REACTION FILTERS. CHARGED-PARTICLE MULTIPLICITY AND LINEAR MOMENTUM TRANSFER

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The relation between charged-particle multiplicity and linear momentum transfer to heavy reaction residues has been investigated with a 4π charged-particle detector for the reactions $^{36}Ar+^{238}U$ at $E/A=35$ MeV and $^{14}N+^{238}U$ at $E/A=50$ MeV. The multiplicity of charged particles at backward angles ($\theta>35°$) increases linearly with linear momentum transfer while the multiplicity of charged particles in the forward direction is almost independent of the linear momentum transfer.

For nucleus–nucleus collisions at intermediate energies, $E/A\approx 20$–200 MeV, particle emission from the early stages of the reaction can exhibit a complex interplay of dynamic and geometric effects [1,2]. Inclusive experiments determine only impact-parameter averaged quantities. The resulting loss of information can lead to ambiguous interpretations, which could be overcome by employing suitable reaction filters capable of selecting specific classes of collisions. Such filters are particularly useful if they can be used to select well defined narrow ranges of impact parameters.

A number of different techniques have been explored. The folding angle, $\theta_{\rm ff}$, between coincident fission fragments provides information about the linear momentum transfer to fissionable heavy reaction residues [3–10]. Folding angle measurements can discriminate between peripheral, quasi-elastic collisions and central, fusion-like reactions [4,5,9,10]. An alternative technique employs neutron multiplicity measurements [11,12]. For the $^{20}Ne+U$ reaction at $E/A=14.5$ MeV, the measured neutron multiplicity was found to exhibit a monotonic and nearly linear dependence on folding angle [11], indicating a close relation between these two kinds of reaction filters, at least at low incident energies.

Existing 4π neutron detectors are mostly sensitive to low-energy neutrons emitted in the statistical decay of fully equilibrated reaction products. Hence, the measured neutron multiplicity is closely related to the amount of energy deposited into equilibrated degrees of freedom. Since energies and angles of the emitted neutrons are not measured, other details of the reac-

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tion remain undetermined, e.g. the orientation of the reaction plane or the transverse momentum of the emitted particles [13]. Charged-particle detector arrays [14] can overcome such limitations and provide information about the multiplicities of energetic emissions for which 4π neutron detectors become inefficient. For low incident energies, the multiplicity of charged particles emitted statistically to backward angles will largely reflect the excitation energies of the nearly equilibrated reaction residues. The multiplicities of charged particles emitted to forward angles, on the other hand, are mainly dominated by nonequilibrium processes. With increasing energy, the multiplicities of these nonequilibrium emissions should reflect to an increasing degree the impact parameter dependent geometry or "participant volume" characteristic of the early stages of the collision [15]. At intermediate energies, both equilibrium and nonequilibrium emissions are present. The multiplicities arising from non-equilibrium emission are small [16], and the sensitivity of any charged particle array to either process may depend strongly upon the angular range subtended by the device. In this letter, we describe a cross calibration of charged particle multiplicity filters for intermediate energy collisions, through an experimental investigation of the relationship between charged-particle multiplicities and fission fragment folding angles for the reactions $^{36}Ar+^{238}U$ at $E/A=35$ MeV and $^{14}N+^{238}U$ at $E/A=50$ MeV.

The experiment was performed at the K500 cyclotron of the National Superconducting Cyclotron Laboratory of Michigan State University. A 3×6 mm^2 spot target of $^{238}UF_4$ (areal density ≈ 400 μg/cm^2), evaporated on a carbon foil (areal density ≈ 50 μg/cm^2), was irradiated by ^{36}Ar and ^{14}N ions of $E/A=35$ and 50 MeV, respectively. Charged particles, $Z=1$–8, were detected with the "Dwarf Ball-Wall" array developed at Washington University [17] [#1]. From the original array of 105 phoswich detectors, seven detectors were removed to provide openings for the target holding mechanism and for the passage of fission fragments; two additional detectors malfunctioned during the experiment. The remaining total of 96 functional phoswich detectors covered a solid angle corresponding to 85% of 4π. Each phoswich detector consisted of a thin fast plastic scintillator foil followed by a thick CsI(Tl) scintillator. The thicknesses of the scintillators varied with angle, 200 μm of plastic and 20 mm of CsI(Tl) at the forward angles, reducing to 40 μm of plastic and 4 mm of CsI(Tl) at the backward angles. To suppress secondary electrons and X-rays, detectors located at $\theta > 35°$ were covered by 5mg/cm^2 thick Au foils. Detectors at more forward angles were covered by 10mg/cm^2 thick Ta foils. Particle identification was achieved by integrating the photomultiplier anode current over three different time gates. A fast gate ($0\rightarrow50$ ns) was used to measure the light emitted by the plastic scintillator foils. The total charge in this gate was combined with the charge in a slow time gate ($50\rightarrow650$ ns) to obtain elemental identification up to about $Z\approx6$. The second time gate was also used to determine the energy of the detected particle and was combined with a third time gate ($1\rightarrow2$ μs) to obtain pulse shape discrimination for particles with $Z\leqslant2$. Light particles not stopped in the CsI scintillators could still be identified elementally. Fission fragments were detected with two X–Y-position sensitive parallel plate multiwire detectors with tapped delay-line readout [18]. Each detector had an active area of 35×18 cm^2. The fission detectors covered angular ranges of $\theta_1=36°$–$116°$, and $\theta_2=-(39°$–$89°)$ in the reaction plane. These angles were calibrated with masks placed in front of the fission detectors. Energy calibrations for the phoswich detectors were obtained from the elastic scattering of 20, 44, and 52 MeV α-particles from a uranium target and from the energies of light particles which punch through the scintillators. In the off-line analysis, energy thresholds of 12 and 18 MeV for hydrogen and helium nuclei, respectively, were used for detectors located at $\theta > 35°$. For $\theta < 35°$, the thresholds were 20 MeV for both hydrogen and helium. All heavier particles which passed through the absorber foils were analyzed; the resulting fragment energy thresholds were $E/A\approx6$–9 MeV and $E/A\approx2$–3 MeV for detectors located at $\theta<35°$ and $\theta>35°$, respectively.

Fig. 1 shows two-dimensional contour diagrams of folding angle, θ_{ff}, versus measured charged-particle multiplicities. (These raw multiplicities are not cor-

[#1] Ref. [17] details an early version of the device which used fast-slow plastic phoswich elements. The device was later modified by using plastic-CsI(Tl) phoswich elements. These modifications are the subject of a forthcoming publication.

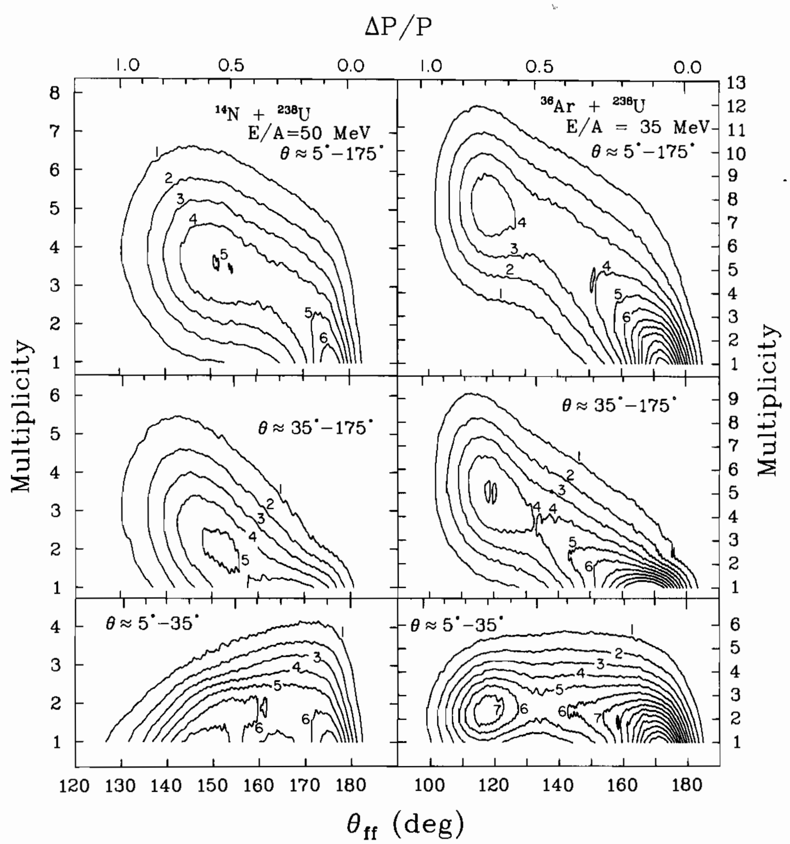

Fig. 1. Measured correlation between charged-particle multiplicity and folding angle for the $^{14}N+^{238}U$ reaction at $E/A=50$ MeV (left-hand side) and for the $^{36}Ar+^{238}U$ reaction at $E/A=35$ MeV (right-hand side). The angular range over which the charged particles are detected is indicated for each panel. The numbers of events (divided by a factor 1 000) for individual contours are given in the figure.

rected for efficiency losses due to detection threshold and imcomplete solid angle coverage; therefore, they are slightly smaller than the true charged-particle multiplicities.) The left- and right-hand panels show data for the $^{14}N+^{238}U$ and $^{36}Ar+^{238}U$ reactions, respectively. For orientation, the upper scales give the linear momentum transfer, $\Delta P/P$, to the heavy reaction residue in units of the projectile momentum, P, assuming symmetric fission of the compound nucleus. The upper panels show the total multiplicities, M, measured with the entire array (covering the angular range of $\theta\approx 5°-170°$). The center panels show the number of particles detected with the "Dwarf Ball" (covering the angular range of $\theta\approx 35°-170°$) and the lower panels show the number of particles detected with the "Dwarf Wall" (covering the angular range of $\theta\approx 5°-35°$).

For both reactions, the average multiplicity of charged particles emitted over the entire angular range ($\theta\approx 5°-170°$) increases monotonically with increasing linear momentum transfer to the heavy reaction residue. This dependence is qualitatively similar to the monotonic relation between neutron multiplicity and folding angle which has been established for reactions at lower incident energies [11,12]. For the $^{36}Ar+^{238}U$ reaction, the dependence of the average multiplicity on folding angle is similar to the results obtained for a similar reaction at a slightly lower energy [6]. A nearly linear correlation between multiplicity and linear momentum transfer is observed for charged particles emitted at intermediate and large angles ($\theta\approx 35°-170°$). In contrast, the multiplicity of charged particles emitted at forward angles ($\theta\approx 5°-35°$) is nearly independent of the linear momentum transfer to the heavy reaction residue [6]. At least for the present reactions, the multiplicities detected in forward arrays [19] cannot be used to select violent projectile–target interactions in which large amounts of energy and/or momentum are dissipated.

Charged-particle multiplicity as well as folding angle measurements represent reaction filters of finite resolution. Even for the ideal case of formation and decay of a composite nuclear system with unique spin, excitation energy, and recoil momentum, multiplicity and folding angle distributions have finite widths. The widths of folding angle distributions reflect the finite widths of the mass and kinetic energy distributions of the fission fragments as well as smearing from light-particle evaporation. For more energetic collisions, additional broadening can be caused by the emission of intermediate-mass fragments [9]. The widths of charged-particle multiplicity distributions reflect the stochastic nature of neutron and charged-particle emission mechanisms. Particularly at lower energies, where the charged-particle multiplicities are small, statistical fluctuations in the multiplicities can be comparable to the mean values and the selectivity of charged-particle multiplicities as reaction filters can be reduced.

The widths of various gated distributions are shown in fig. 2. The upper and lower sections show data for the $^{14}N+^{238}U$ and the $^{36}Ar+^{238}U$ reactions, respectively. The left-hand panels show distributions for total charged-particle multiplicity gated by folding angle intervals, 1° wide and centered at the indicated angles. The right-hand panels show folding angle distributions measured for different total charged-particle multiplicities, $M=1$, 3, 6 for the $^{14}N+^{238}U$ reaction and $M=1$, 6, 12 for the $^{36}Ar+^{238}U$ reaction. The high-multiplicity gates ($M=6$ for $^{14}N+^{238}U$ and $M=12$ for $^{36}Ar+^{238}U$) represent cuts in the tails of the charged-particle multiplicity distributions, at values approximately 50% larger than the most probable multiplicity observed for fusion-like collisions (see left-hand panels, or fig. 1).

Charged-particle multiplicity distributions gated by large folding angles, $\theta_{ff}\approx 175°$, are clearly peaked at $M\leqslant 1$. However, they exhibit remarkably long tails extending to high multiplicities. Multiplicity distributions gated by small folding angles (or fusion-like collisions) are peaked at $M\approx 4$ and 8 for the $^{14}N+^{238}U$ and $^{36}Ar+^{238}U$ reactions, respectively.

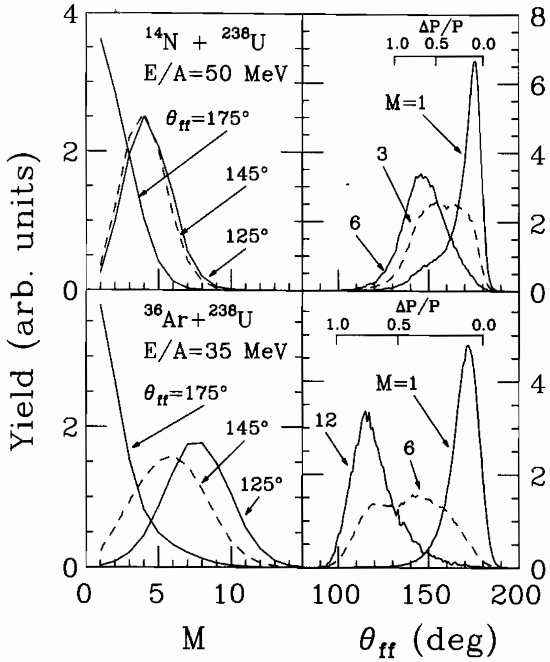

Fig. 2. Gated multiplicity (left-hand panels) and folding angle (right-hand panels) distributions measured for the reactions $^{14}N+^{238}U$ at $E/A=50$ MeV (upper part) and $^{36}Ar+^{238}U$ at $E/A=35$ MeV (lower part). The distributions for each panel are normalized to the same integrated yield. The gates on folding angle, θ_{ff}, are 1° wide; their centers are indicated in the left-hand panels. The gates on multiplicity, M, are indicated in the right-hand panels.

They are rather broad indicating significant fluctuations of the number of emitted charged particles. There is considerable overlap between the multiplicity distributions gated by very different folding angles.

Folding angle distributions gated by low (high) charged-particle multiplicities are peaked at large (small) folding angles, respectively. The widths of these distributions are very similar to the widths measured for the out-of-plane distributions of fission fragments selected by the same multiplicity gates, indicating that these gates do not introduce significant broadening beyond the intrinsic resolution of the folding angle technique. In contrast, folding angle distributions gated by intermediate charged-particle multiplicities ($M=3$ for $^{14}N+^{238}U$ and $M=6$ for $^{36}Ar+^{238}U$) are significantly broader indicating that such multiplicity gates are less selective.

In summary, we have measured the relation between fission fragment folding angles and total charged-particle multiplicities for the reactions $^{14}N+^{238}U$ at $E/A=50$ MeV and $^{36}Ar+^{238}U$ at $E/A=35$ MeV. The mean values of these two quantities exhibit a monotonic relation. Both reaction filters have finite resolution due to the statistical nature of the decay processes, yet the widths of the *total* multiplicity distributions for $^{36}Ar+^{238}U$ collisions are sufficiently narrow to cleanly separate central, large-momentum-transfer collisions from peripheral, small-momentum-transfer collisions by gates on very high ($M \geqslant 12$) or very low ($M=1$) multiplicity, respectively. Less extreme multiplicity gates, however, are less selective and do not result in cleanly separated momentum-transfer distributions. Rather broad momentum-transfer distributions are observed, for example, at intermediate multiplicities. In contract to the total multiplicity or the multiplicity of charged particles emitted to backward angles, practically no selectivity was observed for a reaction filter utilizing the number of charged particles emitted to forward angles, $\theta < 35°$. At least for the present reactions, the multiplicities in such forward arrays cannot be used to select violent projectile–target interactions in which large amounts of energy and/or momentum are dissipated.

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