PHYSICAL REVIEW C

NUCLEAR PHYSICS

THIRD SERIES, VOLUME 49, NUMBER 2 FEBRUARY 1994

RAPID COMMUNICATIONS

The Rapid Communications section is intended for the accelerated publication of important new results. Manuscripts submitted to this section are given priority in handling in the editorial office and in production. A Rapid Communication in **Physical Review C** *may be no longer than five printed pages and must be accompanied by an abstract. Page proofs are sent to authors.*

Collisions between ^{106}Cd and ^{54}Fe at 30 MeV above the Coulomb barrier by high resolution $\gamma\gamma$ coincidences

R. Broda, C. T. Zhang, P. Kleinheinz, and R. Menegazzo
Institut für Kernphysik, Forschungszentrum Jülich, D-52425 Jülich, Germany

K.-H. Maier, H. Grawe, M. Schramm, R. Schubart, and M. Lach*
Hahn-Meitner Institut Berlin, D-14109 Berlin, Germany

S. Hofmann
Gesellschaft für Schwerionenforschung, D-64291 Darmstadt, Germany

(Received 29 June 1993)

In a $\gamma\gamma$-coincidence study of collisions of ^{106}Cd with 247 MeV ^{54}Fe we have quantitatively identified the product nuclei formed in fusion-evaporation as well as in binary reactions. Individual binary processes were sampled through identification of numerous exit partner pairs with the help of $\gamma\gamma$ cross coincidences. The data also provide information on the angular momentum transferred to the product nuclei and on charge equilibration in the collision process. The results reveal important features of heavy-ion collisions that are difficult to obtain in measurements using charged particle detection alone.

PACS number(s): 25.70.Gh, 25.70.Jj, 25.70.Lm, 29.30.Kv

The summary of heavy-ion (HI) reaction studies given in the 1981 review articles of Bromley's monography [1] displayed the advanced knowledge of the processes which take place when two heavy nuclei collide with one another. However, in this review and in later publications it has often been pointed out that along with a relatively good knowledge of fusion and quasielastic processes, the much more complex class of reactions known as damped, dissipative or deep inelastic collisions is still far from being satisfactorily understood. The experimental difficulty arises from the necessity to use heavy-ion detection which—in spite of significant technical progress achieved—practically excludes the possibility to inspect individual reaction processes in heavy systems, as the unique identification of mass and charge of the reaction partners becomes very difficult.

In this work we present an alternative approach to study heavy-ion collisions, namely by measuring the discrete γ radiation emerging from the reaction products. Such data can provide important supplementary insight of a different nature on the collision processes.

Until recently the very rich information carried by the γ radiation accompanying the individual reaction process could not be exploited due to the immense complexity of the γ spectra. This situation changed when anti-Compton-shielded multidetector arrays became available. It has been demonstrated that the superior resolving power of high-quality $\gamma\gamma$-coincidence data obtained with such arrays enables us to study excitations of individual nuclei produced in as complex a process as nuclear fission [2], and also successful spectroscopic studies of nuclei produced in damped HI collisions have been reported [3,4]. Moreover, it has been shown [5] that one can also observe coincidences between γ rays emitted from two different nuclei, namely the two binary reaction partner products, which naturally occur simultaneously in the

*On leave from Institute of Nuclear Physics, Cracow, Poland.

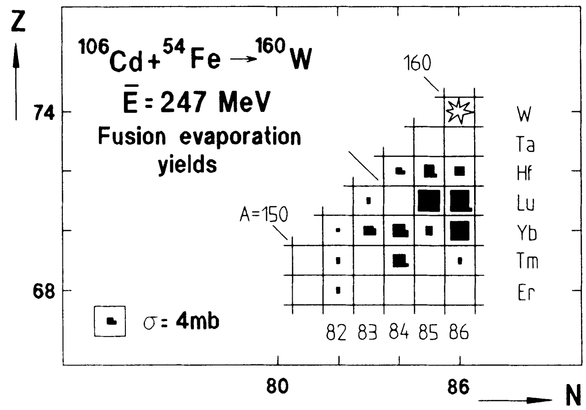

FIG. 1. Cross sections for direct production of fusion-evaporation residues in bombardment of ^{106}Cd with 247 MeV ^{54}Fe beam. The dark area is proportional to the cross section; the smallest unit represents 0.8 mb.

exit channel. Such $\gamma\gamma$ cross coincidences provide straightforward isotopic identification of both outgoing nuclei. Hereby it is firmly established whether or not nucleons were emitted in the process, and thus the primary or secondary character of the reaction products is specified.

In order to explore further the potential application of this technique in HI-reaction studies we performed $\gamma\gamma$-coincidence experiments for the ^{106}Cd+^{54}Fe system. In the present Rapid Communication we give a condensed overview of the results; a more complete and quantitative account of our findings, as well as details of the data analysis, will be contained in a forthcoming article [6].

The ^{54}Fe beam energy of 255 MeV, approximately 30 MeV above the Coulomb barrier, was chosen to enable observation of a wide variety of reaction types covering the range from inelastic scattering to fusion. The 1.2 mg/cm^2 thick target of 90.8% enriched ^{106}Cd (^{108}Cd 0.4%, ^{110}Cd 1.5%), backed by 15 mg/cm^2 ^{208}Pb, ensured stopping of virtually all reaction products and the 300 ns pulsed ^{54}Fe beam from the VICKSI accelerator at HMI Berlin allowed the separation of the prompt in-beam events from those originating from radioactive or isomeric decays which occur between beam bursts. The OSIRIS multidetector ring was oriented perpendicular to the beam direction, and a large-volume four-sector neutron detector was placed in the forward direction at 0°. Gamma–x-ray and γ-neutron coincidences were vital for the identification of the essentially unknown excitation

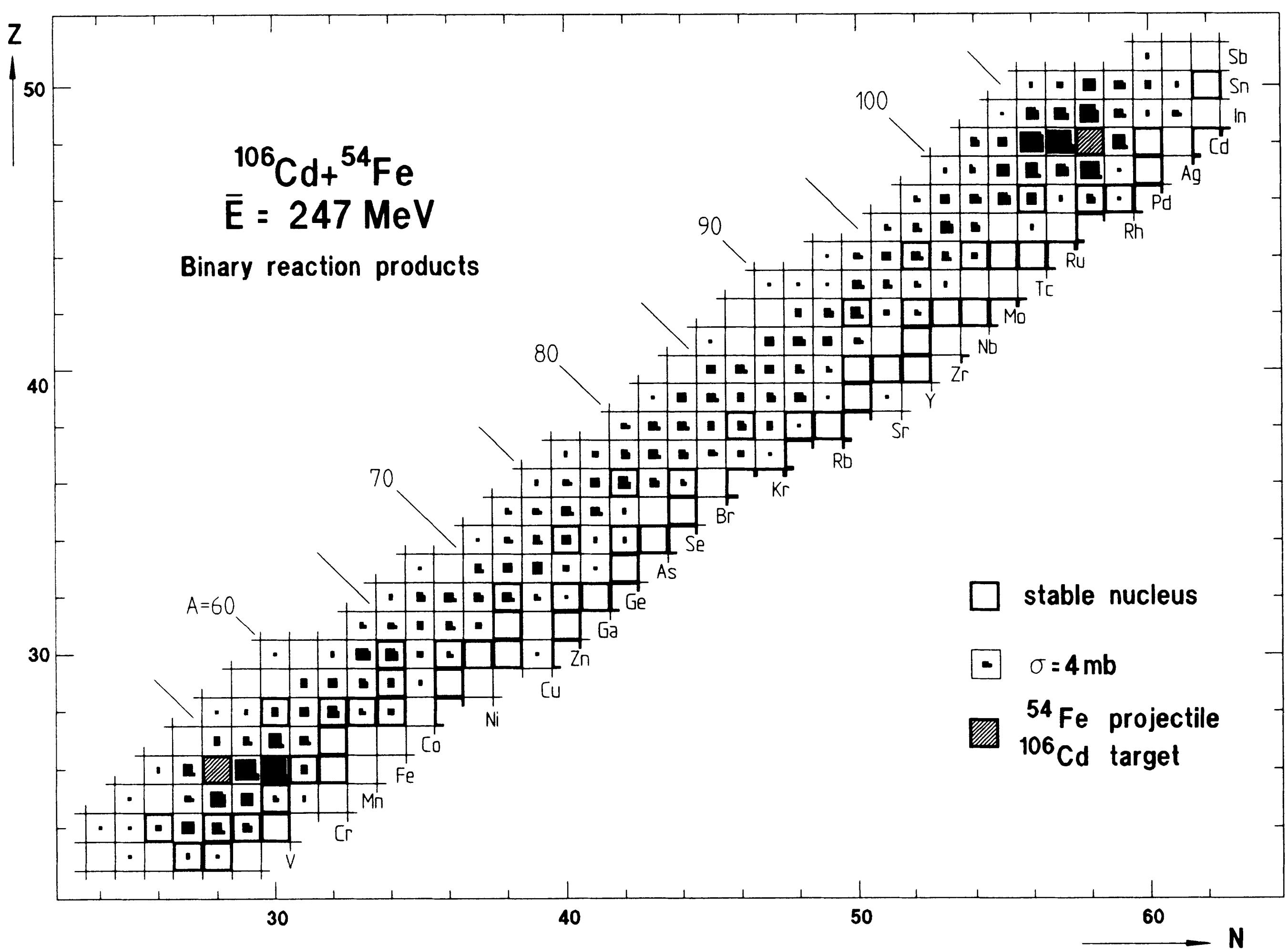

FIG. 2. Production cross sections of binary reaction products for 247 MeV ^{54}Fe on ^{106}Cd. Inelastic scattering cross sections for target and projectile are not shown.

RAPID COMMUNICATIONS

spectra in several $N \leq 86$ nuclei above Er produced in fusion evaporation. The detailed spectroscopic study of these species is a separate goal of the present experiment.

Following the in-beam experiment the radioactivity collected in the target was measured and its decay was followed over a period of four months. These data provided accurate production yields of many long-lived products. Quantitative analysis of the off-beam coincidence data gave relative yields for short-lived radioactive products including $T_{1/2} > 20$ ns isomeric decays. More laborious analysis of the prompt in-beam coincidence data established the direct production of nearly 200 nuclei. For most of them, sequences of several coincident, predominantly yrast γ-transitions known from previous studies, could be identified. Some of these in-beam coincidence results were also used to estimate the production yields of stable nuclei and of those with unfavorable radioactive decays. For evaluation of the radioactivity spectra the γ-ray tables of Reus and Westmeier [7] were of crucial significance; interpretation of the in-beam spectra was largely based on the latest Nuclear Data Sheets compilations. A summary of the production yields resulting from these analyses is graphically displayed in Figs. 1 and 2; numerical values will be given in [6]. The principal significance of our data is primarily the determination of the relative yields for all reaction products. In the figures we give them in millibarns, which is based on earlier absolute cross-section measurements for the ^{156}Lu and ^{157}Hf α-decaying fusion-evaporation products performed for the same ^{160}W compound nucleus formed at similar excitation and angular momentum at the SHIP recoil separator of GSI [8]. These results are, however, only accurate to within a factor of 2. The fusion evaporation cross sections are shown in Fig. 1. Among the 15 observed evaporation channels, $3p$, $3pn$, and $4p$ evaporation are the strongest and, as expected for the very neutron-deficient ^{160}W compound nucleus, charged particle evaporation strongly dominates. Here we only mention that calculations as described in Ref. [8] reproduce our measured fusion-evaporation cross sections except for alpha evaporation which is underestimated by a factor 2 to 3. Consideration of all measured yields leads to the conclusion that fusion evaporation accounts for close to 1/5 of the total reaction cross section (see below). As expected, we observed no reaction products of the elements from Ho down to Te.

The predominant part of the ^{106}Cd$+^{54}$Fe collisions leads to various binary reactions, producing isotopes in the range from Sb to V. Figure 2 displays the cross sections for all binary exit products that are identified in the collisions. This result probably represents the most completely identified distribution of products arising in col-

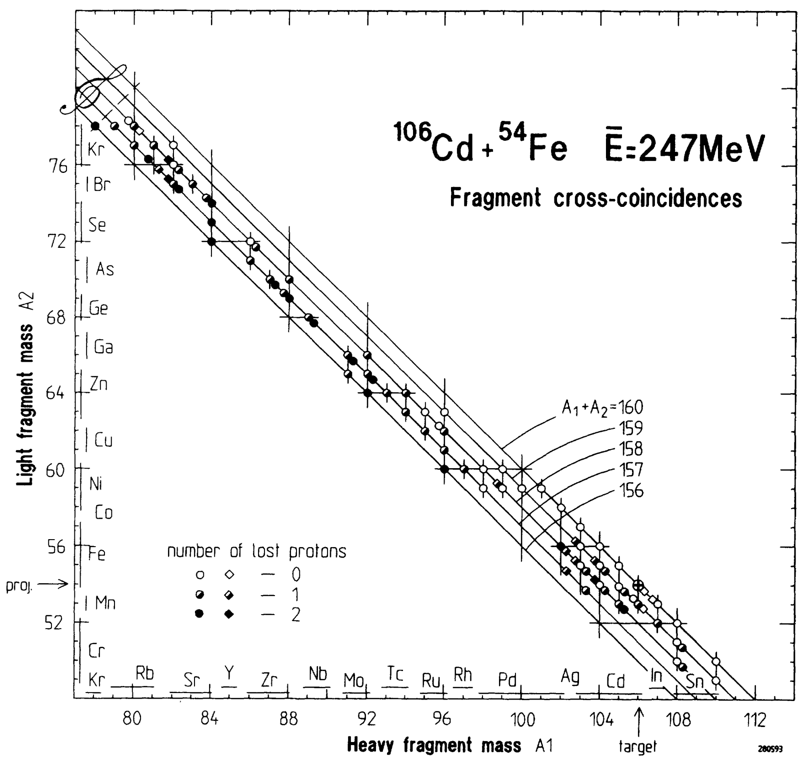

FIG. 3. Binary reaction partners established from $\gamma\gamma$ cross coincidences between discrete transitions in the respective light and heavy fragments. The figure shows that in most cases one to four nucleons are lost, and consequently the primary reaction products remain unspecified. Only the 11 data points on the $A_1 + A_2 = 160$ line represent coincidences between fully defined primary products. For circular symbols placed precisely on the respective (A_1, A_2) position the isotopic assignment for light and heavy fragment as given on the two axes is correct. Heavy-fragment assignment is correct also for off-center circular symbols, but in these cases the light-fragment Z value has to be raised or lowered by one unit depending on whether the point is shifted (left upwards or (right) downwards. Square symbols indicate an analogous change of the heavy-fragment Z value. The associated light-fragment isotopic assignment in these cases is obtained from the nucleons lost in the collision.

lisions of two heavy nuclei and illustrates the excellent resolving power of γ-ray coincidence arrays. The grouping of the largest cross sections in the vicinity of target and projectile reflects the contribution from quasielastic processes and their yields are similar to the strongest fusion-evaporation channels. We note, however, that many nuclei even far remote from the initial masses are still produced with more than one-tenth of those most intense exit channels.

It is important to note that most of the binary products are of secondary character due to particle evaporation from the primary ones. As mentioned above, this point can be clarified by the analysis of $\gamma\gamma$ cross coincidences. From in-beam coincidence spectra with gates set on specific transitions the population of known states in a given nucleus could be determined. In those spectra one can also recognize the γ lines from reaction partner nuclei produced in binary reactions. Usually several different partner nuclei were observed, as expected for data which are integrated over the kinetic energy loss. The correlation between light and heavy reaction products established from the observed $\gamma\gamma$ cross coincidences is summarized in Fig. 3. The points in the figure mark all cases, independent of the detected coincidence intensity, where the data allowed to conclude firmly the simultaneous appearance of two specific final products. The location of points on the A_1+A_2 lines indicates how many neutrons or protons were lost, most likely evaporated from the excited primary products. Although the results of Fig. 3 represent only a fraction of the binary processes occuring in the collisions, the nearly 100 cases explicitly established from the data should quite accurately sample the average properties of the reaction.

One notices that only 11 points in Fig. 3—those on the $A_1+A_2=160$ line—represent the detection of the primary reaction products, as they all occur in a narrow mass transfer region around the ^{106}Cd target and ^{54}Fe projectile nuclei. But also here processes with subsequent nucleon emission are quite frequent. For reactions with larger mass transfer, when the heavy fragment mass is below $A=98$, the points scatter around the $A_1+A_2=157$, 158 lines, in similar manner over the entire mass range down to symmetric partition. From these data one concludes that in this region on the average 2.6 nucleons are emitted, of which 1.2 are protons. The experimental finding that in the studied system neutron and proton evaporation are equally probable leads to the important conclusion that the secondary emission on the average does not affect the N/Z ratio attained by the primary products. Thus by inspection of the measured yield distribution one can directly obtain the mass and charge transfer taking place between the colliding nuclei.

The integral results related to mass, charge, and angular momentum transfer are displayed in Fig. 4. The upper panel shows the mass distribution, i.e., the projection of the individual yields in Fig. 2 on the mass axis. The regions where the different types of reactions are expected to occur are indicated. For target and projectile mass inelastic scattering cross sections are excluded. Due to the very strong Coulomb excitation these values are singularities and are marked in the figure by arrows, while the open points given below represent the cross section for the isobars only. The results of this figure were used to extract the integral cross section for the binary reactions compared above with the fusion-evaporation cross section. We obtain it as the cross-section sum of the heavy fragments from mass 79 upwards since here the experimental results are of better quality than for the light fragments.

The average N/Z shown below was calculated for each mass using the measured yields of all observed isobars, and as discussed above the results equally refer to the primary reaction products. As a function of mass the points give the most probable ratio of neutrons and protons in the binary reaction exit channel products, which contains essential information on the charge equilibration taking place during contact of the two colliding ions. All points lie within the limiting lines given by the N/Z ratios of the ^{106}Cd target and ^{54}Fe beam nuclei, which confirms that together with the direction of the mass flow from the heavy to the light collision partner one observes a tendency towards charge equilibration involving enhanced proton transfer in the opposite direction. However, it is evident that complete charge equilibration, i.e., the com-

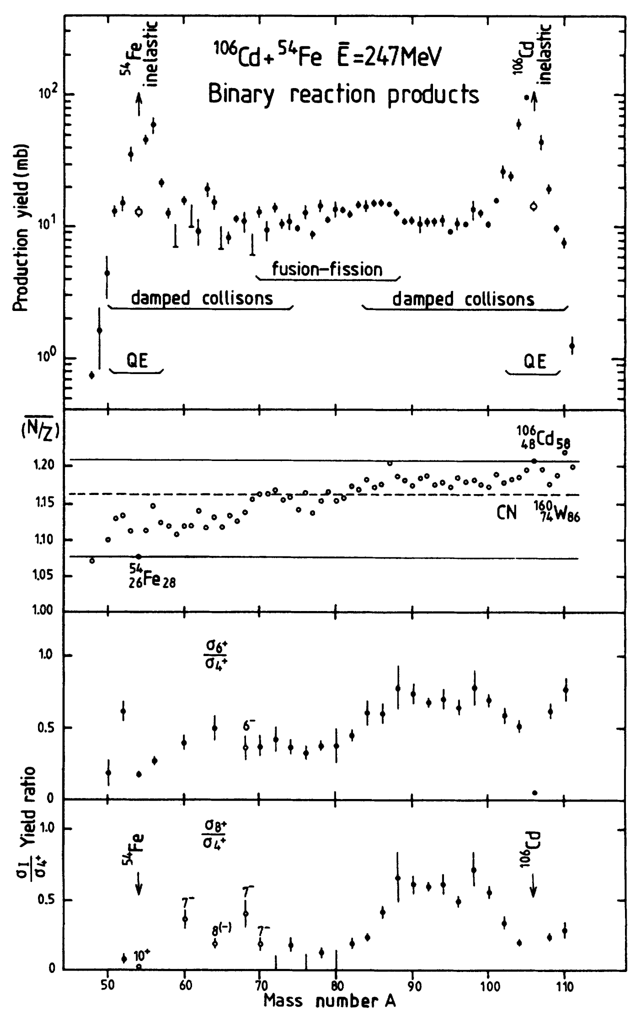

FIG. 4. Production yields, N/Z ratios, and population of 6^+ and 8^+ levels relative to 4^+ as a function of mass.

pound nucleus N/Z value, is obtained only in the region of symmetric parton, apparently corresponding to fission following compound nucleus formation. Outside this region the data seem to indicate that only partial, but a nearly constant, degree of charge equilibration was reached. One may argue that it is enough to transfer one proton from ^{54}Fe to get the observed N/Z change, but it should be kept in mind how the points were obtained. Each of them contains several processes, and on both the heavy and the light product side one observes in a broad mass range a similarly constant shift of the most probable N/Z, which corresponds roughly to half of the shift towards complete charge equilibration. This observation is surprising in view of earlier knowledge [9] and recent results [10], which suggest charge equilibration to be a continuous process strongly correlated with energy loss and thus also with mass transfer. However, in our experiment where both target and projectile were the most neutron-deficient isotopes the conditions to study this effect were not optimal. Much greater mismatch of beam and target N/Z should be chosen in a future study of charge equilibration.

The two lowest panels of Fig. 4 display results indicating general features of angular momentum transfer. Selecting the $2^+ \rightarrow 0^+$ ground state transition gates in even-even nuclei throughout the full mass spectrum, the population of 6^+ and 8^+ states relative to 4^+ population was determined. In a qualitative way these ratios reflect the amount of angular momentum transferred to the final product. These results clearly show that the highest spin population occurs for heavy fragments produced in damped collisions, while fusion-fission products as well as nuclei emerging from quasielastic processes are populated at much lower spin values. For selected nuclei much more detailed features of the population could be extracted from the data; such results will be discussed later [6].

In summary, we have investigated the ^{106}Cd + ^{54}Fe system at a collision energy 30 MeV above the Coulomb barrier by γ-spectroscopic techniques. A comprehensive analysis of in-beam $\gamma\gamma$-coincidence and radioactivity data provides the production cross sections for the individual fusion-evaporation and binary reaction products, the correlation of heavy and light fragments in binary reactions, and the main features of the angular momentum transfer to individual product nuclei. It is thus shown that such studies can provide unique, exclusive information concerning aspects of mass, energy, charge, and angular momentum transfer in heavy-ion collisions.

We are indebted to H. Folger for preparing excellent targets, and we acknowledge a productive discussion with H. Freiesleben.

[1] D. A. Bromley, *Treatise of Heavy Ion Science* (Plenum, New York, 1984).

[2] J. L. Durell, Acta Phys. Pol. B **24**, 105 (1993).

[3] R. Broda *et al.*, Phys. Rev. Lett. **68**, 1671 (1993).

[4] M. Schramm, H. Grawe, J. Heese, H. Kluge, K. H. Maier, R. Schubart, R. Broda, J. Grebosz, and W. Krolas, Z. Phys. A **344**, 121 (1992).

[5] R. Broda, M. A. Quader, P. J. Daly, R. V. F. Janssens, T. L. Khoo, and W. C. Ma, Phys. Lett. B **251**, 245 (1990).

[6] R. Broda, C. T. Zhang, P. Kleinheinz, R. Menegazzo, K.-H. Maier, H. Grawe, M. Schramm, and R. Schubart, unpublished.

[7] U. Reus and W. Westmeier, At. Data Nucl. Data Tables **29**, Nos. 1&2 (1983).

[8] S. Hofmann, W. Reisdorf, G. Münzenberg, F. P. Hessberger, J. R. H. Schneider, and P. Armbruster, Z. Phys. A **305**, 111 (1982); and unpublished.

[9] H. Freiesleben and J. V. Kratz, Phys. Rep. **106**, 1 (1984).

[10] R. Planeta *et al.*, Phys. Rev. C **38**, 195 (1988).