Projectile Splitting at 12.1 MeV/u

A. Olmi, U. Lynen, and J. B. Natowitz[(a)]
Max-Planck Institut für Kernphysik, D-6900 Heidelberg, Germany

and

M. Dakowski,[(b)] P. Doll, A. Gobbi, H. Sann, H. Stelzer, and R. Bock
Gesellschaft für Schwerionenforschung, D-6100 Darmstadt, Germany

and

D. Pelte
Universität Heidelberg, Heidelberg, Germany
(Received 22 October 1979)

A measurement of the projectilelike fragments is reported for the collision of ^{86}Kr on ^{166}Er at a bombarding energy of 12.1 MeV/u. The results seem understandable only if a dynamical splitting of the projectilelike fragments is assumed.

Deeply inelastic collisions (DIC) have been found to proceed essentially through a binary reaction followed by the sequential decay of the excited primary fragments. At incident energies of ~ 3 MeV/u above the Coulomb barrier, the relative velocity, v_{rel}, of the colliding nuclei is considerably smaller than the internal Fermi velocity, v_F, of the nucleons, so that the system has sufficient time to equilibrate and shows sharing of the excitation energy proportional to the masses of the reaction products.[1,2] The observed element distributions are symmetric bell shaped curves of nearly Gaussian form, whose width increases as a function of the total kinetic energy loss (TKEL) of the system.[3-5]

With increasing bombarding energy nonequilibrium effects are expected to become more and more important. Moreover, the enhanced momentum associated with the coherent motion of the nucleons of the projectile relative to the nucleons of the target favors collective modes of excitation and new phenomena may be expected. In this respect it is interesting to investigate whether the energy is dissipated locally in space (hot spots) or whether it is dissipated via few collective degrees of freedom. The former would be evidenced by the nonequilibrium emission of energetic light charged particles whereas the latter mechanism could lead to a prompt splitting of the fragments. Investigations with "light" heavy ions ($A < 20$) at bombarding energies[6] above 10 MeV/u show the fragmentation of the projectile into lighter products. Since for projectiles with $A < 20$, light-particle emission and splitting leads practically to the same final products, a heavy projectile should be better suited. We report here, for the first time, results gained from an experiment where projectiles heavier than $A \simeq 60$ are accelerated above 12 MeV/u.

The ^{86}Kr-^{166}Er collision has been chosen because it was already extensively studied at the lower bombarding energies of 6, 7.2, and 8.2 MeV/u.[1,4,5,7,8] Raising the bombarding energy from 8.2 to 12.1 MeV/u, the initial available energy above the Coulomb barrier increases from 3.5 to 7.5 MeV/u.

A beam of about 1 particle-nA, delivered by the Unilac accelerator at Gesellschaft für Schwerionenforschung, was used to irradiate ^{166}Er targets, 96% enriched and 160 μg/cm^2 thick, on a carbon backing of 30 μg/cm^2. The projectilelike reaction products were detected in a large-area ($D\Omega = 50$ msr, $D\theta = 21°$), position-sensitive ionization chamber,[9,10] which measures their charge, energy, and (x,y) position coordinates. Because of the strongly forward peaked kinematics (grazing angle, $\theta_{gr} = 17°$), the ionization chamber was set at a very forward position, covering the angular range from 3° to 24°. The detector could be reliably operated at counting rates up to 100 kHz.

The center-of-mass transformation was performed event by event and neutron evaporation was taken into account in an iterative way.[5] The absolute cross section was determined by normalization of the elastic events to the Rutherford cross section. In one-particle inclusive measurements of DIC the total kinetic energy (TKE) of products is usually deduced assuming a binary reaction. For comparison to the low-energy data ($E_{lab} \leq 8.2$ MeV/u) this procedure was also applied to the data at 12.1 MeV/u: The results are presented in Figs. 1 and 2.

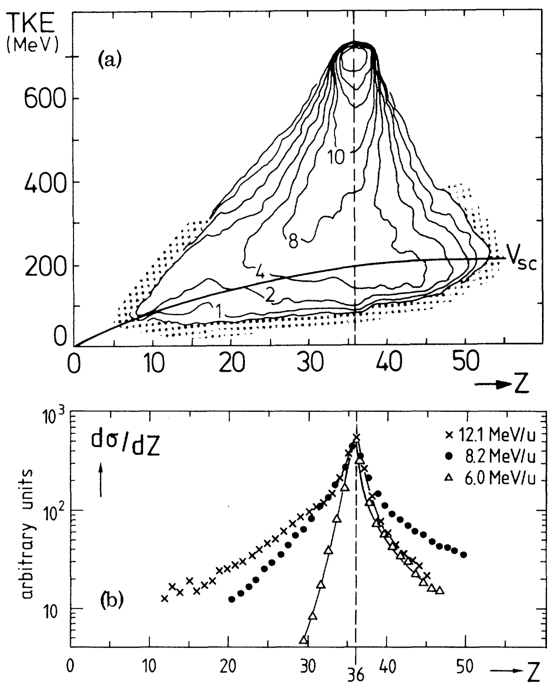

FIG. 1. (a) Contour plot of the angle integrated (3° $< \theta < 24°$) cross section $d^2\sigma/dEdZ$ as a function of TKE and of the nuclear charge Z of Kr-like fragments. The absolute cross section is given in units of mb/[(20 MeV) $\cdot Z$]. Dotted background shows the region of experimental limitations. The V_{sc} line indicates the Coulomb barrier at scission; it is calculated using two prolate elipsoids (ratio of axis = 0.6) with a distance between surfaces of 2 fm. (b) Element distributions $d\sigma/dZ$ integrated over all ineleastic events and observed angles. The relative yield of distributions is normalized at Z = 36.

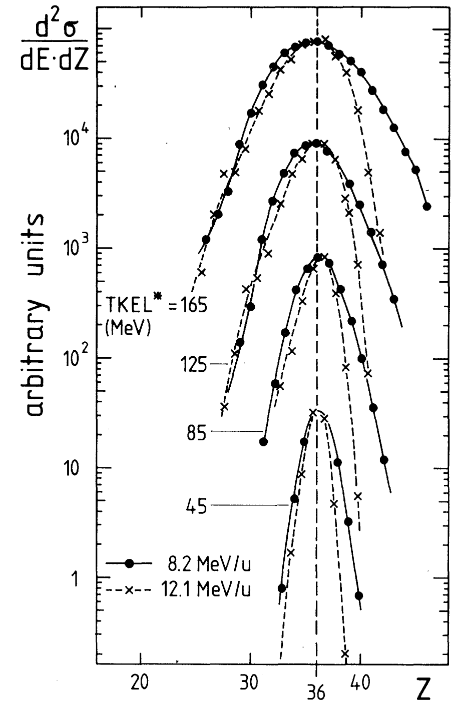

FIG. 2. Comparison of element distributions for given bins of available energy TKEL* = TKEL − V_c (in) + V_c (out) for energies of 8.2 and 12.1 MeV/u. V_c is the Coulomb potential of two touching spheres. The relative yields are normalized for each energy bin at Z = 36.

Figure 1(a) shows a contour plot of the TKE versus the atomic number Z of projectilelike fragments. The dominant feature is that with increasing energy loss a ridge in the element distribution develops towards light elements. This can also be recognized in Fig. 1(b) where the energy and angle-integrated element distribution is shown together with the corresponding results for 6 and 8.2 MeV/u. For a detailed comparison at small energy losses, Fig. 2 displays the element distributions at 12.1 MeV/u bombarding energy together with the results obtained for the same energy losses at lower bombarding energy. The striking new result at the high incident energy is a pronounced skewness which develops into the shift apparent in Fig. 1(a). At lower bombarding energies, on the contrary, generally symmetric Gaussian-shaped element distributions are observed and a mass drift was found only towards symmetry.[5]

Contributions from the targetlike products are, from kinematic considerations, quite unlikely and could only affect the distributions for TKE less than 250 MeV. In addition, since measurements using an uranium target gave very similar TKE vs Z contour plots, target fission as the origin of the enhanced production of elements with $Z < 36$ can be ruled out. Although at 12.1 MeV/u the shape of the distributions is different from the one observed at lower energies, the measured width agrees well with systematics[8] deduced from the experiments at lower energies, assuming that the right side of the distributions (for $Z > 36$) reflects the primary population of the elements, whereas the left side is modified by an additional process.

In order to exclude as a possible explanation a drift during the primary nucleon exchange, we have measured the nearly symmetric system ^{86}Kr-^{89}Y which shows the same features as in Figs. 1 and 2. Since for a symmetric system the element distribution must be symmetric unless more than two charged products are emitted, the projectilelike products must undergo a fragmentation into light charged particles or into heavier products (splitting).

However, the yield of light charged particles (protons and alphas), measured in coincidence with the projectilelike fragments using a plastic scintillator, was not sufficient to explain the effect.[11] The multiplicity of alpha particles is estimated to be one for energy losses TKEL greater than 300 MeV. For smaller energy losses the multiplicity is rapidly decreasing by more than one order of magnitude. The overall proton multiplicity is even smaller. As a consequence the projectilelike fragments are expected to decay by the emission of products heavier than alphas.

If the projectilelike products are splitting into two massive fragments only one of which is detected, then the two-body kinematic assumption is no longer valid and the reconstructed TKE is, in general, too low. The wrong interpretation of the nonbinary events may simulate a shift of the element distribution, like the one observed in Fig. 1(a). Even a small splitting probability of the projectilelike fragments will have a large effect on the distributions at low TKE and small Z values because of the strong decrease of the primary cross section $d^2\sigma/dZdE$ as a function of decreasing energy.

In order to present the data without using the two-body kinematic assumption the results of Figs. 1 and 2 are displayed in Fig. 3 as a function of the measured laboratory velocity $v_{\rm lab}$ of fragments. The events for $Z < 15$ show a large spreading around the V_{sc} line. This line indicates the limiting velocity given by the Coulomb energy of the fragments at scission (see caption of Fig. 1). Such a spreading can be expected if the light nuclei result from a splitting of the projectilelike fragments after a DIC.

Another mechanism which results in an enhanced production of elements lighter than the projectile is the fragmentation as observed at relativistic energies.[12,13] In such a case the projectile velocity is preserved and the ridge of the distribution should develop from the quasielastic peak in direction of arrow (a) shown in Fig. 3, which is not the case.

For a more direct proof of the splitting hypothesis a third experiment was performed[14] in order to detect both splitting fragments in coincidence at very forward angles. Very preliminary results given in Fig. 4 for the reaction ^{86}Kr-^{89}Y show that indeed two coincident products are observed whose total charge and energy are distributed like charge and energy of the projectilelike fragments in the DIC at lower incident energies. Assuming that the splitting fragments

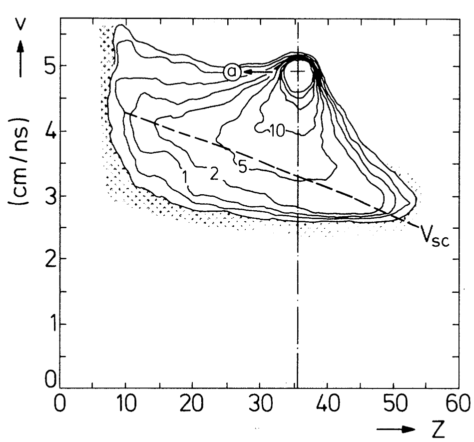

FIG. 3. Angle-integrated double-differential cross section $d^2\sigma/dvdZ$ as a function of nuclear charge Z and laboratory velocity. Absolute cross sections are given as mb/[(cm/ns)$\cdot Z$] on the contour lines. V_{sc} indicates the low-velocity limit for a two-body reaction as given by the Coulomb energy at scission (see caption of Fig. 1).

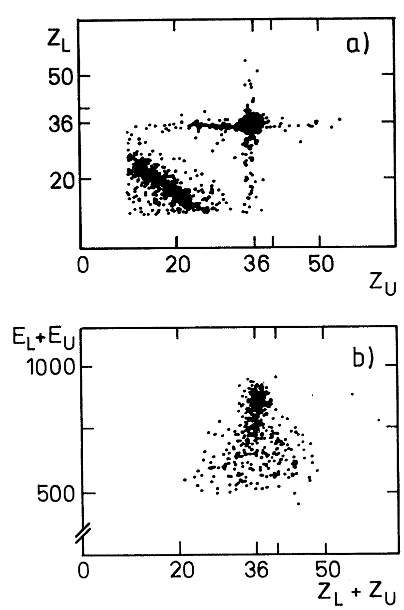

FIG. 4. Scatter plots for splitting fragments in ^{86}Kr-^{89}Y collisions: (a) Correlations of Z numbers (L and U are for lower and upper fragment detector). The true coincidences lie around the line $Z_1+Z_2=36$ with broad mass distribution. The random coincidences with elastically scattered Kr ions lie on vertical and horizontal lines. (b) Summed laboratory energy vs summed charge Z of coincident fragments.

are emitted isotropically within a cone of ± 45° opening around the beam axis, a rough estimate for the splitting probability was 4%.

The interesting question is whether the splitting of the Kr-like products is a fast nonequilibrium decay or a sequential decay of an equilibrated nucleus. From the data of Fig. 2, the first hypothesis seems more likely. The fact that for comparable excitation energies (same TKEL* bins) the presence of the splitting products is observed at 12.1 MeV/u but does not appear in the distributions at 8.2 MeV/u is hard to understand in a pure statistical picture. An explanation based on the sequential fission of the Kr-like nuclei would require a drastic decrease of the fission barrier due to an increased angular momentum dissipation at the higher bombarding energy. This however is not predicted by model calculations[15] based on the γ-multiplicity experiments at lower bombarding energies.[7]

In conclusion the new feature emerging from the reaction ^{86}Kr-^{166}Er at a bombarding energy of 12.1 MeV/u is the enhanced production of elements lighter than the projectile, which at low-energy losses appears as a skewness of the element distributions and at high-energy losses develops into a pronounced shift of the maximum. The experimental results can be understood in terms of a dynamical splitting of the projectile-like fragments which prevails over the emission of light charged particles. This suggests that in DIC between heavy nuclei at high incident energies a considerable fraction of the dissipated energy is at first concentrated in few collective degrees of freedom, rather than in a small local region (hot spot).

We thank G. Augustinski, H. Daues, H. J. Beeskow, and M. Ludwig for their assistance in preparing the detection system, H. Folger for the target preparation, and the operators of the Unilac accelerator for the production of an excellent Kr beam of 12.1 MeV/u.

[a]On leave from Texas A & M University, College Station, Tex. 77840.

[b]On leave from the Institute of Nuclear Research, Swierk, Poland.

[1]Y. Eyal *et al.*, Phys. Rev. Lett. 41, 625 (1978).

[2]B. Tamain *et al.*, Nucl. Phys. A330, 253 (1979).

[3]W. U. Schröder *et al.*, Ann. Rev. Nucl. Sci. 27, 465 (1977).

[4]H. Sann *et al.*, in *Proceedings of the Topical Conference on Heavy-Ion Collisions, Fall Creek Falls State Park, Tennessee, 1977*, CONF-770602 (National Technical Information Services, Springfield, Va., 1977).

[5]G. Rudolf *et al.*, Nucl. Phys. A330, 245 (1979).

[6]C. K. Gelbke *et al.*, Phys. Lett. 70B, 415 (1977).

[7]A. Olmi *et al.*, Phys. Rev. Lett. 41, 688 (1978).

[8]M. Dakowski *et al.*, to be published.

[9]H. Sann *et al.*, Nucl. Instrum. Methods 124, 509 (1975).

[10]U. Lynen *et al.*, Nucl. Instrum. Methods 162, 657 (1979).

[11]P. Doll *et al.*, Gesellschaft für Schwerionenforschung Annual Report No. 79-11, 1978 (unpublished).

[12]D. E. Greiner *et al.*, Phys. Rev. Lett. 35, 152 (1975).

[13]Y. P. Viyogi *et al.*, Phys. Rev. Lett. 42, 33 (1979).

[14]U. Lynen, in Proceedings of the Symposium on Heavy Ion Physics from 10 to 200 MeV, Upton, New York, 1979 (to be published), and to be published.

[15]G. Wolschin *et al.*, Phys. Rev. Lett. 41, 691 (1979), and private communication.

Observation of Selected Molecular-Orbital X Rays in Coincidence with Separated-Atom *K* X Rays

J. J. O'Brien, E. Liarokapis, and J. S. Greenberg
A. W. Wright Nuclear Structure Laboratory, Yale University, New Haven, Connecticut 06520
(Received 20 June 1979; revised manuscript received 7 December 1979)

A cascade relationship between molecular-orbital (MO) and separated-atom x rays has been utilized to study selected MO transitions. Depending on the mechanism of vacancy production, the observed MO spectra are interpreted as reflecting $2p\sigma \rightarrow 1s\sigma$ transitions or a mixture of $2p\sigma \rightarrow 1s\sigma$ and $2p\pi \rightarrow 1s\sigma$ transitions. The coincidence selection also directly corroborates a previous assignment of MO transitions to the $2p\sigma$ state.

Although the study of molecular-orbital (MO) x rays is expected to provide one of the more direct sources of information on quasimolecular states formed in heavy-ion collisions, the acquisition of such information has been severely limited by the lack of distinctive features in MO x-ray spectra.[1] Moreover, since previous experiments have been confined to the observation of

