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IN COMPLETE CHARGE DISTRIBUTIONS FROM
COMPOUND NUCLEUS DECAY

L.G. Moretto, G.J. Wozniak, and L.G. Sobotka

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The Businaro-Gallone Transition as Observed in Complete Charge Distributions from Compound Nucleus Decay*

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THE BUSINARO-GALLONE TRANSITION AS OBSERVED IN COMPLETE CHARGE DISTRIBUTIONS FROM COMPOUND NUCLEUS DECAY*

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Abstract: The compound nucleus emission of fragments covering the entire mass range has been observed in reactions exploiting both ordinary and reverse kinematics. The compound nucleus mechanism has been inferred from full momentum transfer, angular independence of the fragment center of mass kinetic energies and excitation functions. The drastic change in the observed charge distributions as one crosses A ≈ 100 illustrates the effect of the Businaro Gallone point.

The experimental distinction between the processes of evaporation and fission in relatively heavy compound nuclei can be understood in terms of a specific topological feature in 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 expected for compound nucleus decay is approximately proportional to $\exp[-V(Z)/T_Z]$, where T_Z is the temperature of the conditional saddle point, and indeed shows a peak at symmetry (fission peak) and two wings at the extreme asymmetries (evaporation wings).

In progressively lighter compound nuclei the potential energy surface undergoes a topological change as the fissionability parameter x crosses the Businaro-Gallone point.[1] At this point the second derivative of the potential energy with respect to the mass asymmetry coordinate evaluated at symmetry vanishes.[1-3] Thus below the Businaro-Gallone point there is no longer a true fission saddle point, and the monotonically increasing potential energy towards symmetry determines the disappearance of fission as a process distinct from evaporation. In other words the mass distribution should show the two evaporation wings extending as far as symmetry where a minimum should be observed.

Within this framework, it has been possible to describe, in a continuous way, the transition from light particle emission to fission.[3] This theory also predicts changes in the shapes of both the kinetic energy spectra and angular distributions of the emitted fragments as their masses increase from α-particles toward fission fragments. These predictions[3] are amenable to experimental test; unfortunately, there is a surprising lack of experimental data that can be compared with the above unified treatments or with more standard formalisms.

In this paper we present two experiments, concerned with the compound nucleus emission of large fragments. The first experiment is based upon the compound nucleus formation in the interaction between ^{3}He and Ag. The second experiment uses reverse kinematics with Ge, Nb, La projectiles impinging on Be, C targets.

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The purpose of the first experiment was to obtain experimental evidence for the emission of complex nuclei from helium through flourine by compound nuclei produced in the reaction $^3He + {}^{nat}Ag$. The specific choice of ^3He as projectile was dictated by two reasons. First, it is desirable to have a low velocity projectile to minimize preequilibrium losses but massive enough to bring in sufficient energy. Second, the mass of the projectile should be sufficiently smaller than that of the fragments of interest so that the ambiguity of projectile fragmentation or multinucleon transfer can be ruled out.

The presence of an isotropically emitting source associated with complex particle emission is visible in the invariant cross-section plots in velocity space presented in Fig. 1 for the 70 MeV $^3He + {}^{nat}Ag$ data. The peak cross section for a heavy complex fragment, such as carbon, has a constant value and occurs at the same c.m. velocity from 170° to 40° (as indicated by the position of the X's relative to the circular arc). At the most forward angle, the peak cross section occurs at a slightly increased velocity. Similarly, the higher velocity region (the region near the arc with the larger radius) shows no significant change in the backward hemisphere, but does stretch out at forward angles. For a light complex fragment such as Li, the peak of the cross section occurs at a constant c.m. velocity for a smaller backward angle region (170° to 120°). Forward of 120° the peak increases both in cross section and in velocity. The slope of the high-energy tail does not change significantly for the three most backward angles, but the intensity of the tail increases as the scattering angle decreases. The ^9Be and B fragments show a behavior intermediate between that of Li and C. In general, the heavier ejectiles show patterns more consistent with the emission from a single source.

Two conclusions can be drawn from these invariant cross-section plots. First, for all elements there is an angular region in the backward hemisphere where only a single source is observed, which can be characterized by c.m. velocity. This angular region increases and extends to more forward angles as the ejectile mass increases. Second, there is a component strongly focused in the forward hemisphere.

The mean energies of the spectra are Coulomb-like and increase as the charge of the fragment increases. The energy spectra of the equilibrium component evolve from a Maxwellian shape for α-particles (not shown) or Li ions through a more symmetric shape for B or C to a symmetric shape for the heaviest ejectiles, as predicted in Ref. 3.

The experimental yields of the equilibrium component for the 90 MeV bombarding energy are shown in Fig. 2. To minimize contributions from sources other than the compound nucleus, we have plotted the yields only for the most backward angle ($\theta_{cm} = 171°$). These yields drop precipitously in going from Z = 2 to Z = 3, after which they decrease more slowly. The one exception is the enhanced Z = 6 yield.

The yield from an equilibrium statistical emission process is roughly proportional to a factor $\exp[-B_Z/T_Z]$, where B_Z is the emission barrier for fragment Z and T_Z is the temperature at the barrier. More quantitatively, the decay width is given by

$$\Gamma_Z \propto T_Z[E/(E - B_Z]^2 \exp[2\sqrt{a(E - B_Z)} - 2\sqrt{aE}] \qquad 1)$$

$$\tilde{\propto} \exp[-B_Z/T_Z]. \qquad 2)$$

The theoretical yields were calculated using the following expression for the barrier was used

$$B_Z = U_1 + U_2 + \frac{Z_1 Z_2 e^2}{d} + U_{prox} - U_{CN} \quad , \qquad 3)$$

where U_1 is the experimental mass of the light fragment, U_2, U_{CN} are the droplet model masses of the residual and compound nucleus, respectively, and U_{prox}

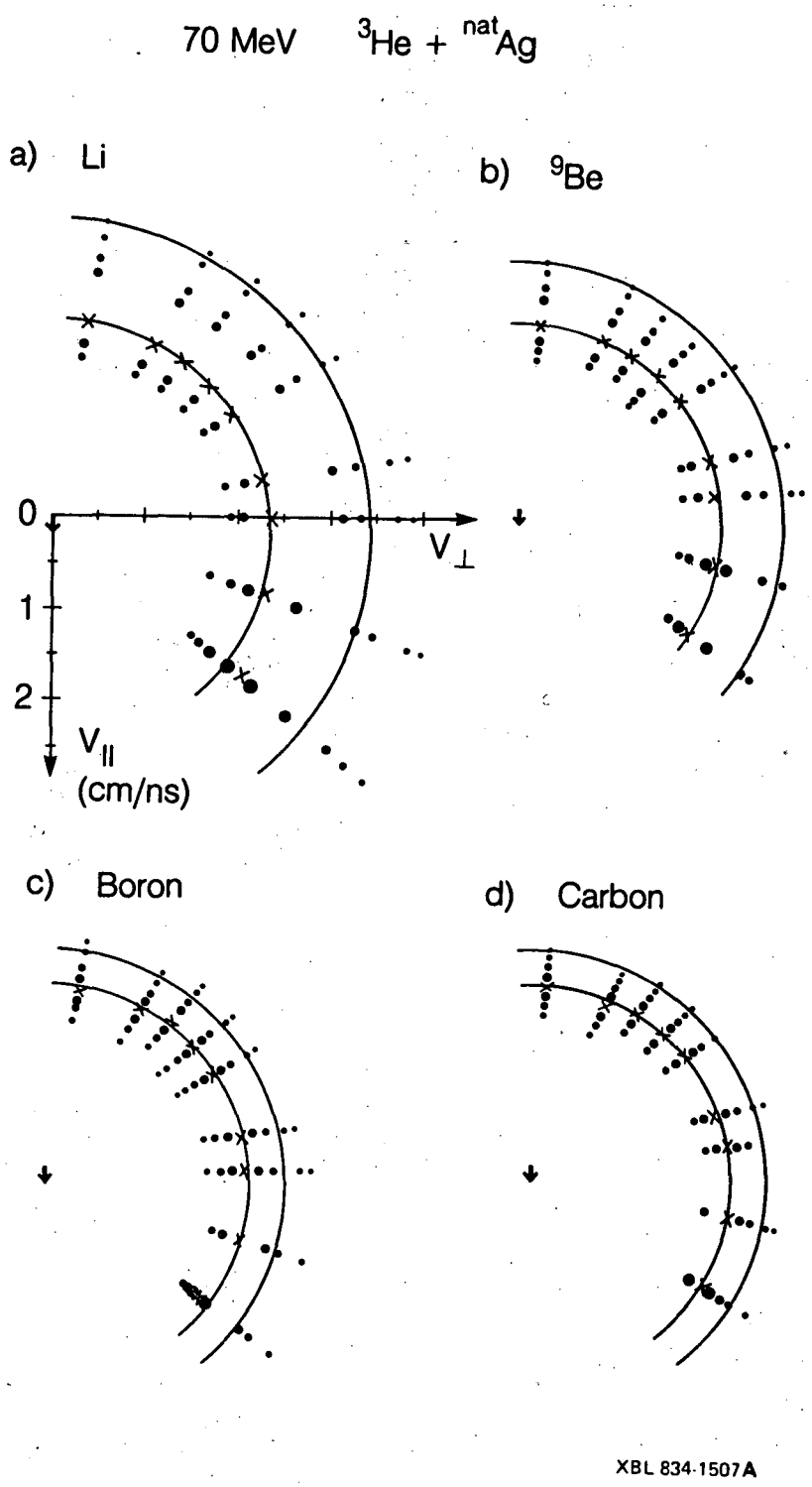

Fig. 1. Invariant cross-section plots $\left(\alpha \frac{1}{V^2} \frac{d^2\sigma}{d\Omega\, dV}\right)$ for representative ejectiles (Li, ^{9}Be, B, and C). The diameter of the dots is proportional to the logarithm of the cross section and the X's indicate the peak of velocity distribution. The two large arcs are sections of circles centered on the c.m. velocity (center arrow) appropriate for complete fusion. The beam direction (0°) is indicated by the c.m. velocity vector.

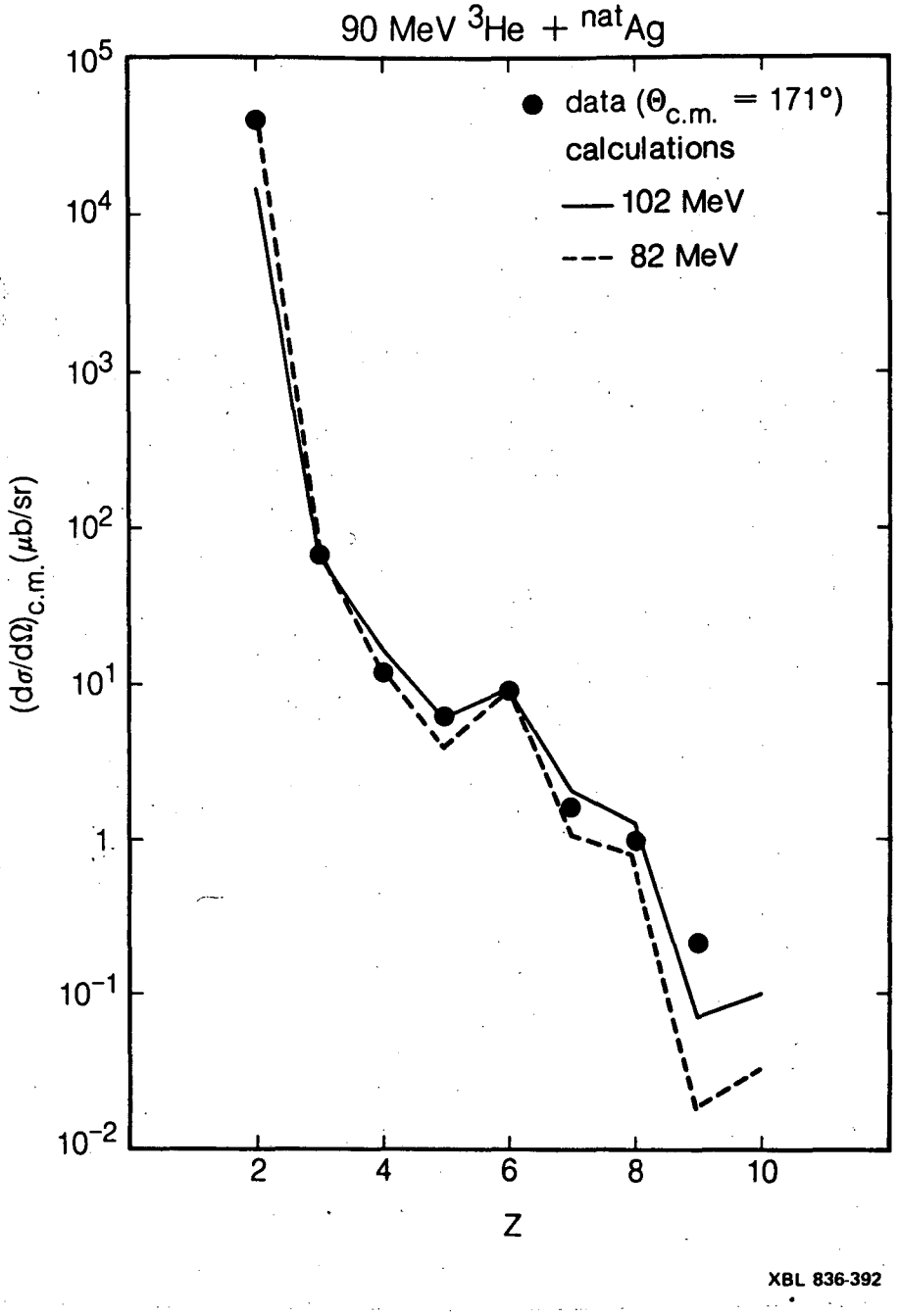

Fig. 2. Experimental (circles) and theoretical yields versus ejectile atomic number (Z).

is the proximity potential. The center-to-center distance d in the inter-fragment Coulomb term was taken to be $d = 1.225(A^{1/3} + A^{1/3}) + 2$ fm. The addition of 2 fm to the sum of the radii was done to obtain approximate agreement with the energy spectra. The temperature (T_Z) was evaluated using the relation $E^* - B_Z = aT^2$. A compound nucleus excitation energy (E^*) of 102 MeV (the value for full momentum transfer) and a level density parameter $a = A/8$ were assumed. The calculated yields (Eq. 1) for each isotope were multiplied by $2I + 1$ (where I is the ground state spin of the light fragment) and then summed. The theoretical ejectile yields were calculated as a ratio Γ_Z/Γ_6 and have been normalized to the data at Z = 6 in Fig. 2.

The agreement between the data (circles) and this simple equilibrium statistical calculation (solid line) is remarkably good for Z = 3–9. The calculation underpredicts the α-particle yield because it only takes into account first chance emission, whereas substantial amounts of higher chance

α-emission occur. Precompound emission is expected to leave the compound nucleus with a broad excitation energy distribution with a most probable value of ~85 MeV. A calculation (not shown) with this lower excitation energy also reproduces the relative yields of the heavy fragments quite well but overpredicts the yield of first chance α-emission. More detailed comparisons between the data and theory require calculations that include precompound emission; however, the substantial agreement depicted in Fig. 2 does indicate that an equilibrated process is responsible for the emission of these complex fragments.

The angular distributions in the center of mass undergo a change from flat to backward peaked as the ejectile mass increases in the angular region from ~100° to 180°. Such an increase in anisotropy with increasing particle mass is well understood from angular momentum considerations and discussed in some detail in Ref. 3. These angular distributions, which for the heaviest elements have a minimum at ~90°, are consistent with an equilibrium process for the complex fragments observed in the backward hemisphere.

Measurements of the excitation functions for a series of fragments shown in Fig. 3 on one hand provide an additional proof of their compound nucleus origin, with their sharply rising cross sections; on the other they allow us to determine the height of the various conditional saddle points of the ridge line just like the fission excitation function allowed us to measure the fission barriers.

In the second experiment where targets of Be, C were bombarded with Ge, Nb, La projectiles we could achieve additional relevant goals.

First, it was possible to prove accurately that the fragments were emitted with constant center of mass energy from an intermediate with full momentum transfer. Second, it was possible to obtain the full charge distribution extending from the extreme asymmetries (p, α emission) as far as the symmetric splitting. This latter achievement is of particular importance because it is the first time that the mass asymmetry coordinate has been explored completely and that the topological changes in the potential energy vs mass asymmetry that are expected to occur in the region of the Businaro-Gallone point have been verified.

In this experiment we were helped by the kinematical boost of the fragment velocities and by the lack of interference from target contamination that tended to mar the previous experiment.

The measured atomic number (Z), laboratory energy and angle allow one to verify that the recorded events both originate from a system with full momentum transfer and have a c.m. energy independent of angle. This is shown for two representative elements in Fig. 4.

The mean laboratory energies for each Z-value were converted to velocities with two different assumptions for the relationship between the atomic number and the mass of the detected fragments. The first method assumes that the Z partition for each mass split is that given by charge equilibration. The second method assumes that the light fragment mass and charge follow the valley of β-stability. 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. 4.) In this way, for each laboratory angle one can draw a curve representing the dependence of the c.m. energy upon the c.m. velocity. This procedure is followed throughout the kinematically allowed angular range. 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. 4 reflect the uncertainty in the mean laboratory energies. The mass uncertainty was investigated by using the two charge-mass relationships mentioned above.

The results from this type of analysis for the $^{93}Nb + ^{12}C$ system are shown in Fig. 5. The upper part of this figure demonstrates that, with

either mass assumption, all of the measured products can be associated with 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. 5. These energies are reproduced by a Coulomb calculation for two spheres with a surface separation

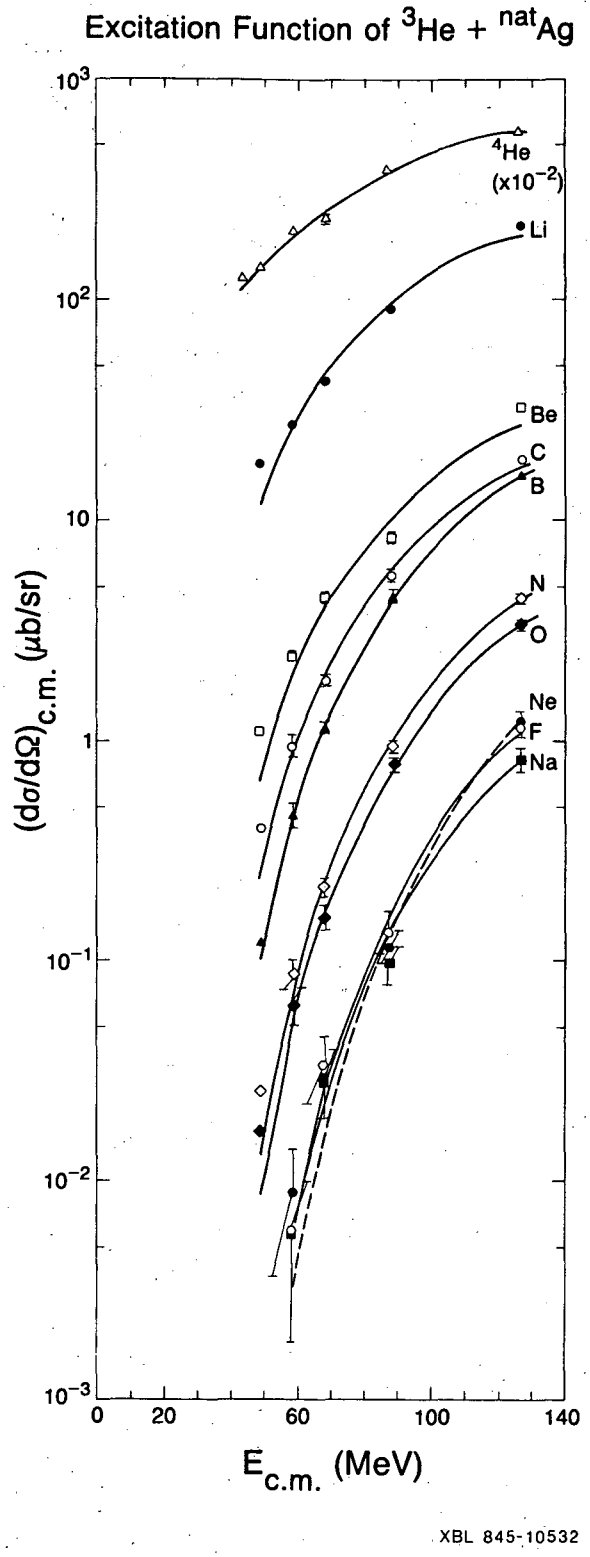

Fig. 3. Excitation functions for $2 \leq Z \leq 9$ from the reaction ^{3}He + Ag.

of 2 fm. This same separation also reproduces the c.m. energies from the ^{74}Ge induced reations; however a larger separation is required for the ^{139}La

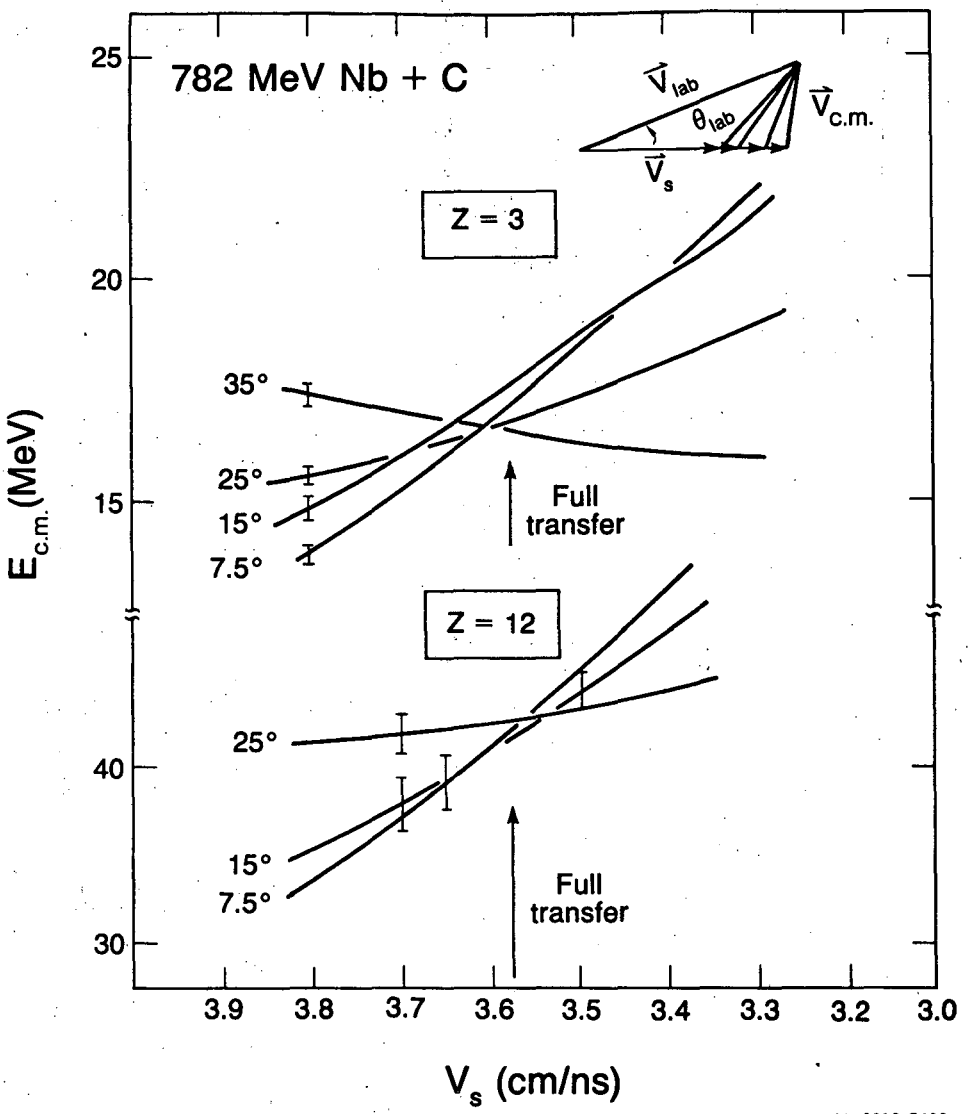

Fig. 4 Method for deducing the source velocity (V_S) and the c.m. energies ($E_{c.m.}$). The line for each angle gives the locus of solutions for both $E_{c.m.}$ and V_S. The intersection of the various lines fixes these quantities. The velocity corresponding to complete linear momentum transfer is indicated. The error bars reflect the uncertainty in the mean laboratory velocity due to the inherent width of the spectra. This figure is drawn assuming that the masses follow the line of β-stability.

data. Both the full momentum transfer and the invariance with angle of the c.m. energies are consistent with compound nucleus decay.

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. 6. The cross sections are plotted as a function of charge asymmetry ($Z_{asy} = Z_{detected}/Z_{total}$). 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 qualita-

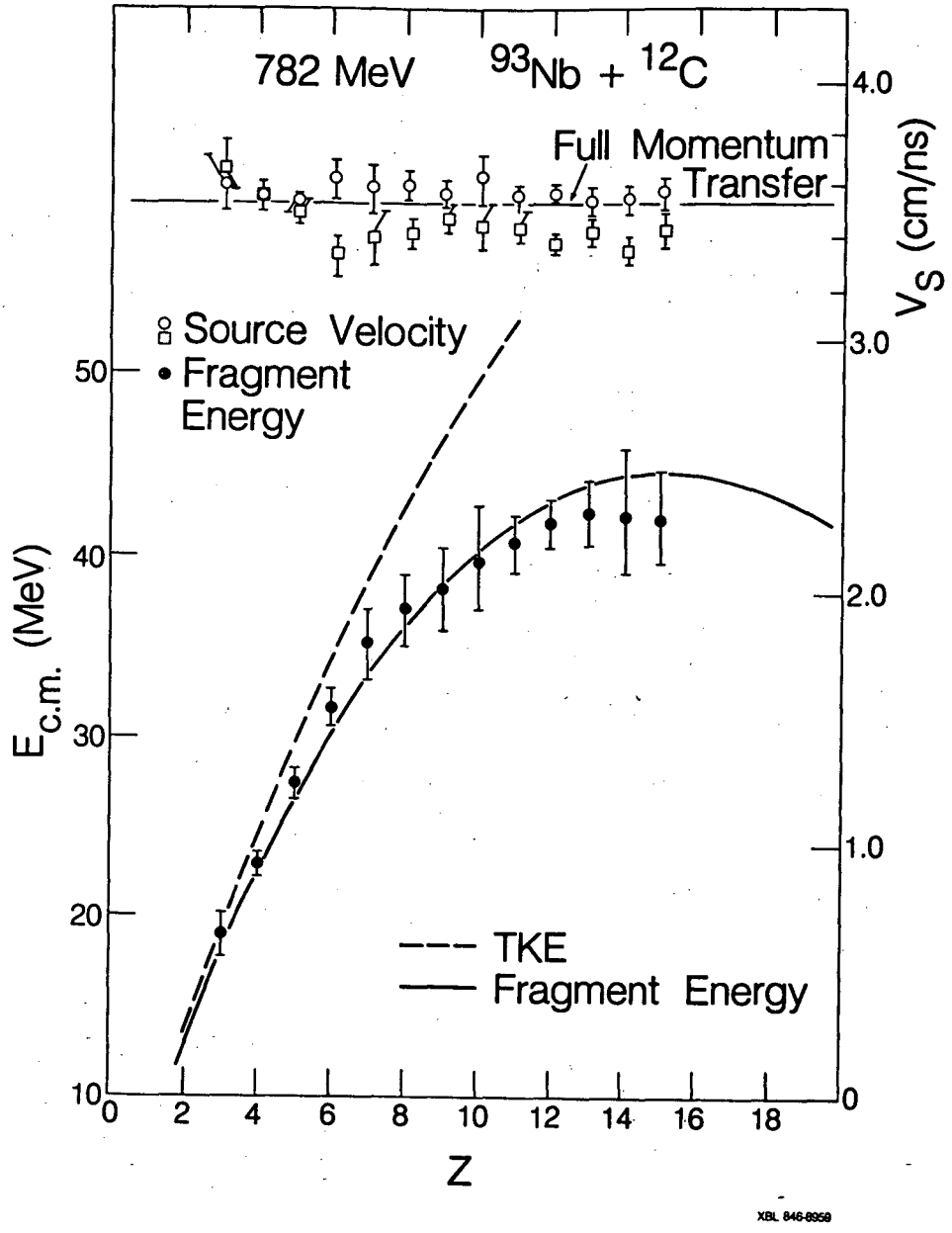

Fig. 5 The deduced c.m. energies (filled circles) and source velocities (open symbols) for the ^{93}Nb + ^{12}C system. Source velocities were determined assuming that the product mass followed the line of β-stability (open circles) or the charge equilibration line (open squares). A Coulomb calculation for two spheres with a surface separation of 2 fm 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. 4.

tive trends expected from the topological changes in the potential energy surface predicted by the liquid drop model[2,3].

A quantitative comparison between these data and a compound nucleus calculation based upon the liquid drop model is also shown in Fig. 6. The absolute yields were calculated from the expression

$$\sigma_Z = \pi \lambda\!\!\!^{-2} \sum_{\ell=0}^{\ell_m} (2\ell + 1) \frac{\Gamma_Z(\ell)}{\Gamma_n + \Gamma_p + \Gamma_\alpha} \quad .$$

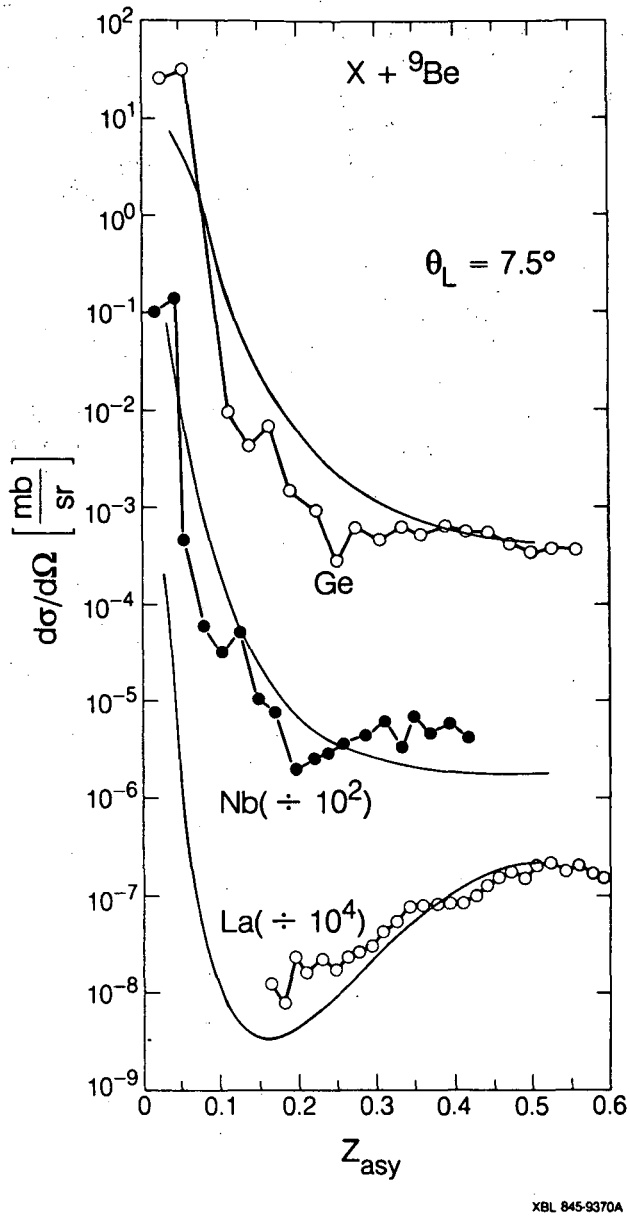

Fig. 6 a. Center-of-mass cross sections for products from the ^{74}Ge, ^{93}Nb and ^{139}La + ^{9}Be systems detected at $\theta_{Lab} = 7.5°$. The solid line is a liquid drop model calculation of the fragment yield at $\theta_{c.m.} = 30°$. See text.

where ℓ_m is the minimum of either ℓ_{max} (the grazing angular momentum) or ℓ_{crit} (the critical angular momentum for fusion[5]).

The angular distribution expressions given in Ref. 3 were employed to calculate the differential cross section ($d\sigma/d\Omega$). The c.m. angles of the data in Fig. 6 vary as a function of Z. However, the average c.m. angle is approximately 30°, so this angle was chosen for comparison. The agreement in absolute magnitude and in trend between this calculation and the data confirms the compound nuclear origin of these fragments.

In summary, we have shown that fragments with atomic numbers covering the entire range of the mass asymmetry coordinate are produced from the decay of an excited compound nucleus. The observed Z distributions indicate that the topological transition expected at the Businaro-Gallone point does indeed take place in the region of A ~ 100. The exact position of the Businaro-Gallone point and its angular momentum dependence can in principle be established by a systematic study of the Z or A distributions as the fissility parameter x and the rotational parameter y are varied.

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