# Nuclear Disassembly of the Pb + Au System at $E_{lab} = 29$ MeV per Nucleon

E. Piasecki,[(1)] S. Bresson,[(2)] B. Lott,[(3)] R. Bougault,[(4)] J. Colin,[(4)] E. Crema,[(2),(5)] J. Galin,[(2)] B. Gatty,[(6)] A. Genoux-Lubain,[(4)] D. Guerreau,[(2)] D. Horn,[(4),(7)] D. Jacquet,[(6)] U. Jahnke,[(8)] J. Jastrzebski,[(9)] A. Kordyasz,[(1)] C. Le Brun,[(4)] J. F. Lecolley,[(4)] M. Louvel,[(4)] M. Morjean,[(2)] C. Paulot,[(2)] L. Pienkowski,[(9)] J. Pouthas,[(2)] B. Quednau,[(10)] W. U. Schröder,[(10)] E. Schwinn,[(8)] W. Skulski,[(9)] and J. Töke[(10)]

[(1)]*Institute of Experimental Physics, Warsaw University, Hoza 69, 00-681 Warszawa, Poland*
[(2)]*Grand Accélérateur National d'Ions Lourds (GANIL), BP 5027, 14021 Caen CEDEX, France*
[(3)]*Centre de Recherches Nucléaires Strasbourg, BP 20 CRO, 67037 Strasbourg CEDEX, France*
[(4)]*Laboratoire de Physique Corpusculaire Caen, Boulevard du Marechal Juin, 14032 Caen CEDEX, France*
[(5)]*Instituto de Fisica, Universidade de São Paulo, São Paulo, Brazil*
[(6)]*Institut de Physique Nucléaire, BP 1, 91406 Orsay CEDEX, France*
[(7)]*Chalk River Laboratories, Atomic Energy of Canada Limited, Chalk River, Ontario, Canada K0J 1J0*
[(8)]*Hahn Meitner Institut, D1000 Berlin 39, Germany*
[(9)]*Heavy Ion Laboratory, Warsaw University, ul. Banacha 4, 02-097 Warszawa, Poland*
[(10)]*University of Rochester, Rochester, New York 14627*
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Nuclei with $Z$ up to 82 emitted in the $^{208}$Pb + $^{197}$Au reaction at $E_{lab} = 29$ MeV per nucleon have been measured as a function of the associated neutron multiplicity. The data reveal the presence of strong correlations between character of a collision and neutron multiplicity. The trends suggest a disassembly of the nuclear system into a large number of nucleons and small fragments in the events with the highest neutron multiplicity. In such events, approximately one-third of the neutrons are released from the system and fragment yields decrease in an exponential fashion with increasing mass.

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Recent experiments[1] studying interactions of intermediate-energy Ar projectiles with massive targets (Au,Th) have shown that, above a bombarding energy of 30 MeV per nucleon, the measured most probable multiplicity of neutrons emitted from the reaction in dissipative collisions remains almost independent of the bombarding energy. Since for heavy systems the neutron multiplicity is a good measure of the total excitation energy introduced into the system, such a "saturation" effect could have represented a manifestation of limits to the temperature attainable by a heavy nucleus.[2] However, in subsequent experiments it has been observed[3] that a further increase in excitation energy per nucleon is possible when heavier projectiles such as Kr are used at similar velocities ($E_{lab} = 32$ MeV per nucleon). Such a dependence of the limiting temperature on the projectile-target combination suggests that the limits reached in the above experiments are not yet those characteristic of nuclear systems in general but, rather, are a reflection of the influence of the collision dynamics on the efficiency of heat-generation mechanisms.

The purpose of the present work is to extend the above systematics to very-heavy-projectile–target combinations and to search for evidence for changes in reaction mechanisms, at the higher temperatures that can presumably be generated in such heavier systems. Therefore, an experiment was carried out at GANIL, using the 29-MeV-per-nucleon beam of Pb, the heaviest projectile available, to bombard a Au target. Charged reaction products, ranging from protons to projectilelike fragments, were measured with an array of different types of detector telescopes, ensuring a wide dynamic range and a broad angular coverage. In the following, charged-fragment data are discussed as obtained with a forward telescope consisting of 200-$\mu$m ($\delta E$) and 500-$\mu$m ($E$) Si-strip detectors. The 24×24-mm$^2$ strip detectors (with six strips each) were aligned so as to ensure $X$-$Y$ position sensitivity of the telescope. The detector covered the angular range from 6.1° to 20°, including the grazing angle of 6.2°. The 200-$\mu$m detector imposed a detection threshold of 16–18 MeV per nucleon for fragments with atomic numbers from $Z = 30$ to 82.

The sensitive $4\pi$ neutron-multiplicity detector ORION was employed to provide a measure of the number of neutrons produced in a collision. A more detailed description of this detector can be found elsewhere.[4] As demonstrated in previous studies,[5,6] the multiplicity of neutrons emitted in a reaction provides a sensitive measure of the violence of the collision and, hence, of the associated impact parameter. This sensitivity is due to the fact that, for the heavy systems and bombarding energies of interest here, reaction products deexcite dominantly by evaporating neutrons and much fewer light charged particles. Furthermore, evaporated neutrons are relatively slow and can be counted efficiently with a large-volume detector such as ORION. For example, this detector, containing 3 m$^3$ of Gd-loaded liquid scintillator, has a detection efficiency of about 87% for 2-MeV

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neutrons, and even for high-energy 20-MeV neutrons the detection efficiency is over 70%. Monte Carlo simulations have been performed with an enhanced version of the computer code[7] DENIS in order to evaluate the actual ORION efficiency for different reaction scenarios. These calculations show that the average efficiency of ORION for all neutrons is fairly insensitive to the reaction scenario. For example, for peripheral collisions it was found that the high detection efficiency (81%) for low-energy neutrons from the targetlike nuclei is offset by a comparatively low efficiency (50%) for neutrons evaporated by the projectilelike fragments. Consequently, the average efficiency for all neutrons emitted in the most gentle peripheral collisions is very similar to that (64%) computed for neutrons from the most violent, central collisions.

A global information on energy dissipation from the $^{208}$Pb+ $^{197}$Au reaction at $E=29$ MeV per nucleon is provided in Fig. 1 by the inclusive neutron multiplicity ($M_n$) distribution. This distribution was obtained by initiating the neutron counting by the prompt response of ORION to reaction $\gamma$ rays and neutrons. The corresponding trigger signal required an energy release in the scintillator of only 2 MeV and, hence, imposed no significant bias on the data. Consequently, the distribution of Fig. 1 represents the full spectrum of processes in Pb+Au collisions. As will be shown in more detail below, neutron multiplicities are strongly correlated with the impact parameter such that low multiplicities are associated with peripheral, weakly damped collisions, whereas the highest multiplicities result from the most central, violent collisions. The neutron multiplicity distribution of Fig. 1 is similar in character to those measured earlier[1,3] for Ar+Au and Kr+Au with Ar and Kr beams at comparable velocity. The dominant features of these distributions are the presence of a narrow peak at zero multiplicity and a broad bump at a higher multiplicity. For the present Pb+Au system, this latter bump is centered at a significantly higher multiplicity of $M_n=50$, corresponding to approximately 78 neutrons when properly corrected for detection efficiency. Note that the 78 neutrons represent almost one-third of all neutrons of the system. This is a much larger fraction than observed earlier in the Ar+Au and Kr+Au experiments at similar beam velocity. This fact is illustrated in Fig. 2, where the fraction of the efficiency-corrected number of neutrons, as determined at the centroid of the high-multiplicity bump, versus total neutron number is plotted for the three systems. This can be used as an indication that higher temperatures are attained with increasingly symmetric beam-target combinations. Such a behavior is expected from the greater energy available per nucleon in the center of mass for more symmetric systems.

Exclusive charged-product yields are presented in Fig. 3 in an array of isometric $\delta E$-$E$ plots for six contiguous bins of the associated observed neutron multiplicity $M_n$. The sequence of product distributions given in this picture demonstrates a strong correlation between neutron multiplicity and impact parameter. For the lowest multiplicities ($M_n=0$–11), the picture is dominated by a spike of elastically scattered projectiles. This peak only shows up in the innermost strip.

The distribution in yields changes noticeably for $M_n=12$–23. The elastic peak is replaced by a hill of projectilelike fragments (PLF) which spreads in $Z$ and $E$, as expected after quasielastic or weakly damped reactions. Significant yields of these products are observed only close to the grazing angle. In addition to PLF, a double-humped component can be attributed to sequential fission of PLF. The double hump reflects the two kinematical solutions observed at small laboratory angles when the fissioning nucleus moves much faster than the forward- and backward-emitted fragments. Although the corresponding targetlike fragments, of similar mass-

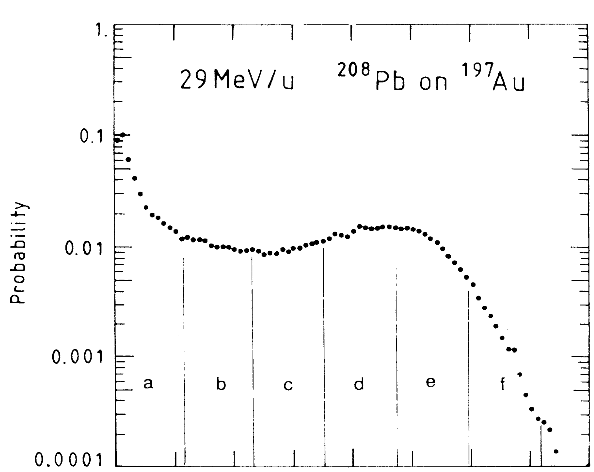


FIG. 1. Neutron multiplicity distribution, as measured (no efficiency correction). Bins labeled (a)–(f) refer to Fig. 3.

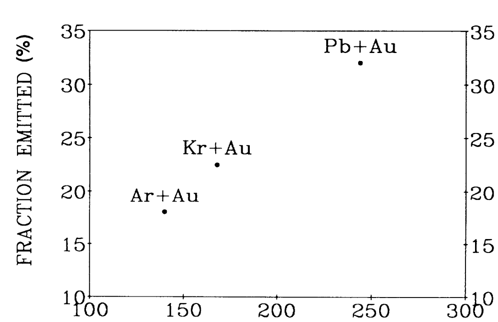


FIG. 2. Most probable fractional neutron multiplicities as a function of the total number of neutrons contained in the (Ar,Kr,Pb)+Au systems, studied at $E_{lab}$ close to 30 MeV per nucleon (Refs. 1 and 3).

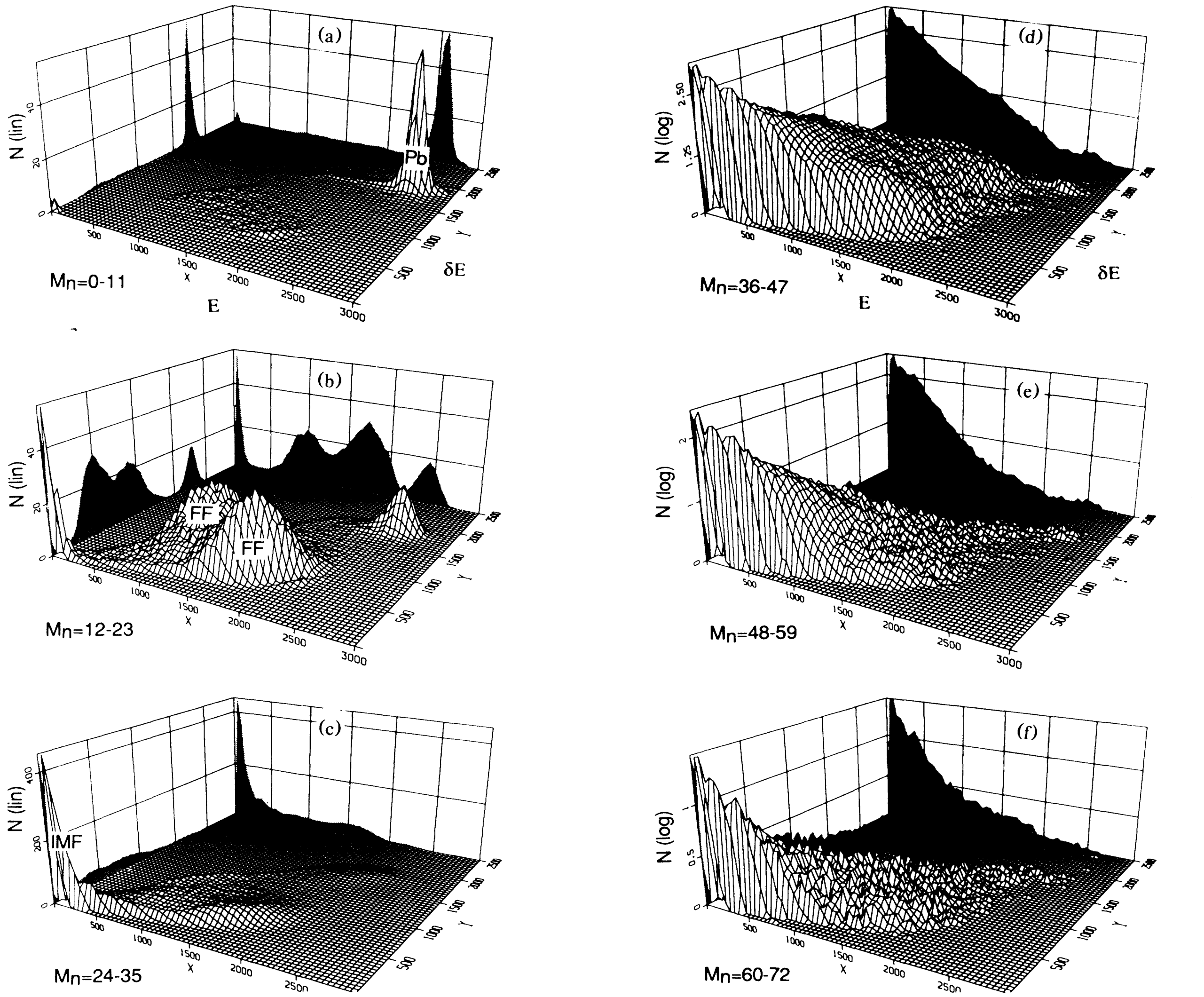


FIG. 3. Distribution of reaction products in the $E$ vs $\delta E$ plane (arbitrary $X$ and $Y$ units) as gated by contiguous neutron-multiplicity bins (see Fig. 1). For emphasizing the effects of interest, the $Z$ scale (number of events) has been chosen linear for gates (a)-(c) and logarithmic for gates (d)-(f).

es, are also expected to undergo sequential fission, their fission products have laboratory energies below the detection threshold. In addition to PLF and fission fragments, the distribution in Fig. 3(b) now features a distinct peak of lighter particles.

With increasing neutron multiplicity ($M_n = 24$-$35$), the charged-product distribution undergoes important changes. The three components described previously have become rather broad and merge with one another. In particular, the component of light charged particles has expanded in width, now covering the region of intermediate-mass fragments (IMF). For even higher neutron multiplicities [cf. Figs. 3(d), 3(e), and 3(f)], the IMF become progressively the dominant charged-product component at the expense of both PLF and fission fragments. The fact that these IMF are essentially observed in events triggered by high neutron multiplicities ascertains that such fragments are produced preferentially in more central collisions. As illustrated in Figs. 3(e) and 3(f), the charge distribution of these IMF exhibits an approximately exponential dependence with increasing atomic number. Such a trend agrees with that reported in other studies.

The difference of kinematical focusing between IMF and heavier products makes the former even more dominant than seen in Fig. 3. For high-neutron-multiplicity events, most of the massive reaction products (PLF and fission fragments) are expected to be strongly focused, because of their intrinsic low emission velocity, whereas IMF are emitted over a wider angular range. As a result of the finite acceptance of the telescope located at a forward angle, the detection of heavy products is favored when compared to the collection of IMF. Therefore, it is not possible to establish an absolute magnitude of the IMF multiplicity from the present data. However, the strong correlation between IMF and high neutron multiplicity and the low probability for heavier products suggest that, in central collisions, the Pb+Au system disintegrates preferentially into a large number of nucleons and small fragments.

In summary, strong correlations are observed between neutron multiplicity and impact parameters. Massive fragments are unlikely to survive the most dissipative, central collisions, selected by high-neutron-multiplicity gates. Instead, for these events, accounting for approximately one-fourth of the reaction cross section, the nuclear system is observed to disassemble. However, on the basis of the present experiment, it has not been possible to establish any time scale for the disassembly or to decide whether the process is sequential[8-10] or instantaneous.[11-15] It is nevertheless interesting to notice that disassembly occurs at low relative velocity in reactions for which compressional buildup is presumably not important.[16] The available energy of 7.2 MeV per nucleon of the system must be efficiently utilized to generate the heat thought to be mainly responsible for the observed nuclear disassembly.

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