Characterization of Hot Compound Nuclei from Binary Decay into Complex Fragments

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The emission of complex particles at intermediate energies has been characterized through the reverse-kinematics reactions 25- and 30-MeV/u $^{93}Nb + ^{9}Be$, ^{27}Al. Complex particles observed in binary decays from very hot incomplete-fusion intermediates are shown to originate from compound-nucleus decay, by means of kinetic energies, angular distributions, and absolute yields. The process of complex-particle emission provides a method, applicable throughout the Periodic Table, for studying compound nuclei with temperatures and excitation energies near the expected limit of their existence.

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One of the foremost questions in the intermediate-energy regime of heavy-ion reactions concerns the maximum excitation energy that a fusionlike product can hold, and the modes of decay of this hot object.[1] In heavy systems, which subsequently undergo fission, very large energy depositions have been inferred from linear-momentum-transfer data.[2-4] Similarly, in lighter systems, a component of the resulting distribution of reaction products has been interpreted as arising from the ordinary evaporation of a very hot compound nucleus.[5-6] Unfortunately, the technique involving the measurement of the folding angle between fission fragments is applicable only in a narrow mass region, while measurements on evaporation residues lead to ambiguities in the determination of the mean momentum transfer. Such difficulties are nicely avoided by utilization of the recently characterized compound-nucleus emission of complex particles[7,8] combined with a reverse-kinematics reaction,[9,10] which permits both a verification of compound-nucleus decay and a determination of the momentum transfer.

Several theories have been advanced for the production of intermediate-mass fragments in reactions at bombarding energies of 10 to 100 MeV/u. The most familiar are those based upon the Fisher model of droplet condensation out of a vapor,[11,12] and those based upon the cold fragmentation of a nucleus.[13] Despite the theoretical appeal of these hypotheses, there are recent experimental indications[10] that the compound nucleus plays a dominant role in the production of these particles. In a series of low-energy experiments,[7-9] where complex-fragment emission was studied as a function of mass and excitation energy (50–140 MeV), it was concluded that in the energy range explored, these processes could be unequivocally and completely characterized as due to compound-nucleus decay.

In this paper we show that the same compound-nucleus mechanism of complex-particle production operating at low bombarding energies prevails also in this higher-energy regime. More specifically, we have obtained conclusive evidence that the reactions 25- and 30-MeV/u $^{93}Nb + ^{9}Be, ^{27}Al$ give rise to a thermalized intermediate formed with a very large momentum transfer and energy deposition as high as 400 MeV, which then undergoes a compound-nucleus binary decay producing fragments of intermediate mass and charge. Although the term compound nucleus is usually employed for complete-fusion reactions, we will use the same term to also refer to the equilibrated product produced in an incomplete-fusion reaction.

The experiments have been carried out at the Bevalac of Lawrence Berkeley Laboratory. Beams of 10^7 particles/pulse of ^{93}Nb with energies of 25 and 30 MeV/u impinged on targets of ^{9}Be (2.3 mg/cm^2) or ^{27}Al (3.0 mg/cm^2). The fragment atomic number could be identified over the entire range of reaction products with two large-acceptance-angle, position-sensitive ΔE(gas)-E(Si) telescopes. These telescopes were placed on either side of the beam at angles of 5.5° and −11° and covered an angular aperture of 5° and 7°, respectively. For the forward telescope and a typical fragment ($Z = 20$), the c.m. angular coverage in the forward and backward hemisphere was 37° and

27°, respectively. With both telescopes, essentially the entire range of c.m. angles (20°–170°) was covered.

The singles invariant cross sections plotted in the velocity-Z plane[14] are shown in Fig. 1. For all systems, the charge distributions consist of three components: (a) a prominent hill, beginning near the projectile Z value (41) and extending toward smaller atomic numbers, (b) two distinct ridges at intermediate atomic numbers whose separation in velocity increases with decreasing atomic number, and (c) a low-velocity hill near the target Z value.

The first and strongest component consists of a large number of events near the projectile Z value and is visible only at small angles in the most forward telescope. This component is consistent with the tail end of the evaporation-residue distribution from a highly excited compound nucleus. A simulation based upon the evaporation code PACE[15] has been used to verify that evaporation residues should extend somewhat beyond the inner edge of our forwardmost telescope.

The third component which is visible at small Z values and low velocities is apparently related to the target. It may be possible to explain this component in terms of a transfer of a few nucleons from the projectile to the target followed by evaporation. These products should be slow moving because of the low momentum transfer. This process may be the counterpart of the dominant process where the projectile abrades and fuses with a good portion of the target.

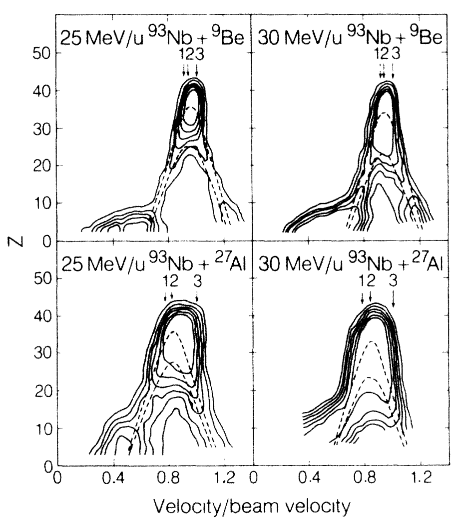

FIG. 1. Singles distribution of reaction products plotted as logarithmic contours of invariant cross section $[(1/V^2)(\partial^2\sigma/\partial\Omega\,\partial V)]$ in the Z-velocity plane for the 5.5° telescope. The arrows indicate the velocities for (1) momentum transfer, (2) the experimentally determined momentum transfer, and (3) the beam. Calculated (dashed lines) average velocities of complex fragments for the maximum lab angles of the telescope (3° and 8°) are indicated. In the c.m. system, the angular ranges covered in the high- and low-velocity arms are 37° and 27°, respectively, for $Z = 20$.

The second component, on which this paper concentrates, consists of fragments of intermediate Z value, which present two well-separated velocity components of nearly equal intensity. The presence of two velocity components is practically by itself spectacular evidence for the binary decay of a compound-nucleus system. In fact, the splitting into two components arises from forward and backward emission of fragments with Coulomb-type energies in the center-of-mass system. Detailed angular distributions have not been measured because of the low statistics. However, for intermediate mass fragments with Z values of 10–20, the ratio of the yields in the high- (forward emission) and the low- (backward emission) velocity arms are consistent with a $1/\sin\theta$ angular distribution.

From the average velocity of the two components, one can also derive the mean source velocity for each reaction system. These are indicated by the arrows labeled 2 in Fig. 1. For comparison, the recoil velocity for complete fusion ($\mathbf{v}_{cf}$) and the beam velocity are indicated by the arrows labeled 1 and 3, respectively. For each reaction, the mean source velocity is somewhat larger than $\mathbf{v}_{cf}$, thus indicating that the complex fragments are emitted following an incomplete-fusion reaction. The extracted momentum transfer and the resulting mass transfer, energy deposition (corresponding to the mass transfer), and temperature are presented in Table I. Our data are in good agreement with other momentum-transfer systematics.[16]

From the above data, it appears that a very large transfer of mass and energy leads to the formation of an object that relaxes into a hot compound nucleus. Such a fast-moving compound nucleus in turn emits fragments in binary decay with Coulomb-type energies, thus leading to the appearance of the double velocity solution for intermediate Z values. From the velocity difference of the two components, one can extract the fragment velocities in the c.m. system. These velocities are well reproduced[17] by the assumption that the fragments possess Coulomb energies [two spheres separated by $R = 1.224(A_1^{1/3} + A_2^{1/3}) + 2$ fm] and by correction of the final charge of the observed fragment for sequential decay.[15] The dashed lines shown in Fig. 1 for all reactions correspond to Coulomb calculations for the extreme acceptance angles of the telescopes and are in good agreement with the data. (The corrections to the final-fragment Z value were made with the assumption of first-chance decay, energy partition proportional to A, and use of the evaporation code PACE.[15]) The widths of the two velocity components increase with the excitation energy. At 25 MeV/u with the ^{9}Be target, the width is almost completely explained by the telescope acceptance angle. At higher energies, the widths increase because of either recoil effects associated with sequential evaporation, the

TABLE I. The momentum transfer, mass transfer, excitation energy, and temperature for the reactions studied.

$E(^{93}Nb)$ (MeV/u)	Target	$\langle p/p_{beam}\rangle$	$\langle M_{trans}\rangle$ (u)	$\langle E^*\rangle$ (MeV)	T[a] (MeV)
25.4	^{9}Be	0.72 ±0.1	6.5 ±1	148 ±20	4.0
30.3	^{9}Be	0.79 ±0.1	7.1 ±1	194 ±23	4.6
25.4	^{27}Al	0.77 ±0.1	20.8 ±3	392 ±45	6.2
30.3	^{27}Al	0.64 ±0.1	17.2 ±3	407 ±59	6.4

[a]Level-density parameter $a = A/11$.

width of momentum transfer, or both.

The angle-integrated cross sections for complex fragments are shown in Fig. 2. The observed Z dependence of the cross section for the former reaction is very similar to what has been observed at much lower bombarding energies.[9] In fact, compound-nucleus calculations[9] (solid line), based upon the liquid-drop model, reproduce both the shape and the magnitude of the charge distribution.

The binary nature of the intermediate-mass-fragment production process is confirmed by the coincidence data shown in Fig. 3. The correlation of the Z_1-Z_2 data is emphasized by the calculated bands (PACE) where binary events should fall after sequential evaporation. The concentration of our data on one side of the band is trivially related to the asymmetric location of our detectors with respect to the beam. The lack of events in the region to the left-hand side of the band in the case of the ^{9}Be target is an indication that the partition into three or more comparable fragments is not an important process in this energy regime. The few events appearing to the left-hand side of the band in the case of the ^{27}Al target, especially at 30 MeV/u, may be higher-multiplicity events and are clearly related to the higher excitation energy of this system. These events may possibly indicate the onset of multiple-fragment decay.

The consistency of the binary-decay picture is further emphasized in Fig. 4, where the sum $\langle Z_1 + Z_2\rangle$ is presented as a function of Z_2. The dashed lines are estimates of the mean compound-nucleus charge extracted from the linear momentum transfer. The measured total charge is smaller due to light-particle evaporation from the excited primary products and/or the initial system. For the ^{9}Be target, the average charge loss is 2–4 Z units, while for the ^{27}Al target, it is 13–15 Z

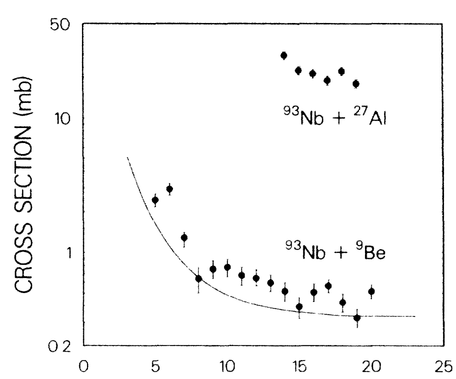

FIG. 2. Angle-integrated cross sections (symbols) for complex fragments emitted from the reactions 30-MeV/u $^{93}Nb + ^{27}Al, ^{9}Be$. Liquid-drop-model calculation (solid line) of the fragment yield for the latter system.

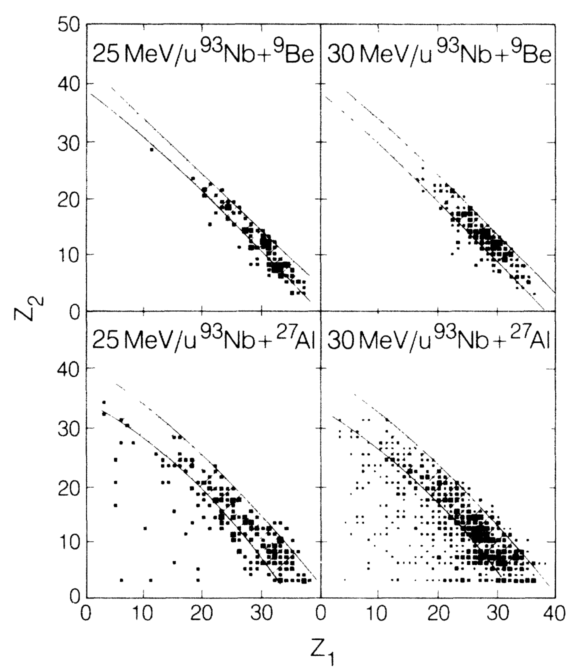

FIG. 3. Scatter plots of coincidence events between the 5.5° telescope (Z_1) and the −11° telescope (Z_2). The shaded areas represent an estimation of regions where binary events should lie following sequential evaporation from the primary fragments.

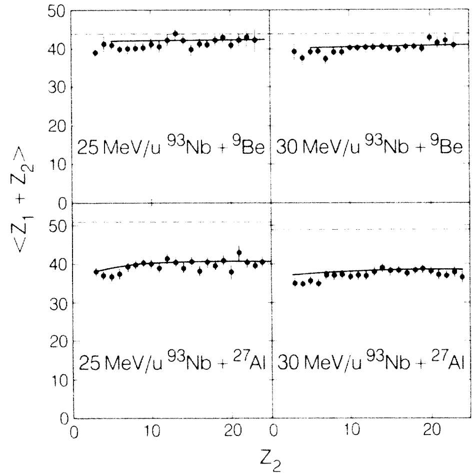

FIG. 4. The mean sum $\langle Z_1+Z_2\rangle$ of coincidence events (solid symbols) plotted as a function of Z_2. The dashed lines indicate the average charge of the compound system as estimated from the mass transfer. The charge loss for binary events, due to sequential evaportation, was estimated using the code PACE (Ref. 15) and the residual Z_1+Z_2 values are indicated by the solid curves.

units, reflecting the differing amounts of excitation energy with which the compound nuclei are formed. In the same figure, calculations (solid lines) are presented which assume first-chance decay and use the code PACE[15] to calculate the evaporation from the primary fragments. The excitation energies employed (see Table I) were those deduced from the measured momentum transfer, partitioned proportionally to the fragment charge. The agreement with the data is quite good and supports the general picture.

Formation of a compound nucleus in an incomplete-fusion process and its decay by emission of complex particles has been demonstrated by the observed binary decay, Coulomb energies, source velocities, forward-backward yields, and the charge distributions. No other emission source of these intermediate-mass fragments is observed. The momentum transfer is consistent with the Viola systematics.[16] The excitation energies range from 150 to 400 MeV (up to 4 MeV/nucleon) with corresponding temperatures of 4.0 and 6.4 MeV, respectively. Throughout this range of excitation energies, complex-particle emission occurs consistently and abundantly as an important decay process, easily identifiable because of its binary nature and very useful for the determination of momentum and energy transfer. It appears that despite temperatures comparable with the nuclear binding energy and energies per nucleon approaching the same, the system still manages to fuse, relax, and decay as a compound nucleus. Thus it appears that multifragmentation does not yet play a major role for these systems at these bombarding energies.

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