Compound nucleus fission at high angular momentum studied in the reaction $^{132}Xe + ^{30}Si$

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Reaction products from the bombardment of ^{132}Xe onto ^{30}Si at energies between 5.4 MeV/u and 8.2 MeV/u have been measured by a time-of-flight system combined with an ionization chamber. At all energies fission fragments are found to be well separated from deep inelastic reaction products. The rapidly increasing excitation function for fission shows an onset at 65–70 $\hbar$. This value and an l_{crit} of 98 $\hbar$ at 8.2 MeV/u are compatible with the concept of a fissioning compound nucleus. However, at the highest bombarding energies the Z distributions indicate the emission of charged particles which is difficult to reconcile with the idea of a fully equilibrated compound nucleus. Incomplete momentum transfer reactions (incomplete fusion) followed by fission are considered as an explanation for the strong increase of the width of the Z distribution with excitation energy. Consequences for the formation of compound nuclei at high angular momenta are discussed.

[NUCLEAR REACTIONS $^{132}Xe + ^{30}Si$; $E/A = 5.4–8.2$ MeV/u; measured Z and A distributions of fission fragments and $\sigma_{fission}(E)$; compound nucleus fission and nonequilibrium effects. Enriched target.]

I. INTRODUCTION

The formation of compound nuclei in heavy-ion reactions enables the study of the behavior of nuclei subject to high centrifugal forces. A variety of experiments has been devoted to measuring particle emission and subsequent γ decay from such highly excited rapidly rotating nuclei. A very successful method is the γ-multiplicity technique which has been used to determine the angular momenta involved.[1] Other studies have concentrated on the fission of these nuclei.[2] By predicting their stability limits rather well the rotating liquid-drop model (RLDM)[3,4] has very much stimulated such investigations.

The nucleus ^{162}Er has attracted much attention as it can be formed by a large variety of entrance channels. By using different experimental techniques the following conclusions have been reached: In the reactions $^{16}O + ^{146}Nd$ and $^{32}S + ^{130}Te$ (up to spins of 60 $\hbar$) the measured fusion-evaporation cross section as a function of bombarding energy was used to determine the maximum angular momenta leading to fusion by applying the relation ${l_{crit}}^2 = \sigma_{ER}/\pi\lambda\!\!\!^{-2}$. Between this l_{crit} and the measured γ multiplicities a linear dependence was found.[5] This justifies the use of γ-multiplicity data in order to deduce l_{crit}. When ^{162}Er was formed in the reaction $^{40}Ar + ^{122}Sn$ at higher energies,[6,7] a saturation of the γ multiplicities at about 65 $\hbar$ was observed. A slightly higher l value is predicted as the onset of fission by the RLDM. Indeed, a small fission cross section has been observed in the reaction ^{32}S on ^{130}Te at 163.5 MeV[8] where compound nuclei were formed with spins of this order.

In this paper we report on a study of the fission of ^{162}Er at high angular momenta. Bombarding ^{132}Xe on ^{30}Si at energies between 5.4 MeV/u and 8.2 MeV/u angular momenta up to 80 $\hbar$ and 130 $\hbar$, respectively, are available in the entrance channel. Thus we are likely to form compound nuclei at angular momenta ranging from the onset of fission up to and beyond the critical value of 95 $\hbar$, where the RLDM predicts the fission barrier to vanish. Two aspects are then to be investigated: (1) Are fully equilibrated compound nuclei formed at these high angular momenta? (2) Do the properties of the fission fragments reflect the fact that the fission barrier is vanishing? We will discuss both questions utilizing the fission excitation function (Sec. III A) and the properties of the fission fragments (Sec. III B), in particular the width of the fragment mass distribution (Sec. III C), after briefly presenting the experimental technique.

II. EXPERIMENTAL TECHNIQUE

^{132}Xe beams between 5.4 and 8.2 MeV/u were delivered by the UNILAC at GSI. The targets consisted of a 70 $\mu g/cm^2$ thick layer of $^{30}SiO_2$ (enriched to 94.7%) on a carbon backing. Mass, atomic number, and energy of the outgoing fragments were determined with a time-of-flight system combined with an ionization chamber. The start detector was a channel-plate assembly with a vertical 20 $\mu g/cm^2$ carbon foil coated with a 10 $\mu g/cm^2$ layer of MgO to increase the efficiency for secondary electrons. The emerging electrons were accelerated and bent in the field of a permanent magnet by 180° onto the channel plate. After a flight path of 1 m the particles entered the ionization chamber consisting of a 12 cm gas counter[9] (pure methane) and a silicon-surface-barrier detector which measured the residual energy and supplied the time-stop signal. A time resolution of 300 ps was achieved. As we were interested in gross properties of the reaction, it was not necessary to resolve the masses and Z values over the whole domain. However, mass and Z calibrations were carefully carried out with recoils from Fe and Ni targets. Measurements with good statistics for fission fragments were performed at only one angle close to the Fresnel peak. At all energies angular distributions of the elastic scattering were measured for normalization purpose as well as for derivation of the reaction cross section. These data will be published elsewhere with a variety of other elastic scattering data.

The raw data (energy loss, residual energy, and time of flight) were written on magnetic tape event by event and processed off line. Using standard GSI procedures[10] the final parameters (energy, mass, and atomic number) were deduced. Figure 1 shows the mass-energy matrix obtained at the highest energy of 8.2 MeV/u. Fission fragments are centered near half the compound nucleus mass and are well separated from deep inelastic processes around mass 132. Owing to the high center-of-mass velocity we also observe part of the second kinematic solution, represented by reaction products at low energies emitted in the c.m. system towards backward angles. All components lie on a curve given by the Coulomb repulsion between two spheres, resulting in the horseshoe-like plot in the lab system.

The double differential cross sections $d^2\sigma/d\theta dZ$ were evaluated by transforming the measured kinetic energies into Q values, correcting for particle emission by an iteration procedure as described elsewhere.[11]

III. RESULTS AND DISCUSSION

A. Cross sections

As shown in Fig. 1, the fission fragments are concentrated around half the compound nucleus mass and are clearly separated from products originating from deep inelastic collisions. Figure 2 demonstrates this quantitatively for all energies by the Z spectra of the fully relaxed reaction products. Their properties are discussed in the next subsection. The total fission cross section has been evaluated assuming $1/\sin\theta$ angular distributions (see Sec. III B). The excitation function is shown in Fig. 3. The result of the very similar

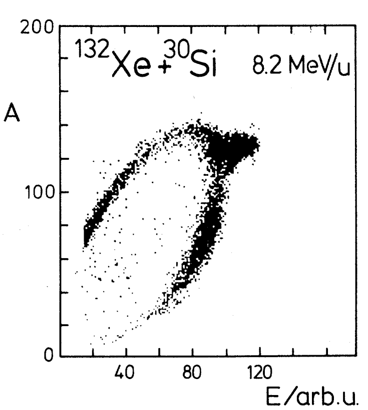

FIG. 1. Scatter plot of mass versus laboratory energy of reaction products from bombarding ^{132}Xe on ^{30}Si at 8.2 MeV/u. The branch at low energies with masses between 70 and 120 is due to reaction products being emitted backwards in the center-of-mass system (second kinematic solution).

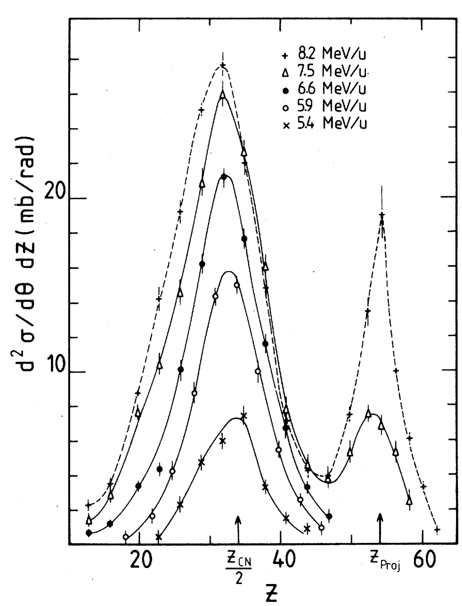

FIG. 2. Double differential cross section $d^2\sigma/d\theta dZ$ of the fully relaxed reaction products at various bombarding energies versus atomic number. At low energies the cross section for deep inelastic projectile-like fragments could not be determined. The lines are to guide the eye.

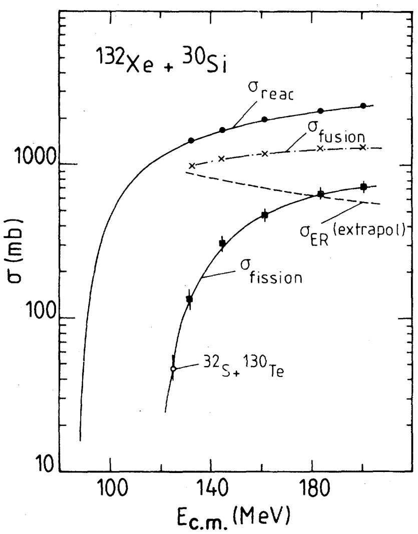

FIG. 3. Measured fission excitation function (■). The solid line is to guide the eye. The dashed line represents the evaporation residue cross section which has been assumed to be due to partial waves $\leq 65\,\hbar$. σ_{fusion} is the sum of $\sigma_{fission}$ and σ_{ER}. The reaction cross sections (●) result from fits to the elastic scattering data and the connecting solid line represents the calculations for other energies.

entrance channel, $^{32}S+^{130}Te$ (Ref. 8), is represented as an open symbol where the energy has been scaled according to the different barriers. The fission excitation function has a threshold around $E_{c.m.} = 120$ MeV. At this incident energy the compound nucleus is populated with spins up to 65 $\hbar$, and this value has been established to be the limiting angular momentum for evaporation residue formation.[6,7] Hence, our rapidly increasing fission excitation function indicates that the higher angular momenta brought into the compound nucleus lead to fission. This is in good agreement with the RLDM which predicts that at 69 $\hbar$ the fission barrier B_f is equal to the neutron binding energy, B_n.

The dashed line in Fig. 3 represents an estimate of the evaporation residue cross section σ_{ER} which has been obtained assuming that compound nuclei with spins lower than 65 $\hbar$ decay by particle emission only. Summing σ_{ER} and the measured $\sigma_{fission}$ to yield a purely operationally defined fusion cross section, σ_{fusion} (dashed-dotted line in Fig. 3), the maximum angular momentum leading to fusion l_{crit} can be extracted for all energies. The results are given in Table I together with the cross sections for the various components and parameters characterizing the reaction. At the highest energy the maximum spin of 98 $\hbar$ almost coincides with the l value at which the fission barrier vanishes (RLDM). However, the data do not allow one to conclude whether the fission cross section will continue to rise at higher energies. A brief experiment at 8.5 MeV/u indicated that the fission cross section is still increasing. It should be mentioned that the assumption of a maximum value of 65 $\hbar$ for the evaporation residue cross section introduces an uncertainty in the deduced values of l_{crit}. There are some indications that the maximum l values for the fusion-evaporation process may increase; values up to 80 $\hbar$ have been reported.[7] Therefore the values l_{crit} in Table I should be regarded as lower limits. In the case of 8.2 MeV/u, for example, the assumption of 80 $\hbar$ for fusion evaporation would increase l_{crit} from 98 $\hbar$ up to 108 $\hbar$.

The cross sections for quasielastic and deep inelastic processes could not be determined, since the angular distributions had not been measured. The reaction cross sections, however, have been obtained at all energies from an optical-model fit to the elastic scattering angular distributions (full points in Fig. 3). The connecting solid line represents the optical-model reaction cross section as a function of energy.

B. Properties of the fission fragments

It is generally accepted that fission fragments originating from a fully equilibrated compound

TABLE I. Summary of cross sections, deduced angular momenta, and values characterizing the reaction.

E_{lab}/A (MeV/u)	$E_{c.m.}$ (MeV)	$E_{c.m.}/V_{Coul}$	θ_{lab}	$\theta^{sym}_{c.m.}$	E_X^{CN} (MeV)	θ_{saddle} (MeV)	σ_{ER} [a] (mb)	$\sigma_{fission}$ [b] (mb)	σ_{reac} [c] (mb)	$l_{T=1/2}$ [c] ($\hbar$)	l_{crit} (exp) ($\hbar$)
5.4	132	1.43	9°	29°	85	1.51	865	130	1403	82	70
5.9	144	1.56	8°	27°	97	1.68	790	306	1656	93	77
6.6	161	1.75	7°	24°	114	1.89	703	466	1938	107	84
7.5	183	1.99	5.5°	20°	136	2.14	621	653	2222	122	93
8.2	200	2.17	5°	19°	153	2.26	569	716	2397	133	98

[a] Assuming $\sigma_{ER} = \pi \lambda\!\!\!^{-2} (65)^2$.

[b] The total errors are estimated to be of the order of 10%.

[c] From optical-model fit to the measured elastic scattering.

nucleus formed in a heavy-ion reaction exhibit the following characteristics:

(1) angular distributions proportional to $1/\sin\theta$,

(2) full relaxation in energy, i.e., fragment kinetic energies given by the Coulomb repulsion,

(3) symmetric mass and Z distributions primarily centered at half the mass and Z of the combined target and projectile.

These properties can be studied in our system without interference from the deep inelastic reaction component.

This perfect separation suggests that the fragments near the symmetry point are due to rather long interaction times. Then angular distributions proportional to $1/\sin\theta$ are expected, as has been verified for various systems.[12] There is no reason to assume our system to behave differently. The measured total kinetic energy (TKE) for symmetric mass split increases with increasing bombarding energy, with an average of 130 ± 10 MeV. This dependence seems not to be fully accounted for by the rotational energy of the dinuclear system at scission (10–14 MeV), which should be subtracted in order to allow a comparison with Viola's systematics,[13] which predicts 113 MeV. The remaining increase could mean that the distance of the two centers at scission is smaller at high angular momenta. However, the precision of our data does not allow any definite conclusion.

As can be seen qualitatively in Figs. 1 and 2 the fragment distributions in M and Z are rather symmetric. The shift of their centroids with respect to $A_{CN}/2$ and $Z_{CN}/2$ is given in Fig. 4 as function of the excitation energy per fragment.

The upper curve $\langle \Delta A \rangle$ reflects the normal trend of particle emission from excited fragments. As seen in the lower frame, the centroids of the Z spectra are at the symmetry point at small excitation energies, i.e., no charged particles are emitted. However, at the highest excitation energy the loss in mass is accompanied by a loss of up to two charge units per fragment. It can be excluded that the observed shift in the Z spectra is caused by fission reactions on light target contaminants such as ^{16}O abd ^{12}C. This has been proved by bombarding a C target containing a sizable amount of oxygen. Fission of the corresponding compound nuclei is very unlikely because they have too low angular momenta; e.g., for the reaction ^{132}Xe on ^{16}O at 8.2 MeV/u incident energy the critical l value is about 60 $\hbar$; the corresponding fission barrier is about 18 MeV.

The emission of charged particles from equilibrated fission fragments cannot account for the observed shift. Evaporation calculations for the highest excitation energy using the codes CASCADE[14] and GROGI-2[15] yield $\langle \Delta Z \rangle = -0.2 \pm 0.2$ per fragment. This is mainly the consequence of the low spins of the fragments which are estimated in the sticking limit to be less than 20 $\hbar$. It is interesting to note that a similar shift in the Z spectra has been observed in the reaction ^{40}Ar on ^{197}Au at 217 MeV.[16] At higher bombarding energy the emission of charged particles in coincidence with fission seems to increase strongly in this system.[17]

Looking for possible explanations of this charged particle emission one might consider particle emission from the highly excited compound nuclei prior to fission. Again, evaporation codes[14,15] still predict for a compound nucleus with a spin of 100 $\hbar$ a tremendous preference of neutron over charged particle emission. In a recent letter[18] it was pointed out that deformation will increase the α-emission rate. But it seems difficult at present to explain an α multiplicity of two by such a mechanism. Another explanation of unusually large loss of charged particles in fission could be the emission during scission as found in the decay of actinides with a very small probability.[19] It cannot be excluded, but it seems unlikely that such a process is drastically enhanced by excitation energy and angular momentum for the system considered.

So far we have discussed particle evaporation from fully equilibrated compound nuclei which is unlikely to explain the observed charge loss at high energies. Pre-equilibrium emission has to be considered, too. Pre-equilibrium emission of neutrons has already been reported for this compound system.[20] For the system ^{12}C + ^{158}Gd at 152 MeV bombarding energy pre-equilibrium α emission has been observed, accounting for $(28 \pm 6)\%$ of the total (^{12}C, αxn) cross section,[21] a value too small to explain the observed charge loss in our

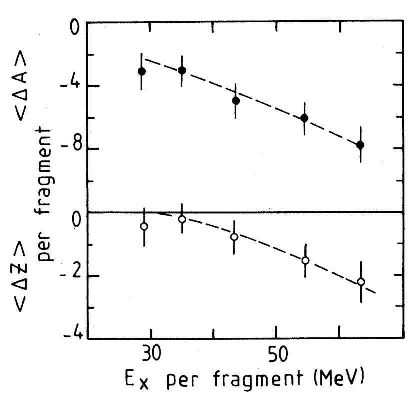

FIG. 4. Shift of the centroid of the observed mass and Z distribution with respect to $A_{CN}/2 = 81$ and $Z_{CN}/2 = 34$, i.e., the loss of mass and charge per fission fragment, plotted versus excitation energy per fragment.

system. Promptly emitted particles (PEP) have been proposed[22] to appear at energies of ≈ 4 MeV/u above the barrier, which corresponds roughly to our highest bombarding energy. In some cases, e.g. break-up reactions, only a part of the projectile is absorbed, i.e., the momentum of the projectile has not been transferred completely to the composite system. The occurrence of such incomplete momentum transfer reactions has been known for many years for ^{12}C, ^{14}N, and ^{16}O reactions induced on Au and Bi targets.[23] After such a process, however, an equilibrated system lighter than the combined target and projectile mass can still be formed. This has been shown in various heavy-ion-induced reactions, e.g. studies of the evaporation residue cross section in $^{12}C + ^{19}F$ (Ref. 24) and in particles-γ-coincidence experiments with ^{10}B to ^{20}Ne ions on rare-earth targets.[25,26]

An extreme point of view has been adopted by Mikheev *et al.*,[27] who explained the large α cross section observed in $^{40}Ar + Ag$ at 285 MeV as being due to a very asymmetric deep inelastic reaction, since the α cross section appears to be consistently described applying the Q_{gg} systematics and a diffusion model for deep inelastic reactions.[28] Such a process, however, would still belong to the class of incomplete momentum transfer reactions.

In the present reaction, the bombarding energy is high enough to allow various kinds of incomplete momentum transfer reactions. However, an angular momentum consideration may impose restrictions on the possibility of subsequent fission. The nucleus ^{150}Sm, for instance, can be formed (1) by incomplete fusion after breakup of the light partner ($^{30}Si \rightarrow ^{18}O + 3\alpha$), or (2) alternatively after breakup of the heavy partner ($^{132}Xe \rightarrow ^{120}Cd + 3\alpha$), or (3) by a very asymmetric deep inelastic collision in which the ^{150}Sm-^{12}C system is formed. ^{150}Sm fissions only if $B_f \lesssim B_n$, which occurs for $l > 77\hbar$ (RLDM). If the reduction of the entrance-channel angular momentum according to the mass ratio is assumed, the needed l values are not reached in the fast process 1 ($l/l_{in} = 18/30 = 0.60$) even for the highest l values available. Process 2 does not impose a severe limitation, as $l/l_{in} = 120/132 = 0.91$. The deep inelastic process (3) gives in the sticking limit $l/l_{in} = 0.72$, thus presenting an intermediate situation. Promptly emitted particles originating from either target or projectile are supposed to carry away only little angular momentum, and might therefore be considered as a possible mechanism too. Binding-energy arguments would favor process 2, since the separation energies for α particles are close to zero in the Xe region.

The emission of α particles due to the various mechanisms modifies mass and excitation energy of the fissioning nuclei. Hence it explains the observation which could be inferred from Fig. 4, that only 8–10 MeV are carried away per nucleon. This value can be understood as a weighted average between α and neutron emission, where α particles carry away between 4 MeV/u (Coulomb energy) and 8 MeV/u (beam energy), and neutrons the usual 10–12 MeV/u.

We conclude from the experimental findings that at low bombarding energies the properties of the fission fragments indicate that they originate from fully equilibrated compound nuclei. At higher energies the fragment properties again are indicative of fission; however, the definite loss of charge strongly suggests that they are due to fission of nuclei which are lighter than the compound nucleus (fission after incomplete fusion).

C. Width of the fission fragment mass distribution

The width of the fission fragment mass distribution has often been taken as a further characteristic feature of compound nucleus fission, since it is rather well described by the liquid-drop theory of nuclear fission.[4] In particular, the observed dependence of the variance $\sigma_A{}^2$ on temperature (i.e., excitation energy) agrees with the predictions, while the absolute value is larger by 30–80% for α-, ^{12}C-, and ^{16}O-induced fission of compound nuclei with masses of about 200 (Ref. 29). It could be argued that the theory[4] systematically underestimates $\sigma_A{}^2$ since it uses a restricted parametrization of the shapes of the nuclear surface and assumes that a fissioning nucleus is describable by an irrotational flow of nonviscous incompressible fluid.

The full width at half maximum (FWHM) of the observed fission-mass distribution in $^{30}Si + ^{132}Xe$ as a function of the temperature θ at the saddle point is displayed in Fig. 5 together with the theoretical prediction.[4] This temperature has been calculated from the excitation energy of the compound nucleus, taking into account the fission barrier height and the rotational energy at the saddle and using a level-density parameter of $a = A/8$ MeV^{-1}. Correction for particle emission from the primary fragments has not been applied. It is expected to increase the width slightly, by not more than 1–3 masses, with increasing excitation energy. The absolute magnitude agrees surprisingly well. However, the energy dependence of the data is significantly stronger.

An increase of the width with bombarding energy stronger than expected from the liquid-drop theory[4] has been reported by Lébrun *et al.*[30] for the

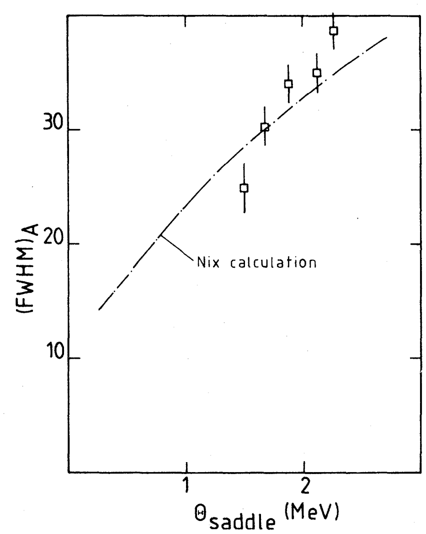

FIG. 5. Full width at half maximum of the observed mass distribution versus the temperature at the saddle of the compound nucleus. The dashed-dotted line is the prediction of the liquid-drop theory of fission, Ref. 4.

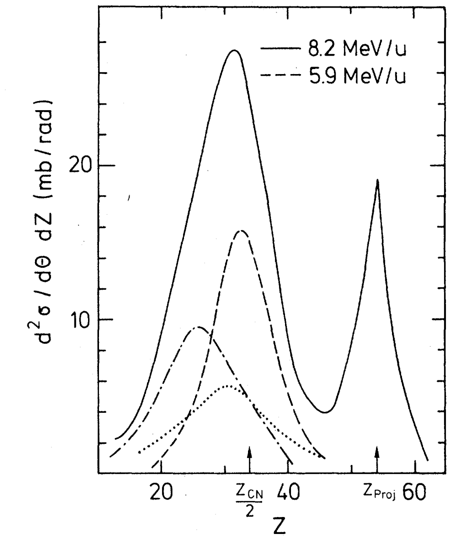

FIG. 6. Z distribution, arbitrarily decomposed into three components: Dashed line: experimental data at 5.9 MeV/u; dotted line: difference of the cross section at 6.6 MeV/u and 5.9 MeV/u; dashed-dotted line: difference of the cross sections at 8.2 MeV/u and 6.6 MeV/u.

^{20}Ne + ^{nat}Re and ^{40}Ar + ^{165}Ho systems. They conclude that the width starts to rapidly increase as soon as the fission barrier vanishes, and attribute this increase to the influence of angular momentum. Since at our higher bombarding energies the fission barrier is close to zero, a similar conclusion might be drawn.

However, we believe this conclusion not to be compelling. We have shown that a significant loss of charge occurs prior to fusion. Hence, our fission fragment mass distributions might be a superposition from various fissioning nuclei as it is already suggested by the broadening of the Z distributions seen in Fig. 2. We assume for the sake of a qualitative argument that the distribution at 8.2 MeV/u bombarding energy contains three components. Its arbitrary decomposition is given in Fig. 6. The first component is due to full momentum transfer and corresponds to the distribution at 5.9 MeV (dashed line), the second is the difference between the 6.6 MeV/u, and the 5.9 MeV/u cross sections (dotted line), and the third is the difference between the 8.2 MeV/u and the 6.6 MeV/u cross sections (dotted dashed line). These narrow and symmetric distributions resemble fission after various degrees of incomplete momentum transfer, as their centroids are at $\langle Z \rangle \leq Z_{CN}/2$. Added together they broaden the distribution significantly.

IV. CONCLUSION

In the bombardment of ^{30}Si with ^{132}Xe of 5.4 to 8.2 MeV/u the fission excitation function and fragment mass and Z distributions have been measured. Critical angular momenta leading to fusion (operationally defined as measured fission plus extrapolated evaporation residue cross section) have been determined and found to extend from 70 to 98 $\hbar$. These properties are consistent with fully equilibrated fissioning compound nuclei at the lower bombarding energies. At the two highest energies, however, the fragment distributions are no longer centered at half the compound nucleus atomic number. It is suggested that this observation can be explained by the occurrence of a two-step process. In the first step, already at angular momenta much lower than the expected stability limit of the compound nuclei ($B_f = 0$), a small part of one of the reaction partners is sheared off. The remains amalgamate and the combined system, which is lighter than the compound nucleus, fissions. Fission after incomplete momentum transfer (incomplete fusion) can be viewed as one of many pre-equilibrium processes in a very global sense. It results in a shift of the centroid of the fission fragment Z distributions to values smaller than $Z_{CN}/2$. It also explains the measured increase of the width of the mass distributions with bombarding energy as being due to a superposition of various fissioning systems. An increased width then does not necessarily reflect the vanishing fission barrier.

This two-step mechanism—if it is proved to be correct—has several consequences for our present understanding of heavy-ion reactions in this energy regime. The possibility of forming compound nuclei at very high angular momenta is greatly reduced due to the disintegration of one of the reaction partners. The cross section for evaporation residues, however, is enhanced. Utilizing their properties to infer compound nucleus characteristics at high angular momentum becomes, therefore, at least difficult if not doubtful. In particular, the determination of a meaningful fusion cross section, which defintiion has to be reconsidered, gets even more complicated.

To experimentally prove our conclusions elaborated studies are needed, where instead of one-particle inclusive data, kinematical complete information is obtained.

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