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L.G. Moretto, M.A. McMahan, L.G. Sobotka,
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Nuclear Science Division
Lawrence Berkeley Laboratory
University of California
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ABSTRACT

Two sets of experiments showing the compound nucleus origin of complex fragments and the Businaro-Gallone transition are presented.

COMPOUND NUCLEUS EMISSION OF COMPLEX FRAGMENTS AND THEIR EXCITATION FUNCTION

Complex fragments have been observed in high-energy proton reactions. The origin of these fragments cannot be easily or unequivocally traced to a well-characterized compound nucleus because precompound processes dominate and multiple fragmentation of the target is possible. At bombarding energies above ~8 MeV/ nucleon, the fragments of interest are also produced by projectile breakup in heavy ion reactions, thus complicating the study of the compound nucleus decay.

We have obtained experimental evidence for the emission of complex nuclei from helium through fluorine by compound nuclei produced in the reaction $^{3}He + ^{nat}Ag$. The specific choice of ^{3}He as projectile was dictated by two reasons. On one hand it is desirable to have a relatively low velocity projectile in order to minimize preequilibrium losses, but massive enough to bring in sufficient energy. On the other, the mass of the projectile should be sufficiently smaller than those of the complex fragments of interest

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in order to rule out the ambiguity of projectile fragmentation or multinucleon transfer.

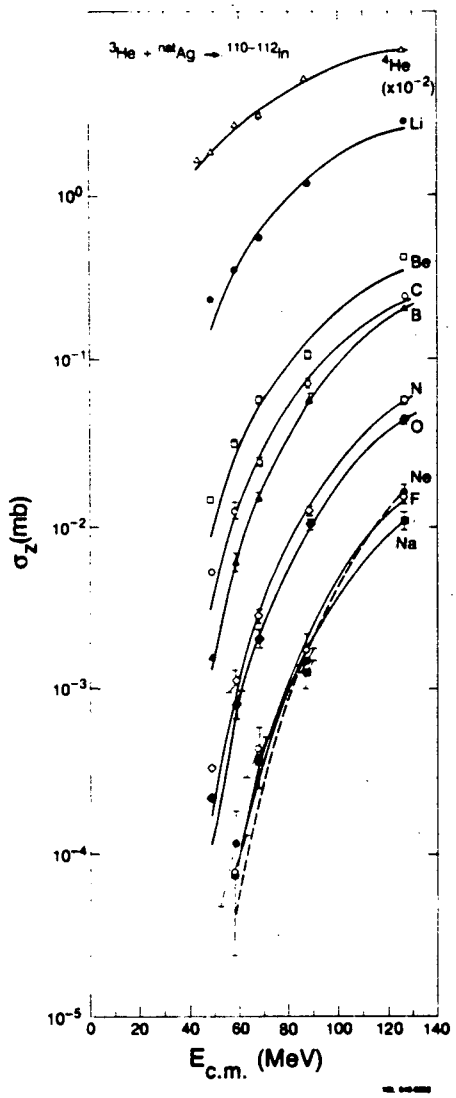
Complete excitation functions obtained from the $^{3}He + ^{nat}Ag$ measurements are shown in Fig. 1 for a series of decay products. The measurements were restricted to the backward angles (120° - 160°) in order to insure measurement of only the equilibrium component. The total cross sections were obtained by integrating over angle using the angular distribution formula of Moretto.[1)]

With increasing bombarding energy, the cross sections (see Fig. 1) rise rapidly and then flatten at higher energies. This is a characteristic signature of compound nucleus emission, and reinforces the assignment of compound nucleus decay that was made previously on the basis of data obtained at 90 MeV. The cross section for Z = 3 is a factor of 1000 lower than that for Z = 2, and for the heavier fragments it is even lower. In spite of these low cross sections, we were able to measure an excitation function over 2-3 orders of magnitude up to Z = 11, with a detection limit of about 50 nb.

The experimental excitation function data have been fitted using a transition state formalism, analogous to that used to fit fission excitation functions.[1)]

The barriers B_z, and the ratio a_z/a_n, of the level density parameters were extracted from fits to the experimental data σ_z/σ_R. These fits are shown by the solid lines in Fig. 1. The agreement between the data and the fits is remarkably good for all Z-values and confirms that these products originate from compound nuclear decay.

The barriers and values of a_z/a_n extracted from the fits are shown by the circles in Fig. 2 as a function of Z/Z_{CN}. The extracted barriers increase dramatically as the exit channel becomes more symmetric. Some evidence of shell effects in the exit channel is visible in the barrier for carbon emission, Z = 6, which is lower than those of the neighboring elements. The values of a_z/a_n extracted from the fits tend to oscillate in the rangeof 0.98-1.02, or 1.07-1.12 if preequilibrium emission is included.



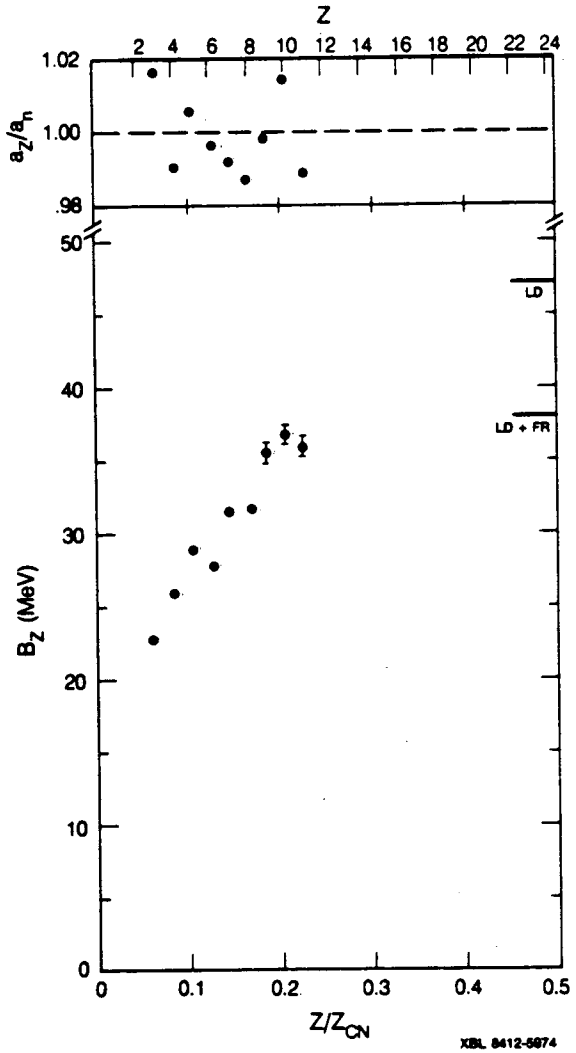


Fig. 1. Dependence of the total integrated cross sections for emission of complex fragments on the center-of-mass energy, $E_{c.m.}$ in the reaction ^{3}He + ^{nat}Ag. The points and error bars correspond to the experimental cross sections. The curves are fits with the parameters of Fig. 2.

Fig. 2. The emission barriers, B_Z, and ratio of level density parameters, a_Z/a_n, extracted in fitting the excitation functions as a function of asymmetry, Z/Z_{CN}. (Z/Z_{CN} = 0.5 corresponds to symmetric splitting.) The points are the extracted parameters, excluding pre-equilibrium emission.

Sensitivity tests show that the extracted emission barriers have an uncertainty of ~2 MeV. These results are ideal for testing the finite-range correction to the liquid drop model.

COMPLETE CHARGE DISTRIBUTIONS AND THE ROLE OF THE BUSINARO-GALLONE POINT

The sharp distinction between evaporation and fission in relatively heavy compound nuclei is a result of a specific topological feature of the liquid drop model potential energy surface V(Z) as a function of mass asymmetry Z. This feature is a deep minimum at symmetry (fission region) flanked at greater asymmetries by the Businaro-Gallone mountains which in turn descend at even larger asymmetries ("evaporation" region). The corresponding mass distribution from compound nucleus decay is approximately proportional to $\exp[-V(Z)/T_Z]$ and shows a peak at symmetry (fission peak) and two wings at the extreme asymmetries (evaporation wings).

With decreasing total mass the potential energy surface undergoes a topological change when the fissility parameter x crosses the so-called Businaro-Gallone point. At this point ($x_{BG} = 0.396$ for $\ell = 0$ and decreases for larger ℓ values) the second derivative of the potential energy with respect to the mass asymmetry coordinate evaluated at symmetry vanishes. Thus below the Businaro-Gallone point there is no longer a traditional fission saddle point, and the monotonically increasing potential energy towards symmetry implies the disappearance of fission as a process distinct from evaporation. Thus the mass distribution should show the two evaporation wings extending as far as symmetry where a minimum should be observed.

We have measured complete charge distributions from protons to symmetric splitting for a variety of nuclei and we have observed the Businaro-Gallone transition. Such a transition is inferred from the disappearance of the fission peak in the mass yield as the compound nucleus mass was decreased from ^{148}Eu, ^{102}Rh to ^{83}Kr.

The use of reverse kinematics (projectile heavier than the target) was crucial in performing these measurements.

The experiments were carried out at the Lawrence Berkeley Laboratory SuperHILAC utilizing beams of 550-Mev ^{74}Ge, 782-MeV

^{93}Nb and 1157-MeV ^{139}La, to bombard targets of 0.54 mg/cm^2 ^{12}C and 1.0 mg/cm^2 ^{9}Be.

The mean laboratory energies for each Z-value were converted to velocities with two different assumptions for the relationship between the Z and the mass of the detected fragments. These velocities are then decomposed into two components. One component, along the beam direction, is assigned an arbitrary value; the other component is that required to reconstitute the original velocity. (For convenience this second component is shown as the c.m. energy in Fig. 3.) In this way, for each laboratory angle we can draw a curve representing the dependence of the c.m. energy upon the source velocity. This procedure is followed for each angle that is smaller than the kinematically allowed maximum angle. The intersection of these lines determines, in a model independent way, both the momentum transfer and the energy in the center of mass. The error bars shown on the lines in Fig. 3 reflect the uncertainty in the mean laboratory energies.

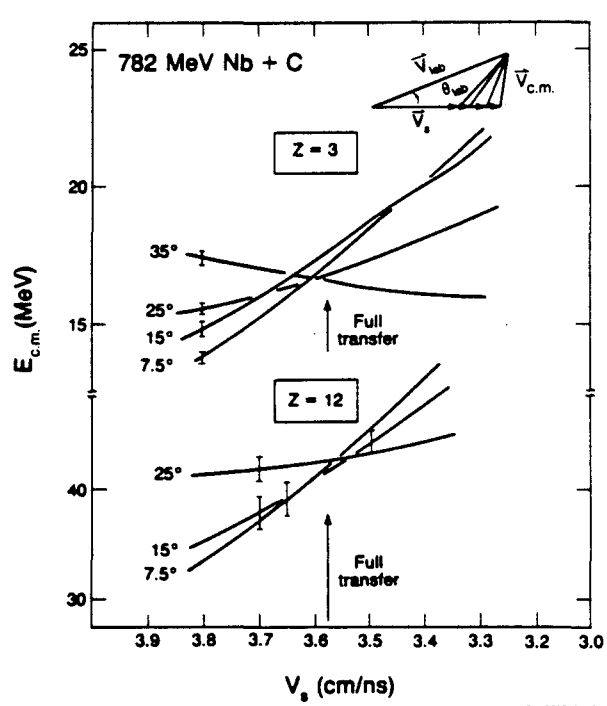
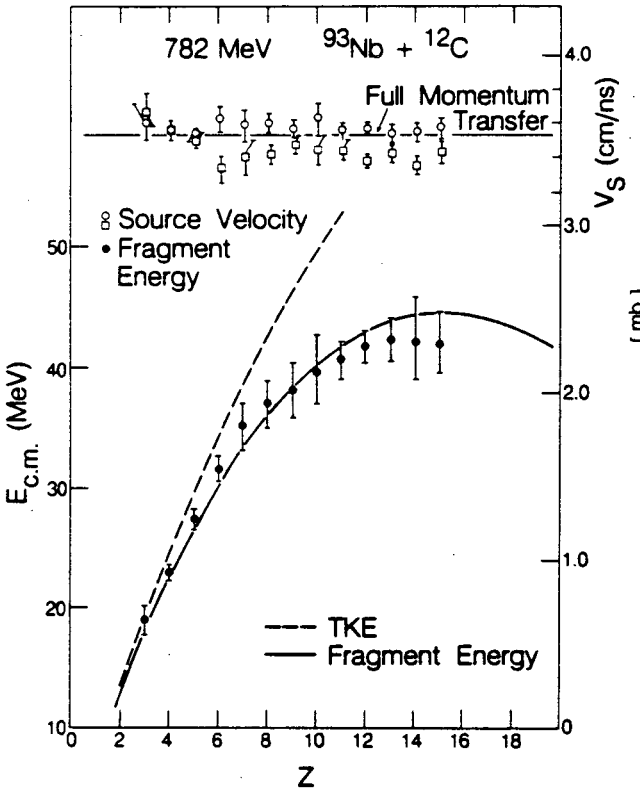


Fig. 3. The line for each angle gives the locus of solutions for both $E_{c.m.}$ and V_s. The intersection of the various lines fixes these quantities. The velocity corresponding to complete linear momentum transfer is indicated. This figure was drawn assuming that the masses follow the line of β-stability.



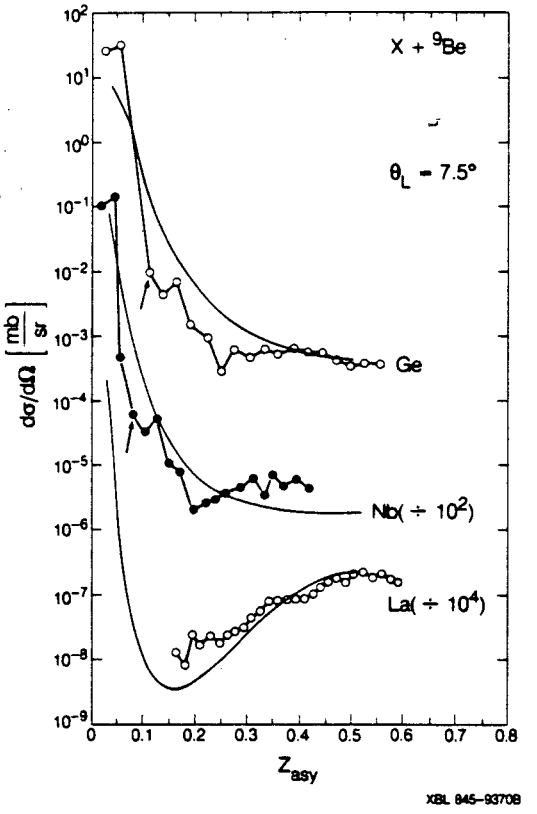


Fig. 4. The deduced c.m. energies (filled circles) and source velocities (open symbols) for the ^{93}Nb + ^{12}C system. Source velocities were determined assuming that the product mass followed the line of β-stability (open circles) or the charge equilibration line (open squares). A Coulomb calculation for two spheres is shown both for the c.m. energy of the light fragment (solid line) and the total kinetic energy (dashed line). The value of the source velocity expected for full momentum transfer is indicated by the horizontal line. The error bars indicate the uncertainty of the intersection point shown in Fig. 3.

Fig. 5. Center-of-mass cross sections for products from the ^{74}Ge, ^{93}Nb and ^{139}La + ^{9}Be systems detected at θ_{Lab} = 7.5°. The solid line is a liquid drop model calculation of the fragment yield at $\theta_{c.m.}$ = 30°. The arrows indicate the entrance channel asymmetry. See text. Data below z_{asy} = 0.15 were not obtained for the La + Be system, due to a limited dynamic range of the telescope.

The results from this type of analysis for the $^{93}Nb + ^{12}C$ system are shown in Fig. 4. The upper part of this figure demonstrates that with either mass assumption all of the measured products result from the decay of a system with full momentum transfer. For the other systems studied, the extracted source velocities are also independent of Z within a few percent of the velocity expected for full momentum transfer. The deduced c.m. energies are shown in the lower portion of Fig. 4. These energies are reproduced by a Coulomb calculation for two spheres with a surface separation of 2 fm.

The experimental cross sections for 530-MeV ^{74}Ge, 782-MeV ^{93}Nb and 1157-MeV $^{139}La + ^{9}Be$ systems are shown in Fig. 5. The cross sections are plotted as a function of charge asymmetry ($Z_{asy} = Z_{detected}/Z_{total}$). The lack of enhancement in yield near the target Z supports the compound nucleus origin of the products rather than a deep-inelastic origin. The yield from the $^{74}Ge + ^{9}Be$ system, with a fissility parameter of x = 0.31, decreases steadily as one moves towards symmetry. The yields from the $^{93}Nb + ^{9}Be$ system (x = 0.40) are essentially constant from Z_{asy} = 0.2 to 0.4 while the yields from the $^{139}La + ^{9}Be$ system (x = 0.50) show the characteristic fission peak at symmetry. These three systems clearly exhibit the qualitative trends expected from the topological changes in the potential energy surface predicted by the liquid drop model.

A quantitative comparison between these data and a compound nucleus calculation based upon the liquid drop model is also shown in Fig. 5.

The agreement in absolute magnitude and in trend between this calculation and the data confirms the compound nuclear origin of these fragments.

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1. Moretto, L.G., Nucl. Phys. A247, 211 (1975).

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