n-p interaction at 16.9 MeV.

[(a)]Present address: Physikalisches Institut, University of Tübingen, Tübingen, West Germany.

[(b)]Present address: P-11 Division, Los Alamos Scientific Laboratory, Los Alamos, N. M. 87544.

[1]R. E. Seamon, K. A. Friedman, G. Breit, R. D. Haracz, J. M. Holt, and A. Prakash, Phys. Rev. 165, 1579 (1968).

[2]M. H. MacGregor, R. A. Arndt, and R. M. Wright, Phys. Rev. 182, 1714 (1969).

[3]R. A. Arndt, R. H. Hackman, and L. D. Roper, Phys. Rev. C 15, 1002 (1977).

[4]C. L. Morris, T. K. O'Malley, J. W. May, Jr., and S. T. Thornton, Phys. Rev. C 9, 924 (1974).

[5]D. T. L. Jones and F. D. Brooks, Nucl. Phys. A222, 79 (1974).

[6]R. Garrett, A. Chisholm, D. Brown, J. C. Duder, and H. N. Burgisser, Nucl. Phys. A196, 421 (1972).

[7]G. S. Mutchler and J. E. Simmons, Phys. Rev. C 4, 67 (1971).

[8]J. L. Gammel and R. M. Thaler, Prog. Cosmic Ray Phys. 5, 99 (1960).

[9]J. K. Perring, Rev. Mod. Phys. 39, 550 (1967).

[10]P. W. Lisowski, R. L. Walter, C. E. Busch, and T. B. Clegg, Nucl. Phys. A242, 298 (1975).

[11]G. G. Ohlsen, J. L. McKibben, G. P. Lawrence, P. W. Keaton, and D. D. Armstrong, Phys. Rev. Lett. 27, 599 (1971).

[12]W. Tornow, P. W. Lisowski, R. C. Byrd, S. E. Skubic, R. L. Walter, and T. B. Clegg, in *Proceedings of the Fourth International Symposium on Polarization Phenomena in Nuclear Reactions*, edited by W. G. Grüebler and V. König (Birkhäuser, Basel, Switzerland, 1976), p. 439.

[13]R. Fischer, F. Kienle, H. O. Klages, R. Maschuw, and B. Zeitnitz, Nucl. Phys. A282, 189 (1977).

[14]T. L. Houk, Phys. Rev. C 3, 1886 (1971).

[15]E. Lomon and R. Wilson, Phys. Rev. C 9, 1329 (1974).

[16]J. L. Gammel, in *Fast Neutron Physics*, edited by J. B. Marion and J. L. Fowler (Interscience, New York, 1963), Pt. 2, p. 2185.

Structure in the Energy Spectra from Inelastic Heavy-Ion Reactions

N. Frascaria, C. Stéphan, P. Colombani, J. P. Garron, J. C. Jacmart, M. Riou, and L. Tassan-Got
Institut de Physique Nucléaire, 91406 Orsay, France

(Received 27 July 1977)

Broad structures have been observed in the incompletely relaxed part of the energy spectra of fragments emitted in the symmetrical reactions ^{40}Ca + ^{40}Ca at 284 MeV and ^{63}Cu + ^{63}Cu at 450 MeV. Excitation energies of these structures, angular distributions, and (Z,N) distributions leading to multiplicities for nucleon emission have been measured. They can be interpreted as being due to a predominantly direct reaction process, possibly proceeding through the excitation of highly collective high-energy modes in the region of giant resonances.

The mechanisms of heavy-ion–induced transfer reactions have usually been described under the assumption that two different processes are taking place: the quasielastic and the so-called "deep inelastic" transfers.[1,2] A detailed study of the reaction ^{40}Ca + ^{40}Ca at 256 MeV has shown[3] that the deep inelastic component could in fact be described by the coexistence of (a) a "slow" process, completely damped in energy, characterized by a $1/\sin\theta$ angular distribution and a broad Z distribution, and (b) a "fast" process, characterized by an incompletely relaxed kinetic energy, an exponentially decreasing angular distribution, and a very narrow, angle-independent Z distribution.

In this Letter, we present more complete data on symmetrical systems, namely, ^{40}Ca + ^{40}Ca and ^{63}Cu + ^{63}Cu, showing the existence of some structure unresolved up to now in the incompletely relaxed component. Complete (A, Z) identification was used, so that the choice of symmetrical systems in the entrance channel gave direct information on the multiplicity for emitted particles in the exit channel, as far as binary processes are considered. The 284-MeV ^{40}Ca and 450-MeV ^{63}Cu beams were accelerated at the Orsay ALICE facility. ^{40}Ca and ^{63}Cu targets were 1 mg/cm^2 thick and self-supporting. Possible contamination of the targets by ^{16}O or ^{12}C was carefully checked by comparison of the results with those obtained by bombarding ^{12}C and B_2O_3 targets. A complete identification of the reaction products in A and Z was performed[4] at 7°, 10°, and 14° (grazing angle) for the reaction ^{40}Ca + ^{40}Ca and at 10° for the reaction ^{63}Cu + ^{63}Cu by means of a E-ΔE telescope in the focal plane of a magnetic spectrometer. The addition of a time-of-flight measurement be-

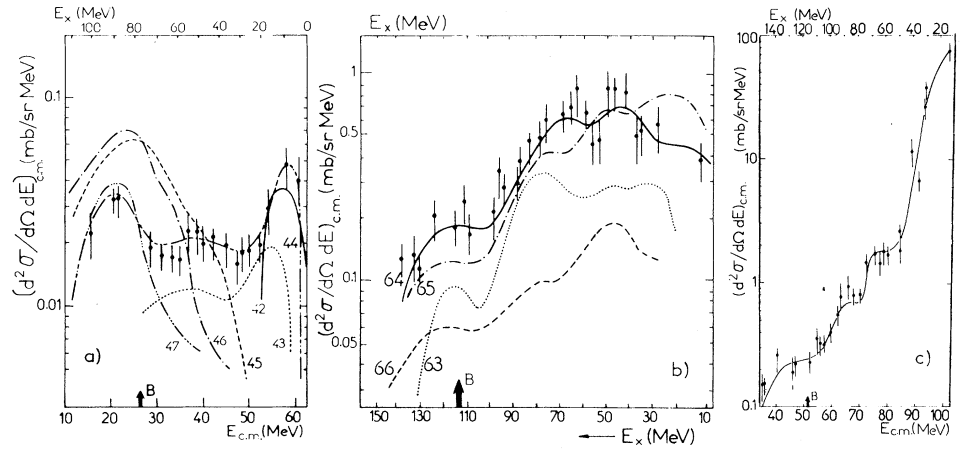

FIG. 1. (a) c.m. kinetic-energy spectra for Ti isotopes produced at $\theta_{\mathrm{lab}} = 14°$ in the reaction ^{40}Ca + ^{40}Ca at 284 MeV. The total excitation energy of the fragments, the interaction barrier, and error bars are also indicated for ^{44}Ti. (b) c.m. differential cross section for Zn isotopes produced at $\theta_{\mathrm{lab}} = 10°$ in the reaction ^{63}Cu + ^{63}Cu at 450 MeV as a function of the total excitation energy. Typical error bars are shown for ^{64}Zn. (c) c.m. kinetic-energy spectrum for ^{63}Cu produced at $\theta_{\mathrm{lab}} = 10°$ in the reaction ^{63}Cu + ^{63}Cu at 450 MeV. The total excitation energy is also indicated.

tween a thin plastic scintillator at the entrance of the spectrometer and the E detector allowed for the identification of heavy fragments detected in the reaction ^{63}Cu + ^{63}Cu. Moreover, a Z identification of the fragments was made by means of a usual E-ΔE system between 10° and 50°.

Center-of-mass kinetic-energy spectra for Ti isotopes detected in the reaction ^{40}Ca + ^{40}Ca are shown in Fig. 1(a). The main features observed for these isotopes are general: For nuclei with Z and N close to those of the projectile, the center-of-mass energy spectra exhibit three different components at all three observation angles. Incompletely relaxed events are peaked in energy at a *total* excitation energy E_x~50 MeV, between the quasielastic and the completely damped events. For heavier isotopes, while the quasielastic peak disappears, the intermediate component remains present. Its position does not vary very much with the considered isotope. For fragments farther removed from the projectile, only completely damped events remain present at all three angles. For the reaction ^{63}Cu + ^{63}Cu, available results show even more clearly the existence of a structure in the incompletely relaxed component of the energy spectrum. Two "bumps" are observed at $E_x \simeq 50$ MeV and $E_x \simeq 80$ MeV, for nuclei with Z and N close to those of the projectile, as shown in Fig. 1(b). The completely relaxed events correspond to $E_x \simeq 125$ MeV. In the ^{63}Cu energy spectrum itself, elastic scattering is also well separated from two incompletely relaxed "bumps" and from the completely relaxed events [Fig. 1(c)]. Within a few MeV (at most 10), the position of the "bumps" are independent of the isotope. It is worth noting that these structures in the incompletely relaxed component were not clearly observed in the energy spectra recorded in the simple E-ΔE telescope at small angles (10°–20° lab). At large angles (> 25° lab) only the completely damped events remain.

A striking feature of the kinetic-energy spectra of fragments observed in the reaction ^{40}Ca + ^{40}Ca is that the position of the "bump" on for the incompletely relaxed component at $E_x \simeq 50$ MeV does not change with the laboratory angle (Fig. 2). Kinematic considerations show that it does not change appreciably with the c.m. angle either. The measurements at 7°, 10°, 14° (lab) also show that the angular distribution of the incompletely relaxed events ($30 < E_x < 60$ MeV) is quite similar to the angular distribution of the quasielastic ones ($0 < E_x < 30$ MeV) and very much different from the approximately $1/\sin\theta$ shape observed fro completely damped events ($60 < E_x < 100$ MeV).

The Z and N distributions of the fragments emitted in a given excitation energy range have been obtained for both reactions and are shown in Fig. 3 in the ^{63}Cu + ^{63}Cu case. In the incompletely relaxed region, the distributions are narrow and centered near the projectile. Particle multiplicities and variances of the distributions are small: On the average, 0.2 proton and 0.7 neutron are emitted by each fragment in the *total* excitation

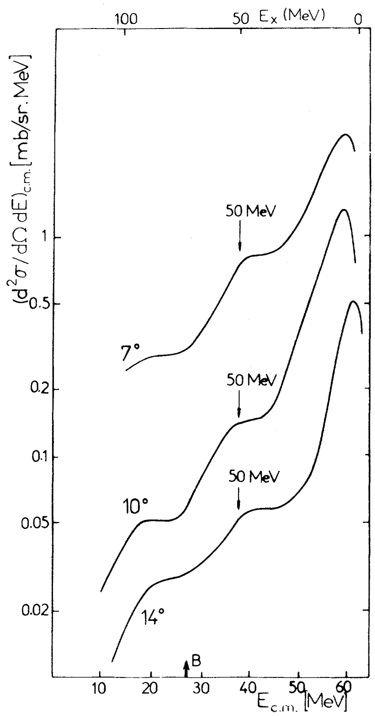

FIG. 2. c.m. kinetic-energy spectra for ^{42}Sc produced in the reaction ^{40}Ca + ^{40}Ca at 284 MeV at various laboratory angles.

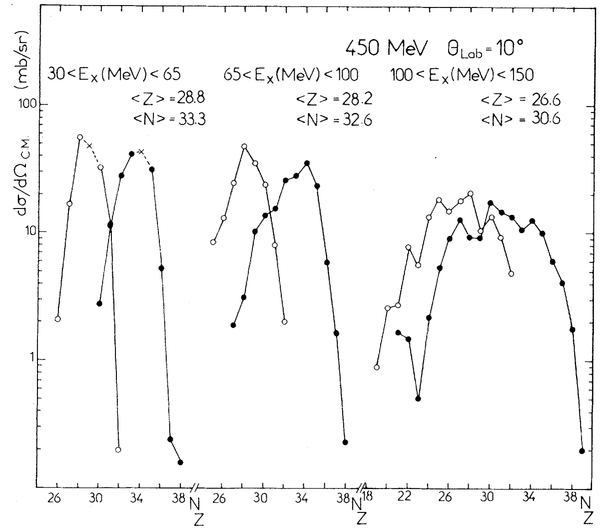

FIG. 3. Z (open circles) and N (full dots) distributions for three excitation-energy windows in the reaction ^{63}Cu + ^{63}Cu. For the low-energy window ($30 < E_x < 65$ MeV), contamination from quasielastic and/or elastic events does not allow an accurate determination of the cross section for the case with $Z = 29$ and $N = 34$ (crosses).

range $30 < E_x < 65$ MeV; the variances are $\sigma_Z = 1.1$ and $\sigma_N = 1.8$. For $65 < E_x < 100$ MeV, the numbers are, respectively, 0.8 proton ($\sigma_Z = 2.4$) and 1.4 neutron ($\sigma_N = 4.1$). The completely relaxed component exhibits a broad distribution centered farther away from the projectile: Particle multiplicities are 2.5 for protons ($\sigma_Z = 8.7$) and 3.5 for neutrons ($\sigma_N = 13.7$). For ^{40}Ca + ^{40}Ca, Z and N distributions for the quasielastic and for the intermediate-energy bump also exhibit a similar behavior, different from what is observed for the completely relaxed component.

Only a small number of nucleons are emitted consecutively in incompletely relaxed collisions for both reactions. In the ^{63}Cu + ^{63}Cu case, if one assumes that the total excitation energy is shared between the two emitted fragments, roughly proportionally to their masses, the average excitation energy for each of them would be ~25 MeV in the first window and ~40 MeV in the second one. With respective multiplicities of 0.9 and 2.2 nucleons, this would give average excitation energies of 28 and 18 MeV per emitted nucleon. These rather large numbers are expected from a nonequilibrium mechanism and would be consistent with the hypothesis of the direct deexcitation by particle emission of a high-energy collective state. In the completely damped region, multiplicities are high and variances are large, and the average excitation energy per nucleon (10 MeV) suggests nucleon and/or α evaporation following a statistical equilibrium.

The interpretation of the observed structures in terms of currently used theoretical models[5] on heavy-ion–reaction mechanisms is not really clear. In terms of the diffusion model, the forward peaking of the angular distribution and the sharp (Z, N) distributions of the incompletely relaxed events imply the existence of an intermediate complex with a lifetime shorter than the mean rotational period. From the nuclear orbiting collision assumption of Wilczynski,[6] one can expect three maxima in the kinetic-energy spectrum. These maxima would correspond to contributions to the cross section observed at a given angle from both the left- and right-hand collisions and a contribution from deexcitation of a colliding system surviving more than half a revolution. However, in this picture at most three components can be predicted and the fact that the total excitation energy of the incompletely relaxed component is angle-independent cannot be explained.

The observed properties of the incompletely relaxed component of the energy spectra clearly suggest a short-lifetime regime probably relevant of a rather direct process (as for quasielastic transfers). The observation of structures at high excitation energy may be interpreted by the excitation of highly collective modes in an early stage of the reaction. This has been predicted by Broglia, Dasso, and Winther[7] as very likely to occur in heavy-ion collisions as a consequence of the excitation of giant resonances. If one assumes a rather weak interaction between the two ions, each of them would be mainly excited through its own resonance mode. The excitation of high-multipolarity modes, as predicted by the calculations of Liu and Brown[8] for ^{40}Ca and ^{90}Zr, would give a plausible explanation of the energy spectra. If the interaction is stronger, one would expect to observe resonant modes for an intermediate complex. The data do not exclude such a possibility.

The data presented here furnish strong evidence for some structures in the incompletely relaxed part of the energy spectrum of fragments emitted after a symmetrical heavy-ion reaction. No definitive explanation of these structures can be given now, but the excitation of highly collective modes seems a reasonable possibility. The observation of such details in the energy spectra was made possible only because of several favorable factors: (a) complete Z and A identification of the fragments and clear separation of the reaction products from the elastic peak, made possible by the use of the magnetic spectrometer; (b) sutdy of symmetrical or near-symmetrical systems in the exit channel, making the observation of broad collective high-energy states easier, since the excitation energies are about the same for each fragment; and (c) use of an energy high above the interaction barrier, allowing a clear separation between the various components. This last point may explain why the second component found at 80 MeV in the Cu + Cu case has not been observed in Ca + Ca, where the excitation energy range is then 50 MeV smaller than in the Cu + Cu case.

Fruitful discussions with L. G. Moretto, R. A. Broglia, and A. Winther are gratefully acknowledged. We would like to thank A. Gamp, H. Doubre, N. Poffé, J. C. Roynette, E. Festa, and C. Stamm for their help during these experiments, and C. Détraz and L. Valentin for a careful discussion of the manuscript.

[1]L. G. Moretto and R. Schmitt, J. Phys. (Paris), Colloq. 37, C5-109 (1976), and references therein.

[2]J. Galin, J. Phys. (Paris), Colloq. 37, C5-83 (1976), and references therein.

[3]J. C. Roynette, H. Doubre, N. Frascaria, J. C. Jacmart, N. Poffé, and M. Riou, Phys. Lett. 67B, 395 (1977).

[4]C. Stéphan, N. Frascaria, J. P. Garron, J. C. Jacmart, N. Poffé, and L. Tassan-Got, CERN Report No. 76-13 (unpublished), p. 46; L. Tassan-Got, thèse de 3ème cycle, Institut de Physique Nucléaire Report No. IPNO-T-77-04 (unpublished).

[5]W. Nörenberg, J. Phys. (Paris), Colloq. 37, C5-141 (1976), and references therein.

[6]J. Wilczynski, Phys. Lett. 47B, 484 (1973).

[7]R. A. Broglia, C. H. Dasso, and A. Winther, Phys. Lett. 61B, 113 (1976).

[8]K. F. Liu and G. E. Brown, Nucl. Phys. A265, 385 (1976).