Violence of Heavy-Ion Reactions from Neutron Multiplicity: (11 to 20)A-MeV ^{20}Ne+^{238}U

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The suitability of the neutron multiplicity as a gauge for the violence of medium-energy heavy-ion reactions is investigated for the first time. For this purpose the number of neutrons emitted from fission reactions induced by 220-, 290-, and 400-MeV ^{20}Ne on ^{238}U is registered event by event with a large 4π scintillator tank. It is shown that the neutron multiplicity is indeed closely related to the two quantities characterizing the violence: the induced total intrinsic excitation and the linear momentum transfer.

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Traditionally the violence of heavy-ion reactions for fissile systems is inferred from the observation of the laboratory folding angle between coincident fission fragments. This quantity measures to a good approximation the longitudinal recoil velocity of the targetlike nucleus undergoing fission and hence the linear momentum transferred to it from the projectile motion. Intrinsic excitations generated in the collision, however, can only be indirectly assessed from the folding angle, namely within the massive-transfer picture, which naively ties the transfer of linear motion and energy to the transfer of single beam-velocity nucleons from the projectile to the target nucleus.

The recent availability of medium-energy heavy-ion beams in the range of 20 to 50 MeV/nucleon, where the transition from mean-field to nucleon-nucleon dominated collisions is expected to occur, has promoted a veritable renaissance[1,2] of this 25-year-old folding-angle technique[3] and also considerable refinements: Energy and velocity of the fission fragments have been measured[4] and coincidence experiments have been performed on both fragments and outgoing projectile remainders.[5] Neither type of experiment, however, allows a complete reconstruction of the reaction kinematics and thus a reliable access to the excitation energies involved, either because of preceding light-particle evaporation or because of sequential breakup of the projectile residues, which is by no means negligible[6] even in the lower-energy domain.

At very high excitation energies of the order of 1 GeV the disintegration of the compound system into three or more heavy fragments becomes quite conceivable.[7] This process, as well as the Coulomb repulsion of heavy projectile remainders, would diminish the significance of the folding angle.

Given this situation, we have investigated another, yet-unexplored observable for the violence of a collision: the total number of neutrons evaporated in the course of each reaction. This neutron multiplicity is expected to measure the degree of inelasticity, that is, the total amount of energy dissipated from the relative motion into intrinsic excitation of the reactants. In order to establish this relation, we observe both quantities, momentum transfer and neutron number, in the present experiment, which has been performed with (11–20)A-MeV ^{20}Ne beams from the VICKSI accelerator on ^{238}U targets (metallic and UF$_4$). The momentum transfer is inferred from the fission kinematics and the number of simultaneously emitted neutrons is recorded in a 1-m-diam spherical scintillator tank surrounding the reaction zone.

The neutron scintillator tank, though successfully used for more than 30 years,[8] has only recently been introduced[6] in heavy-ion accelerator experiments. In it, the neutrons are moderated and stored for an average time of about 11 μs. Then they are individually counted (because they are dispersed in time) via the scintillation light induced by their capture into Gd nuclei. Natural Gd is added for this purpose to the liquid in doses of 0.5 wt.%. The efficiency of this 4π detector, checked with a ^{252}Cf source, is extremely high (82% for each neutron in the present setup) and allows one to count the neutrons from each reaction event to nearly their full extent.

The fission fragments are detected with conventional solid-state detectors and identified by their energy and time of flight. Because of the limited space within the neutron tank, where a 10-cm-diam central vacuum pipe is available for the passage of the beam and for a target wheel in the middle of the tank, we preferred a forward-backward geometry for the fission detectors instead of the left-right arrangement common to folding-angle experiments. This geometry selects the fission axes nearly collinear with the recoil direction of the capture nucleus such that its velocity has hardly any effect on the close-to-180° folding angle but does have a large effect on the fragment energies, and, more importantly, on their laboratory intensities.

The effect on the fission-fragment energies is demonstrated in Fig. 1 for 290-MeV incident energy. The bottom part exhibits the inclusive energy spectra recorded at 6° and 170°, respectively. Above, these

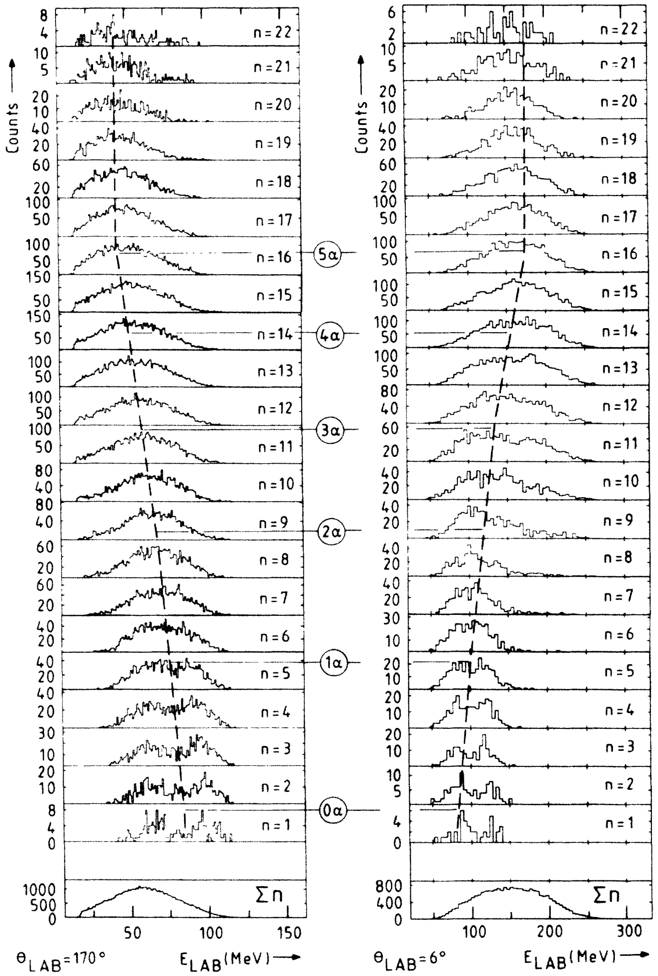

FIG. 1. Energy spectra of fission fragments from 290-MeV $^{20}Ne+^{238}U$, detected at 6° and 170°, respectively. The inclusive spectra at the bottom are decomposed above according to the number n of coincident neutrons (not corrected for the detector efficiency). Dashed lines show the anticipated shift of the centroids with increasing mass transfer (the transfer of 0 to 5 α particles is indicated for orientation).

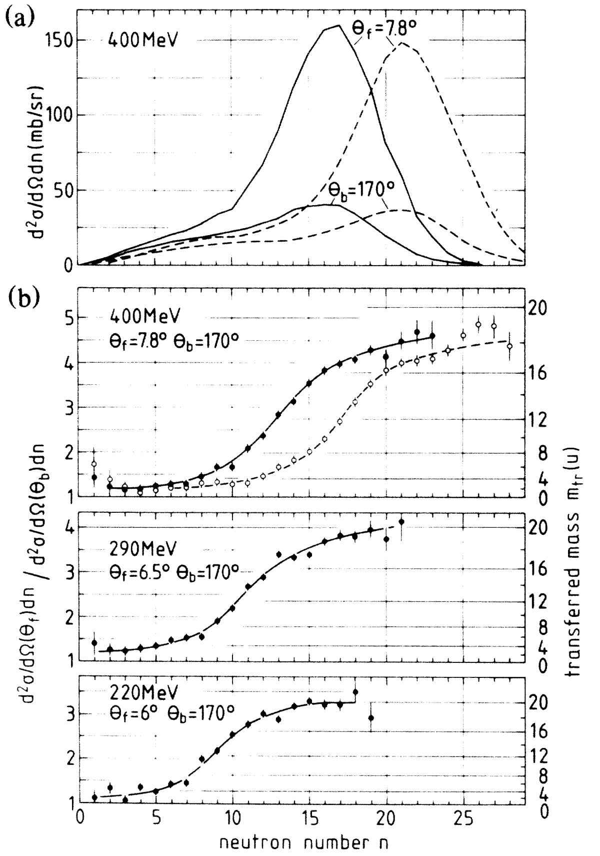

FIG. 2. (a) Neutron-number spectra in coincidence with fission fragments issued from 400-MeV $^{20}Ne+^{238}U$ and detected at $\theta_{lab}=7.8°$ and 170°. Dashed lines demonstrate the effect of the correction for detector efficiency (82%) and electronic dead time (70 ns) on the experimental distribution (full lines). (b) Ratio of forward- (θ_f) to backward- (θ_b) angle laboratory cross sections vs neutron number. Full lines link the black data points as a guide to the eye. For 400 MeV, as an example, the open symbols and the dashed line show the ratio after correction for efficiency. The right-hand scale interprets the ratio in terms of mass m_{tr} captured by the target nucleus. The error bars are purely statistical.

spectra are decomposed according to the number of simultaneously detected neutrons ranging from $n=1$ to 22. We see a dramatic shift of the centroids in opposite directions with growing neutron number, namely towards lower energies at 170° and towards higher energies at 6°—as expected for increasing recoil velocity. For a qualitative comparison, the dashed lines drawn through the spectra indicate the expected positions of the centroids for increasing amounts of linear momentum transfer. The lines start out at an energy close to 85 MeV at both angles for cold ^{238}U fission and end near 45 MeV at 170° and 175 MeV at 6°, as calculated for complete fusion prior to ^{258}No fission. The overall agreement with the data suggests that the neutron number is indeed strongly related to the momentum transfer.

Furthermore, it is satisfying to recognize in the double-humped structure at lower excitation or lower n the asymmetric mass split that is characteristic of fission of actinide nuclei, which gradually evolves into the symmetric-fission shape for higher excitation near $n=5$ or 6.

For a quantitative analysis, however, we would rather rely on the observed fragment intensities because they are less subject to experimental inconveniences such as energy loss in the target or pulse-height defect in the detectors, etc. These intensities as a function of associated neutron number n, i.e., the total counts in the energy spectra (Fig. 1), are displayed in Fig. 2(a) for 400-MeV ^{20}Ne and the two angles, 8° and 170°.

The neutron-multiplicity spectra immediately remind one of the familiar folding-angle distributions, with the high-n peak corresponding to high momentum transfer and the shoulder towards lower n originating from sequential fission following peripheral reactions with low momentum transfer. Both components become somewhat better resolved when the neutron-number spectra are corrected for detector efficiency as indicated by the dashed lines.

The ratio of the differential laboratory cross sections for angles symmetric[9] with respect to 90° in the center-of-mass system is inversely proportional to the proper Jacobians only, and, close to 0° and 180°, simplifies to

$$[d\sigma/d\Omega(0°)][d\sigma/d\Omega(180°)]^{-1} = (v_R + v_{\mathrm{ff}})^2(v_R - v_{\mathrm{ff}})^{-2},$$

where v_{ff} denotes the fission-fragment c.m. velocities, taken here from the systematics of Viola,[10] and v_R denotes the capture-nucleus recoil velocity, to be determined.

In Fig. 2(b) we compare the experimental ratios (left scale) of the differential cross sections versus neutron number to the expected ones (right scale), following the capture of increasingly more massive parts m_{tr} of the projectile, with their share of the incident energy, by the target nucleus. With this simplifying assumption (massive-transfer picture), the calculated ratio increases strongly with the amount of transferred mass m_{tr}, making the comparison with experiment much more sensitive in the vicinity of complete fusion than in the region of few-nucleon transfer.

The cross-section ratios, Fig. 2(b), observed for the three incident energies 220, 290, and 400 MeV, all start out close to 1 for sequential fission and low neutron numbers characteristic of cold U fission, and begin to rise near $n = 6$ to 8. From then on, the more massive the transfer is, the higher the neutron number is. The most probable neutron numbers for 220, 290, and 400 MeV [see Fig. 2(a)] are $n = 12.5$, 14.5, and 16.5 or $n_{\mathrm{corr}} = 15.9$, 18.5, and 21.0 (estimated uncertainty ±7%), when corrected for efficiency, respectively. Once these numbers are reached, the ratios tend to level off, the strongest cross sections dominating their further evolution by virtue of the intrinsic width of the neutron number in the statistical deexcitation cascade. Only for the two lower beam energies is full momentum transfer clearly attained in the high–neutron-number tails of the cross sections. At 400 MeV complete fusion probably is obscured by the much stronger cross sections for mass-16 or -18 capture. The situation here once more is very similar to the folding-angle experiment, where the neutron evaporation introduces a corresponding dispersion in the fragment correlation angle.

The essential feature of the present investigation is that the number of evaporated neutron scales with the recoil velocity of the fissioning nucleus or with the amount of linear momentum transfer. For the three incident energies, we deduce from the neutron-number versus momentum calibration in Fig. 2(b) the most probable mass transfers of 18.4, 17.7, and 16.3 u, or percentage linear momentum transfers of 0.92, 0.88, and 0.82 (±2% to 3%), in good agreement with the overall systematics.[2]

Finally, we would like to show that also the relation between intrinsic excitation, as deduced from the observed neutron numbers, and transferred momentum p_{tr} for the three bombarding energies E_{inc} is roughly accounted for by the crude massive-transfer model. For this purpose we calculate the excitation energy E^* associated with a mass transfer m_{tr} from the projectile with mass m_p to the target nucleus m_t from the simple kinematical relation

$$E^* = (p_{\mathrm{tr}}/2)(2E_{\mathrm{inc}}/m_p)^{1/2}[m_t/(m_t + m_{\mathrm{tr}})] + Q,$$

where Q denotes the respective Q value. From E^*, in turn, we estimate the number of evaporated neutrons with average kinetic energies $\langle E_{\mathrm{kin}}\rangle = 1.45T$, where the nuclear temperature is $T = [(E^* - E_{\mathrm{rot}})8/A]^{1/2}$ and the rotational energy, E_{rot}, which is not accessible to evaporation, is calculated for rigid bodies. With further account taken of the additional neutrons provided from cold fission of ^{238}U to ^{258}No ($\langle n\rangle = 2.2$ to 4.4) on the one hand, and the charged-particle contribution on the other, observed to be equivalent in energy reduction to at most 1 to 3 neutrons at the highest excitations, the solid lines in Fig. 3 indicate the number

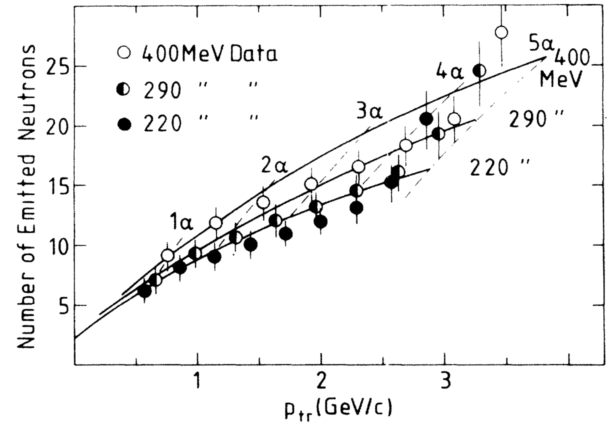

FIG. 3. Expected number of evaporated neutrons (solid lines) as compared to the observed multiplicity (circles; corrected for efficiency) vs linear momentum p_{tr} of the transferred projectile part (1 to 5 α particles as examples) for the 220-, 290-, and 400-MeV experiments. The error bars stand for the uncertainty in the extraction of the m_{tr} vs n values from Fig. 2(b) and for the error in the n efficiency.

of neutrons expected for increasingly heavier transfers.

The experiment (symbols) generally follows these lines: Increasing transfer enhances the neutron number in the anticipated way; the same transfer at higher kinetic energy also provides more neutrons.

The obvious systematic deviation of the data, i.e., the underrating at medium mass transfers as well as the overshooting for transfers beyond the most probable ones, once more originates mostly from the intrinsic dispersion in the number of evaporated neutrons wich allows the strong high-momentum cross sections to dominate over a broad range of neutron numbers. A smaller part of the discrepancies might also be due to the neglect of the dispersion of the fission fragments in mass and energy, as well as the defocusing effect of the light-particle evaporation. These effects could be incorporated in a kinematic reaction simulation similar to the one performed only recently by Duek *et al.*[4] and by La Rana *et al.*[2] for the folding-angle situation.

Furthermore, in these simulations the implicit assumption made above that the uncaptured projectile residues proceed undeflected and with the beam velocity could be relaxed in favor of the experimental observation of a rather broad distribution in energy and angle (see for instance Awes *et al.*[11] for the precompound charged-particle emission).

Finally we would like to add that the overall agreement with the extremely simple massive-transfer model does not strictly mean that the energy dissipation is mediated by a one-way nucleon transfer from the projectile to the target nucleus, but rather that for the reaction at hand the mutual nucleon exchange is dominated by a strong driving force, such that the nucleon drift by far overwhelms their exchange and diffusion.

In conclusion, we have investigated a new observable for the violence of a reaction, its neutron multiplicity, and shown that it is closely related to total energy dissipation and linear momentum transfer. The neutron multiplicity could thus supplement the folding-angle technique in many respects and furthermore provide a relatively easy tool for the event-by-event distinction between central and peripheral collisions. This new technique also should prove valuable for nonfission reactions.

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