R. L. Robinson, F. K. McGowan, J. B. Ball, and J. H. Hamilton (North-Holland, Amsterdam, 1974), Vol. II; see also R. J. Ascuitto and N. K. Glendenning, Phys. Lett. 45B, 85 (1973), and 47B, 332 (1973).

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Study of Strongly Damped Collisions in the Reaction of 600-MeV ^{84}Kr on a ^{209}Bi Target*

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Detailed information on a new reaction mechanism is presented for a 600-MeV ^{84}Kr bombardment of ^{209}Bi. This reaction process represents a major fraction of the total-reaction cross section and is characterized by strong damping of energy degrees of freedom, but on the average, a relatively small amount of mass exchange compared to fission.

The mechanism for reactions induced by very heavy projectiles is a subject of great current interest. Recent experimental studies[1,2] of ^{40}Ar and ^{84}Kr reactions with heavy targets have yielded results which are considerably different from those obtained with lighter-ion–induced reactions In the bombardment of heavy targets with projectiles of mass lighter than argon, a major fraction of the reaction cross section goes into a "compound-nucleus" or "complete-fusion" process. This is no longer the case for ^{40}Ar-induced reactions, and especially not true for ^{84}Kr-induced reactions on heavy targets.

In this Letter we describe current results obtained for a new reaction process observed for a 600-MeV ^{84}Kr bombardment of a ^{209}Bi target using Lawrence Berkeley Laboratory's Super-HILAC accelerator. This recently discovered process, also called "quasifission,"[2] is characterized by strongly damped collisions.

The previously described general technique of correlated fragments was used.[2,3] The use of a large position-sensitive detector (PSD) subtending an angle of 26° in the reaction plane, in conjunction with a 2° acceptance defining detector, permitted the measurement of both angles and both energies of fragments in a binary event with a high geometry factor. This technique allows rejection of unwanted events from a ternary process and from an incomplete momentum transfer of the projectile. Four parameters of data were recorded for each event, including (a) the energy deposited in the defining detector; (b) the energy deposited in the PSD; (c) a signal proportional to the position in the PSD; and (d) a signal related to the difference in flight times of the two fragments. The masses and center-of-mass kinetic energies of the reaction products were calculated off-line using the measured laboratory energies and angles of the coincident products.

A characteristic feature of the singles spectra is the presence of an energy peak well removed and reduced in energy from the elastic ^{84}Kr peak. This peak is clearly resolved at all angles measured except very near the grazing angle where higher-energy events from multinucleon transfer

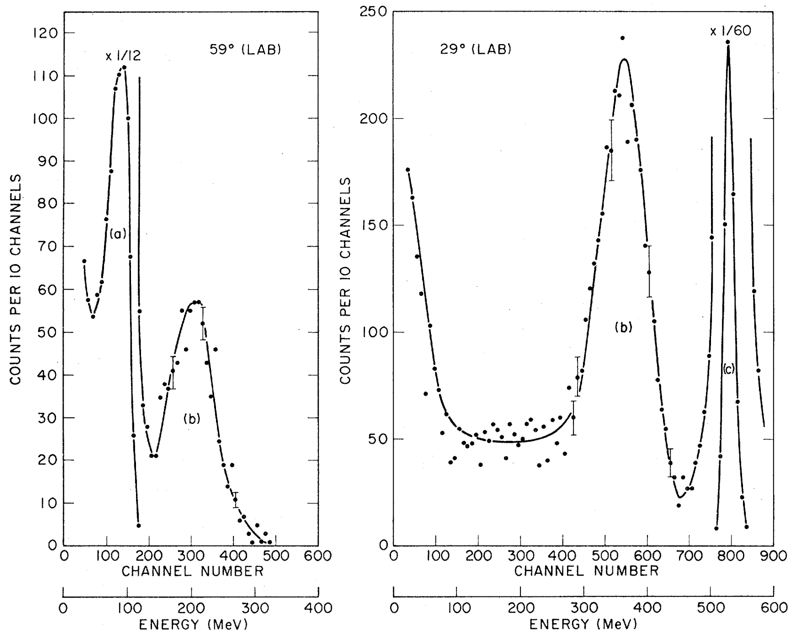

FIG. 1. Singles spectra at laboratory angles of 59° and 29°: peak ***a***, elastic ^{209}Bi recoils; peak ***b***, light-mass fragment from the strongly damped collisions; and peak ***c***, elastic ^{84}Kr events.

reactions fill in the valley between the strongly damped collisions and elastic scattering. Examples of the single-counter-energy spectra taken at 29° and 59°, in the laboratory system, are shown in Fig. 1. These two measurements represent angles well inside and well outside the grazing angle. At 59° (lab) the lower-energy peak a is the elastic ^{209}Bi recoil peak and peak b is the lighter-mass fragment from the strongly damped collision process. The energies indicated in Fig. 1 are "apparent" energies, calculated without the iterative energy-calibration kinematics calculation used for coincidence measurements. At 29° (lab), peak b is again the lighter-mass fragment from the strongly damped collisions and peak c is the elastic ^{84}Kr peak.

At five angles, where coincidence measurements were performed, the low-energy peak in each singles spectrum was shown to be due to the lighter-mass fragment of the strongly damped collision process. This interpretation was assumed at other angles. The resulting angular distribution for the lighter-mass fragment from the strongly damped collisions is shown in Fig. 2. The circles and triangles are for the laboratory and center-of-mass systems, respectively. An important feature of this angular distribution is the sharp peaking at an angle of 58° (c.m.), slightly smaller than the grazing angle, indicative of a relatively fast process. At a ^{84}Kr bombarding energy of 525 MeV, the results of Hanappe *et al.*[2] show a similar angular distribution peaked at an angle of 95° (c.m.). The fact that

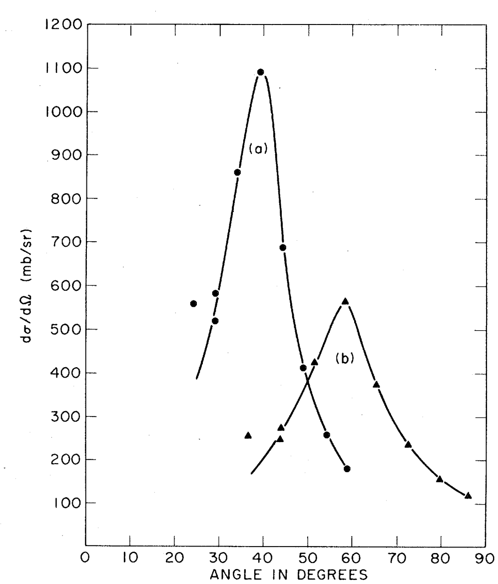

FIG. 2. Angular distribution of the light-mass fragment from the strongly damped collisions. The circles and triangles are for the lab and c.m. systems, respectively.

the angular distribution is falling so fast at small angles argues against a nuclear-orbiting picture[4] where the colliding nuclei survive more than a fraction of a revolution. The present ^{84}Kr data indicate that only a very small fraction of the intermediate systems live long enough to reach angles near 0°. Integration of the angular distribution shown in Fig. 2 gives a cross section of approximately 1.5 b for the strongly damped collision process. There is an uncertainty associated with this value due to possible background introduced by other reaction channels, but it can be concluded that the strongly damped collisions represent a major fraction of the total reaction cross section of 1.8 b (determined from the elastic-scattering data using the $\frac{1}{4}$-point technique[5]). The ratio of the strongly damped collision process to the total reaction cross section at 600 MeV is 0.8 ± 0.1, which is larger than the value of 0.6 found for the ratio at 525 MeV,[2] indicating an increasing importance of this new process as the bombarding energy is increased.

Further information on the nature of the strongly damped collision process may be derived from the total kinetic energy release (TKE) and the mass distributions. Figure 3(a) shows a contour plot of the preneutron-emission total kinetic energy (c.m.) of the fragments versus preneutron-emission mass, obtained from a full calculation. An energy window was set around the light-fragment peak of the strongly damped collision process at an angle of 59° (lab). It was assumed that neutrons were emitted from the fragments in the ratio of their respective fragment masses with the total calculated from energy-balance considerations. The characteristic feature of the strongly damped collisions seen in Fig. 3(a) is the small average total kinetic energy (~275 MeV) relative to the kinetic energy of elastic scattering (~430 MeV). The total kinetic energy is nearly constant with respect to angle, gradually increasing as the light fragment is detected at more forward angles, with an average TKE of 290 MeV at 34° (lab). Kinetic energies of 275–290 MeV correspond to Coulomb energies for charge centers separated by 15–17 fm (depending on the amount of charge transfer), a stretched configuration similar to that encountered in fission. This may be compared to a calculated value of approximately 12 fm for the target-plus-projectile system assuming touching spheres with a radius parameter of 1.17 fm. The entrance and exit channels of the strongly damped collision process must be viewed as being very different with respect to nuclear deformation, with the exit channel consisting of a very elongated system prior to scission. An even larger distance between charge centers is obtained for the exit channel if part of the measured kinetic energy is assumed to be collective energy, e.g., from rotation of the composite system.

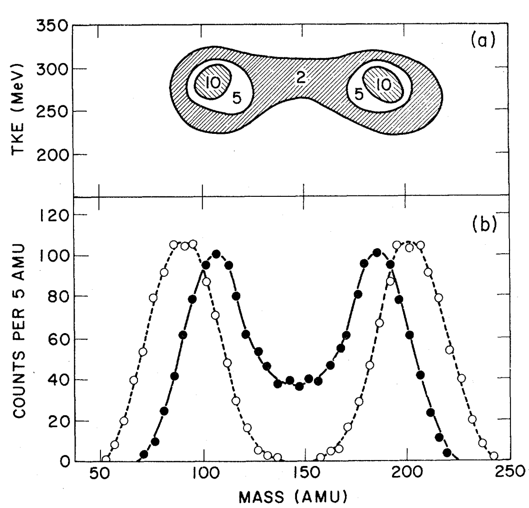

FIG. 3. (a) Contour plot of the kinetic energy (c.m.) versus fragment mass for the defining detector at 59° (lab) with an energy window around the strongly damped peak of the light fragment. (b) Mass distributions for strongly damped collisions when the light fragment is detected at 59° (lab), solid curve, and 34° (lab), dashed curve.

The large cross section measured for the strongly damped collision process for ^{84}Kr bombardments of ^{209}Bi is thought to be associated with the delicate balance between the absolute magnitude of dV_n/dr and $d(V_C+V_l)/dr$, where V_n V_C, and V_l represent nuclear, Coulombic, and centrifugal potentials, respectively, as a function of the radial distance r. If one considers nuclear potentials which do not violate the limiting value[6,7] of dV_n/dr for the liquid-drop model, at most only a limited number of l waves have potential wells. The fact that most of the total reaction cross section is strongly focused into a relatively small angular range suggests that the intermediate systems with small impact parameters have longer lifetimes. This follows because the rotational velocity is slower for the smaller angular momenta and in order to contribute to the measured narrow angular distribution their angle of rotation must be larger. The differences in lifetimes of the intermediate systems formed with different impact parameters may be related to the radial dependence of the force, dV/dr.

The smaller impact parameters have small values of dV/dr for the smaller radial distances, whereas the larger impact parameters have a larger and nearly constant value of dV/dr. These very different driving forces may contribute to the sharpness of the angular distribution. The variation of the mass distribution and the average TKE with angle of detection of the light fragment can also be qualitatively explained. Small values of dV/dr at small r for systems of small impact parameter allow deeper penetration and longer lifetimes for mass transfer. As seen in Fig. 3(b), the mass exchange between target and projectile at 59° (lab) is considerably greater than observed at 34° (lab). Also, the average TKE has its lowest measured value at 59° (lab), consistent with smaller values of angular momentum relative to more forward angles and a correspondingly lower value of the rotational energy to be added to the Coulomb energy to give the observed TKE.

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Observations of a High-Spin Yrast Cascade in ^{50}Cr

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A ground-state band with spin up to $J^\pi = 12^+$ was observed in ^{50}Cr from the reactions ^{40}Ca(^{16}O, $2p\alpha$)^{50}Cr, ^{24}Mg(^{32}S, $2p\alpha$)^{50}Cr, ^{40}Ca(^{14}N, $3pn$)^{50}Cr, and ^{40}Ca(^{12}C, $2p$)^{50}Cr. Spin and parity assignments were made from γ-γ coincidences, angular distributions, and linear-polarization measurements. The higher-spin states are reasonably well reproduced in the $(1f_{7/2})^n$ shell-model frame while discrepancies exist for the lower ones. These levels have collective features at lower excitation but very pure shell-model characteristics towards the maximum spin expected in the $(1f_{7/2})^n$ space.

During a systematic γ-ray study[1-3] of high-spin states in $1f_{7/2}$ nuclei, a strong selective excitation of the ground-state band of ^{50}Cr was observed with various heavy-ion compound reactions: ^{40}Ca(^{16}O, $2p\alpha$)^{50}Cr, ^{24}Mg(^{32}S, $2p\alpha$)^{50}Cr, ^{40}Ca(^{14}N, $3pn$)^{50}Cr, and ^{40}Ca(^{12}C, $2p$)^{50}Cr. In each of these reactions the ground-state–band cascade was found to continue above the known 6^+ state[4] with four additional strong transitions connecting states with presumably high spin. The coincidence spectra for the reaction ^{40}Ca(^{16}O, $2p\alpha$)^{50}Cr are shown in Fig. 1.

The nucleus ^{50}Cr is particularly interesting because its low-energy level structure shows[4] rather high collectivity. Recent measurements[5] of the static quadrupole moment of the lowest 2^+ state suggest a large prolate ground-state deformation. However, the decrease of the $B(E2)$ values of the ground-state band with increasing spin[4] indicates a decrease of the collectivity for the higher-spin states. Thus, it is interesting to see how the ground-state band behaves at the higher-spin side, especially concerning the collectivity. In fact, the states with highest spin until now reported in the $1f_{7/2}$ shell, namely, the $J^\pi = \frac{19}{2}^-$ states in ^{43}Sc [6] and ^{53}Fe,[7] are well described by the pure $(1f_{7/2})^n$ configuration. In the same space, spins up to 14^+ are expected for ^{50}Cr.

In order to investigate the new high-spin levels found in ^{50}Cr the reaction ^{40}Ca(^{16}O, $2p\alpha$)^{50}Cr was studied in detail by several γ-ray spectroscopy techniques. The measurements were performed at the Munich MP tandem Van de Graaff accelerator with 50–60-cm^3 Ge(Li) detectors of typical