Pre-equilibrium α Emission in Reactions of 724-MeV ^{86}Kr with Au: A Coincidence Study of Direct and Evaporation Mechanisms

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

Our purpose here is to explore the qualitative features of mechanisms for production of ^{4}He in the reaction of 724-MeV ^{86}Kr with ^{197}Au. Britt and Quinton[1] found, for ^{12}C- and ^{16}O-indcued reactions, large cross sections for ^{4}He evaporation from the compound nucleus, and in addition, a large number of forward-peaked high-energy particles which were attributed to projectile breakup. Galin *et al.*[2] found no such direct ^{4}He emission in the reaction ^{40}Ar + ^{77}Se. Recently, coincidence measurements in light systems have given indications of pre-equilibrium α emission.[3] In heavy systmes, it is well known that reactions between very heavy nuclei give little, if any, complete fusion reactions, but instead give rise to a continuous range of energy-loss values from near zero to near maximum.[4] As yet, however, no experiments have probed even the qualitative features of ^{4}He-production mechanisms for Kr reactions. This Letter reports results from ^{4}He–heavy-fragment coincidence experiments, in which the observed ^{4}He emission can be partially accounted for by evaporation from equilibrated heavy products, but in addition there is strong evidence for pre-equilibrium ^{4}He emission.

The highly negative Q values for ^{86}Kr + ^{197}Au reactions demand that large excitation energies be deposited in the composite system. That part which equilibrates in the separating fragments will surely lead to evaporation of neutrons and light charged particles. Also, of course, there may be ^{4}He ejected prior to equilibrium from a frictionally heated contact zone or by rapid collective modes of the composite system.[4] We have no clear idea of what kinds of pre-equilibrium processes will appear, but we do know quite a lot about the evaporation processes from compound nuclei of similar energies and spins, for example, ^{75}Br and ^{194}Hg.[5,6] Thus our approach is to detect ^{4}He particles in coincidence with heavy fragments and then ask whether or not their characteristics can be accounted for by evaporation from fragments or the compound nucleus. Our analysis tries to set an upper bound for the evaporation component and therefore a lower bound to the pre-equilibrium component.

Beams of ^{86}Kr (≈ 20 nA) were provided by the Lawrence Berkeley Laboratory SuperHILAC; they were monitored by a Faraday cup after passage through the Au target of 2.66 mg/cm^2. We used a Fowler-Jared gas telescope[7] (GT) (≈ 2 msr) to detect and measure ΔE and E of the heavy fragment, and a three-member solid-state telescope (SST) (45 μm, 500 μm, 5 mm; 17 msr) to detect the light charged particles. A time-to-am-

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plitude converter was started by the second detector in the SST and stopped by the E detector in the GT. These six parameters were recorded on tape and analyzed off line to give atomic numbers and energies of heavy and light particles for each coincident event. The values of ΔE and E from the gas telescope were used to identify Z and energy of one heavy fragment. Energies and pulse-height defects for the E detector were calibrated by the elastically scattered ^{86}Kr beam and fission fragments from ^{252}Cf. The ΔE values deposited in the gas were also calibrated by elastic ^{86}Kr. We have used the Northcliffe-Schilling[8] tables to estimate Z normalized to the elastic scattering of ^{86}Kr. We then assigned the most stable mass to each Z for the detected fragment (Z uncertainties are ± 3 units as estimated from the energy resolution). Also, we made certain assumptions to estimate the pre-evaporation mass of the detected fragment and its kinematic partner. For this purpose we assumed a mass loss of 1 amu per 12 MeV of Q, apportioned between the fragments according to the ratio of their masses. The fragment velocities are assumed to be unchanged by evaporation or other processes.

Our trigger GT detector was placed at 36° (or 42°) which means that the kinematic partners (assuming two-body kinematics) were scattered from 300° to 340° depending on the Q value. The smaller GT angle, 36°, is only slightly greater than the grazing angle, $\theta_{1/4}$, and thus there was a large quasielastic peak for the heavy fragments.[9] However, at 42° this peak was not present in the singles spectra and the heavy-fragment energies indicate that > 95% of the reactions have energy loss values of ⩾ 200 MeV. The vector diagram in Fig. 1 shows typical velocities for the detected fragment Kr*. Added to each fragment velocity is a ^{4}He velocity typical of an evaporation spectrum. Our ^{4}He detection threshold was ~ 9 MeV corresponding to the circle at 2.1 cm/ns. This figure shows that ^{4}He evaporated from the detected Kr* fragment will only be efficiently detected at 81° for our choice of SST angles. Those evaporated from the kinematic partners Au* will be easily detected for $\theta_{\rm SST} \geqslant 225°$ but only with reduced efficiency for the other angles. (Even at 81° some contribution to the observed ^{4}He spectrum will be derived from evaporation from the Au*.)

To test for the presence of evaporated charged particles we transformed the laboratory differential cross sections $d^3\sigma/d\Omega_{\rm Kr^*}d\Omega_\alpha\, d\epsilon_\alpha$ into the

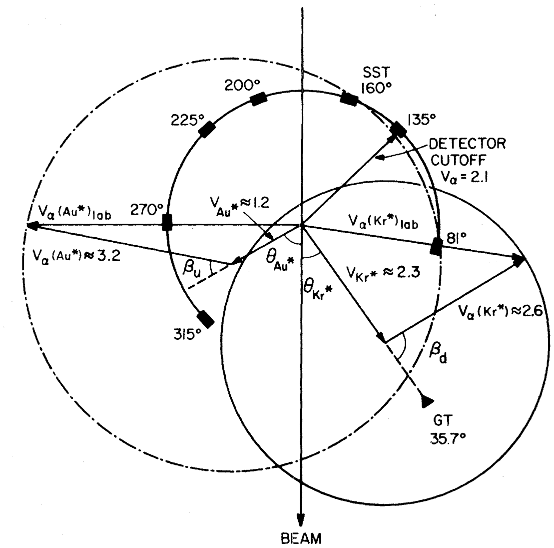

FIG. 1. Velocity vector diagram of a typical hard reactive collision. Velocities are given in centimeters per nanosecond. The fragment labeled Kr* was detected in a GT at $\theta_{\rm lab} = 36°$ ($\theta_{\rm c.m.} \approx 65°$). The undetected fragment Au* recoiled at $\theta_{\rm lab} = 300°-340°$, depending on the Q value. The velocities of ^{4}He particles emitted at Coulomb barrier energies are shown. Their angles of emission with respect to the fragment velocities β_d and β_u are also shown. The SST for ^{4}He detection was situated at the indicated angles with ^{4}He velocity threshold of ~ 2.1 cm/ns. The lab-system ^{4}He velocities for the cases shown are well above this detection threshold at 81° or 270°.

moving frames of the detected and undetected fragment as well as into the c.m. system. For this transformation, the laboratory differential cross section for each event was multiplied by the ratio of the solid angle in the laboratory to that in the moving frame. The resulting differential cross sections were grouped in 3-MeV intervals and are shown in Fig. 2. Figure 1 shows the strong kinematic velocity shifts and illustrates the large differences between laboratory angles and those with respect to the directions of the moving fragments (β_d and β_u). Nevertheless, the half-width of the β distribution for a given laboratory configuration is between 5° and 15° (i.e., a rather well-localized distribution in the moving frame.)

In Table I we summarize some other aspects of the experimental results. Average Q values range from − 250 to − 290 MeV for the 36° trigger angle (of the GT) and − 290 and − 325 MeV for the 42° trigger angle. Standard deviations of the Q distributions are ~ 100 MeV at 42° and ~ 180

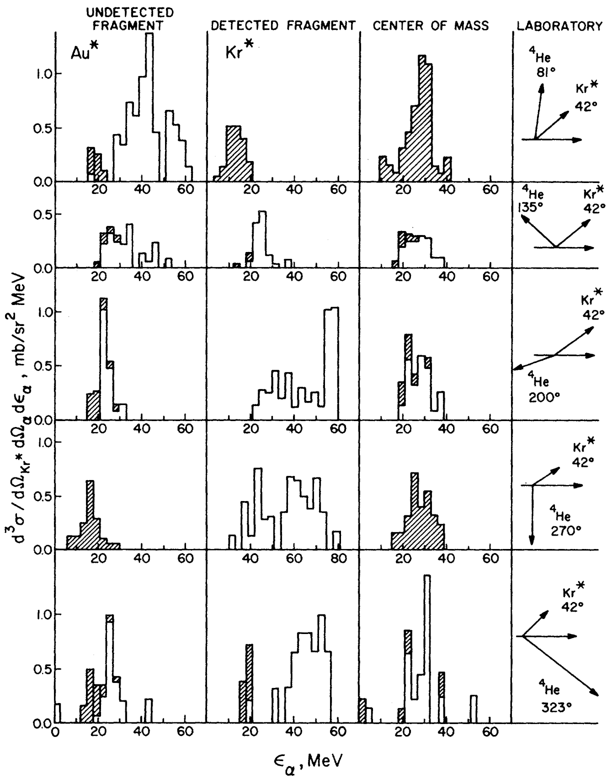

FIG. 2. Values of $d^3\sigma/d\Omega_{Kr^*}\,d\Omega_\alpha\,d\epsilon_\alpha$ vs energy in the frame of the undetected fragment Au*, the detected fragment Kr*, and the c.m. The vector diagram on the right gives for the α and Kr* the laboratory angles and average velocities for each spectrum in that row. Shaded areas are attributed to evaporation from the fragments.

MeV at 36° Average Z values for the detected fragment range from 39 to 46 with second moments of ~8–12 units. The coincident detection of ^{1}H or ^{4}He with a heavy fragment of $\langle Z\rangle \approx 40$ rather than ≈ 57 rules out major contributions from evaporation prior to fission of a compound nucleus of $Z = 115$.

Now we wish to determine the maximum possible contributions of ^{4}He evaporation processes at each angle of observation. We make use of two properties[5,6] of evaporation from ^{75}Br and ^{194}Hg: (1) The energy spectrum peaks somewhat above the barrier energy and is bound between 0.5 and 2 times the barrier; (2) the angular distribution is essentially isotropic for ^{194}Hg, and slightly forward-backward peaked for ^{75}Br. We look first at $\geqslant 200°$ at the energy spectrum of ^{4}He in the frame of the undetected fragment. As mentioned above, at these angles we expect a high detection efficiency for evaporation from Au* and none from Kr*. In the left-hand column of Fig. 2 we see that, at the angle 270°, the energy spectrum in the frame of Au* ranges from 8 to 30 MeV as expected of evaporation from the observed Z distribution.[6] As an upper limit we have attributed this whole spectrum to ^{4}He evaporation, and we have subtracted it from that shown for the Au* frame at each other angle of observation. This subtraction was performed for each energy bin in the Au* frame; the cross section corresponding to individually subtracted events was removed from each respective energy bin both in the Au* frame and in the center-of-mass frame.

Similarly, next we turn to 81° where, from Fig. 1, we expect maximum efficiency for detection of ^{4}He evaporation from Kr*. In Fig. 2 we see that the energy spectrum in the frame of the detected fragment Kr* (after subtraction of the Au* contribution) ranges from 5 to 20 MeV as expected of evaporation.[5] Thus we have attributed this whole spectrum to ^{4}He evaporation and we have subtracted it from that shown for the Kr* frame at each other angle. As expected this subtraction has only a very small effect because our low-energy cutoff had already removed most of these events.

The residual integrated c.m. cross section at

TABLE I. Experimental results for ^{4}He–heavy-fragment coincidences in reactions of 724-MeV ^{86}Kr with Au.

θ_{GT} (deg)	θ_{SST} (deg)	N [a]	$-\langle Q\rangle$ (MeV)	$S_{c.m.}^{o}$ [b] (mb/sr^2)	$S_{c.m.}^{r}$ [b] (mb/sr^2)	$\delta_{c.m.}$ [c] (deg)
35.7	81	68	252	18.3	$\equiv 0$	30
	135	34	250	18.2	13.1	80
	205	35	277	17.5	$\equiv 0$	130
	225	30	288	17.5	1.7	150
	315	63	257	23.0	9	245
41.7	81	60	305	14.2	$\equiv 0$	15
	135	30	322	5.5	4.9	60
	160	16	305	4.3	3.5	80
	200	30	295	9.4	7.7	110
	270	36	299	8.6	$\equiv 0$	195
	315	92	302	13.1	7.8	235
	323	20	323	12.6	10.3	245

[a] Number of coincident events recorded between ^{4}He ($\geqslant$ 9 MeV) and a heavy fragment ($\geqslant$ 120 MeV).

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

[c] $\delta_{c.m.} \equiv \langle\theta_\alpha\rangle_{c.m.} - \langle\theta_{Kr^*}\rangle_{c.m.}$.

each angle are listed in the fifth column of Table I. For angles of 135°–205° and ≥ 315° we find a significant number of events with ^{4}He energies greater than those attributable to evaporation from the fragments. These events must correspond to ^{4}He particles which were not emitted from the excited, equilibrated fragments. The last column in Table I gives the average angle of emission of these pre-equilibrium α particles with respect to the detected heavy fragment (Kr*) in the c.m. system. In this frame they are emitted with greatest probability between 60° and 125° relative to the Kr*. Their average c.m. energy is ~30 MeV or near to the Coulomb barrier for $Z = 115$. This angular preference is reminiscent of the α particles emitted in low-energy fission, and the Coulomb fields of the separating fragments may be responsible for the focusing here as well.

In this series of experiments we also detected protons and have analyzed the results in the same way. Evaporation can account for almost all protons observed in coincidence with the GT at 36°. The total number of protons is roughly comparable to that of ^{4}He; the number of events which could not be attributed to fragment evaporation seems to be greater for ^{4}He. We will report separately the energy and angular distributions of ^{1}H, ^{2}H, ^{3}H, and ^{4}He detected in the singles mode.

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