approximately 90% of the α particles are evaporated from the two fully accelerated fission fragments. The remaining α particles have a strongly enhanced emission probability in the direction perpendicular to the scission axis, suggesting the contact or neck region between the fragments as the source of these particles.

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The emission of neutrons and light charged particles from the neck region of the deformed nuclear system during the scission process is a phenomenon well known in spontaneous and low-energy-neutron–induced fission.[1] Of the light charged particles generally attributed to the sudden rupture of the neck between nascent fission fragments, α-particle emission occurs with the largest probability of $(2-3)\times 10^{-3}$ per fission event. The focusing of these charged particles due to the Coulomb field of the fission fragments provides one of the main signatures for the identity of this rare and unusual process which serves as a powerful probe of the scission process itself. The present work reports on the first observation of α particles with a similar anisotropic (focused) angular distribution in a heavy-ion–induced fusion-fission reaction.

The system ^{165}Ho + ^{56}Fe, at a laboratory bombarding energy of 465 MeV, was chosen for these studies because of the extensive body of data already available for this system.[2-5] The α particles were measured by large-area position-sensitive counters[6] in coincidence with fission fragments detected by a solid-state ΔE-E telescope positioned at $\theta_{\rm lab}({\rm HI}) = -22°$, as illustrated in Fig. 1. A total of 10^5 α-particle–fission-fragment coincidence events were collected.

The data are shown in Fig. 1 in a concise and model-independent form as a contour diagram of the Galilean-invariant cross section, $V_\alpha^{-2}d^2\sigma/dV_\alpha d\Omega_\alpha$, plotted as a function of the α-particle velocity in the laboratory system. The experimental cross sections are represented by heavy curves whereas the light lines show interpolated values. The conspicuous asymmetry of the cross section observed with respect to the beam axis eliminates isotropic emission from the composite

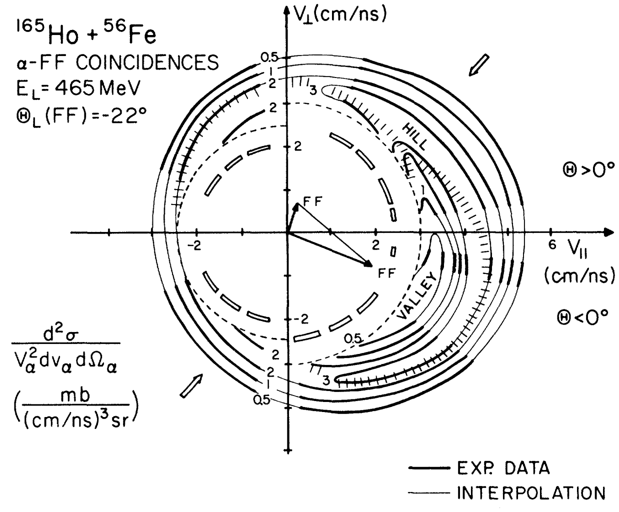

FIG. 1. The heavy (thin) solid contour lines represent the Galilean-invariant experimental (interpolated) cross sections for α particles in coincidence with fusion-fission fragments. The origin in the plot corresponds to the laboratory rest frame. The open-ring segments indicate the α-particle detector positions. The detector thresholds are marked by the dashed lines. The α-particle velocities at the predicted maxima of the cross sections are shown by the hatched rings. These predictions are based on the assumption that α-particle emission is only from the two fully accelerated fission fragments (FF) (their velocity vectors are indicated by the solid arrows). The open arrows represent directions perpendicular to the scission axis where anisotropic α-particle emission is observed.

system as a major production mode of the α particles, in sharp contrast to published results.[7] This conclusion cannot be reached by examination of data at backward angles alone. Isotropic emission of α particles in the rest frames of fully accelerated fission fragments results in contour lines that follow the superposition of two circles centered at the tips of the velocity vectors of the two fission fragments (see Fig. 1). The radii of the circles can be estimated from an empirical relation[8] for the Coulomb barrier energy E_B for α-particle emission from a nucleus of charge Z,

$$E_B\,(\text{MeV}) = 1.4 + 0.1875Z, \qquad (1)$$

and the nuclear temperature T of the emitting system. With an estimated value of $T = 2.7$ MeV, one expects maximum cross sections along the hatched circles in Fig. 1. The location of the hill due to the intersection of the two circles as well as the position of the valley in the data presented in Fig. 1 are well reproduced. Detailed comparison of the data with this model indicates that most ($\approx 90\%$) of the α particles are evaporated from the two fully accelerated fission fragments. Details of these results will be published elsewhere.[9]

Of special interest here are the remaining α particles that arise from a third source giving significantly enhanced yields of α particles in the first and third quadrants of Fig. 1, as indicated by the open arrows. The experimental results at selected angles can more readily be seen in Fig. 2 where velocity spectra corresponding to radial cuts through the distribution in Fig. 1 are shown

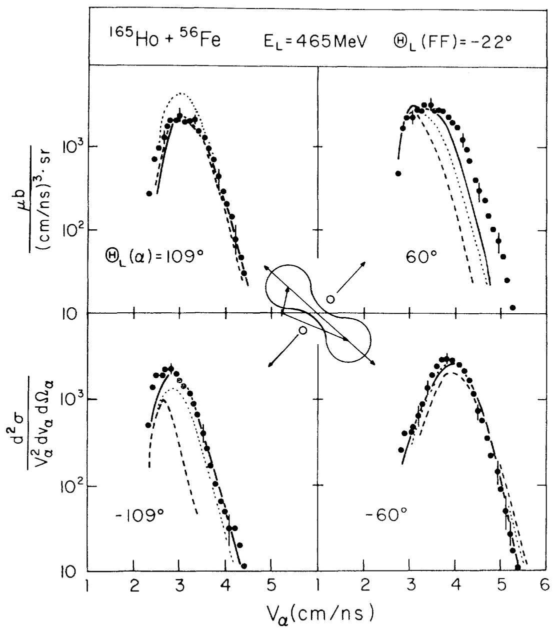

FIG. 2. The experimental Galilean-invariant cross sections at four selected laboratory angles compared to Monte Carlo calculations. The dashed lines result when all the α particles are assumed to come from the two fully accelerated fission fragments. The solid lines result when it is assumed that 91% of the α particles are emitted from the two fully accelerated fission fragments and 9% are emitted from a third source which emits preferentially in the direction perpendicular to the scission direction. The dotted lines result under the assumption that 13% of the α particles are emitted isotropically from the composite system and 87% from the fully accelerated fragments.

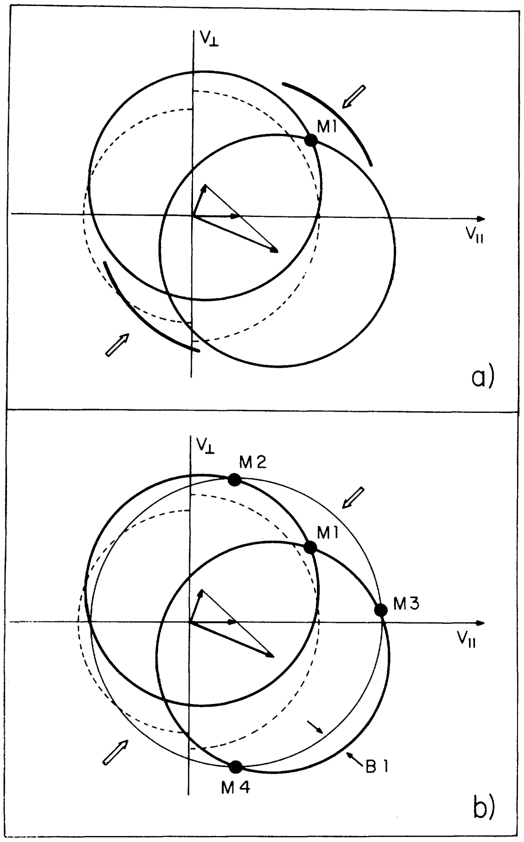

FIG. 3. Contours of the maximum Galilean-invariant α-particle cross section for the reaction ^{165}Ho + ^{56}Fe ($E_{\text{lab}} = 465$ MeV). Emission is assumed from the two fully accelerated fission fragments (heavy circles) as well as either (a) anisotropic emission from the neck region (heavy lines near open arrows) or (b) isotropic emission from the composite system (thin circle). Experimental discrepancies with the latter case are discussed in the text. The dashed lines give the experimental detection thresholds. The solid arrows represent the velocity vectors of the two fission fragments and the composite nucleus.

as solid circles. The dashed curves in Fig. 2 are results of Monte Carlo calculations with a general purpose simulation code[10] assuming a single normalization factor and an isotropic Maxwellian evaporation spectrum for the α particles in the rest frames of the two fully accelerated fission fragments. Account has been taken in the calculation of the finite widths of the fission-fragment Z and total kinetic energy distributions.

The predictions of the two-source model (dashed lines in Fig. 2) which lead to good agreement with the data at 109° and $-60°$, grossly underestimate the magnitude of the cross sections observed for high α-particle velocities at 60° and $-109°$. One then concludes that there is a third α source emitting preferentially into the regions indicated by the open arrows in Fig. 1. Inspection of the velocity diagram for fission fragments shows that this direction is perpendicular to the scission axis. This analogy to α-particle emission in low-energy fission suggests that these α particles arise from the neck region of the highly deformed nucleus. The fact that the fissioning system rotates with a very high average angular velocity ($\frac{2}{3} l_f \approx 84\hbar$) does not affect the position of the centroids for the two expected peaks in the angular distribution of these α particles. This follows because the direction of rotation of a long-lived composite system is not determined by detection of a fission fragment. This directional symmetry results in a broadening or possible splitting of the cross-section peaks as the only net effect of the rotation. An estimate of the upper limit for this rotational broadening can be calculated from the Coulomb deflection function of the fission fragments by neglecting the exit-channel Coulomb interactions between the α particles and fission fragments. For example, with an assumed intrinsic full width at half maximum (FWHM) of 40°, an upper limit for the FWHM including rotational broadening is 80°. However, exit-channel Coulomb interactions will strongly diminish the rotational broadening.

Before discussing further the above α-particle angular correlation, evidence is pointed out that the third source does not emit isotropically in the center of mass. The topologies of Galilean-invariant plots of the α cross section for the ^{165}Ho $+ ^{56}$Fe system are compared in Fig. 3 under the assumption of emission from the two fully accelerated fission fragments combined with either anisotropic emission from the neck region [Fig. 3(a)] or isotropic emission from the composite system [Fig. 3(b)]. In order to distinguish between the above two emission processes for the third component, it is insufficient to observe α particles only perpendicular to the scission axis. However, the isotropic-emission model predicts cross-section maxima at laboratory angles marked M_2 to M_4 in Fig. 3(b). The data show no indication of such enhanced cross-section regions. In addition, a superposition of two peaks is expected in the second and fourth quadrants or at least broader velocity spectra, e.g., the velocity spectrum at B_1 is expected to be much wider than that at M_4 [see Fig. 3(b)]. Such broadening is also not observed. In fact, the absolute widths of the spectra in quadrants two and four agree well with the parameter-free Monte Carlo calculations for the two-source model.

Having established the occurrence of anisotropic α-particle emission, one may tentatively model the associated multiplicity for these α particles by

$$d^2M_{\alpha N}/d\Omega_\alpha dE_\alpha = fM_\alpha(2\pi\sigma_\theta{}^2)^{-1/2}\sum_{i=1}^{2}\exp\{-(\theta-\theta_i)^2/2\sigma_\theta{}^2\}(4\pi T^2)^{-1}(E_\alpha - E_{BN})\exp\{-(E_\alpha - E_{BN})/T\}. \quad (2)$$

Here the angular dependence is the sum of two Gaussians centered at the directions perpendicular to the scission axis. The overall multiplicity M_α of α particles is 0.6 ± 0.3 per fission event and f is a normalization factor obtained by fitting the data. The solid curves in Fig. 2 result from Monte Carlo calculations that include α emission from the two fully accelerated fission fragments and anisotropic in-plane α emission from the neck. Accounting for the latter process with $f = 0.09$, barrier energy $E_{BN} = 21$ MeV, FWHM(θ) $= 40°$, and temperature $T = 2.5$ MeV gives a reasonable fit to the data in all four quadrants. Inclusion of rotational broadening and exit-channel Coulomb interactions may further improve the fit to the data in the first quadrant. The fitted value of $f = 0.09$ leads to $M_{\alpha N} = 0.05^{+0.07}_{-0.03}$ per fission event. For illustrative purposes, the results of a Monte Carlo calculation assuming only isotropic emission from the composite system with the same barrier energy and temperature parameters as for anisotropic emission are also shown in Fig. 2 (dotted lines). The agreement with the data is clearly inferior to that for anisotropic emission.

The present results correspond to a multiplicity of neck α particles an order of magnitude larger than that observed in low-energy fission. However, extrapolating existing multiplicity[1] data to the values of excitation energy and fissility in the present experiment gives an estimate of $M_{\alpha N} \approx 0.01$, with sizable uncertainty. Furthermore, it is known that 80% of the fusion-fission cross section[4] for the ^{165}Ho + ^{56}Fe reaction at $E_{\text{lab}} = 465$ MeV is associated with angular momenta in excess of the stability limit of the rotating-liquid-drop model. Hence, it is not surprising that the observed multiplicity $M_{\alpha N}$ of neck α particles is a few times larger than expected from this extrapolation.

In view of the large value for the multiplicity of neck α particles observed in the fusion-fission process for the ^{165}Ho + ^{56}Fe reaction, it is interesting to speculate about the multiplicity of neutrons (and other particles) from the same source. Three groups[11-13] have recently reported large multiplicities of prefission neutrons from heavy-ion–induced fission. Since neutrons are not focused by the Coulomb field, the observed isotropic neutron distributions may arise from the same source as the anisotropically emitted α particles described in this work. The observed prefission α-particle to neutron multiplicity ratio for heavy-ion–induced fission is similar to that ($\approx 10^2$) for spontaneous fission[1] of ^{252}Cf.

In summary, the present data demonstrate for the first time a significant probability for preferential α-particle emission perpendicular to the symmetry axis of a fissioning heavy-ion system, a process that could provide a new access to the dynamics of nuclear scission in heavy-ion reactions.

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