Angular Distributions and Mechanisms of Fragmentation by Relativistic Heavy Ions

R. W. Stoenner, P. E. Haustein, and J. B. Cumming
Chemistry Department, Brookhaven National Laboratory, Upton, New York 11973
(Received 9 March 1984)

Angular distributions of massive fragments from relativistic heavy-ion interactions are reported. Sideward peaking is observed for the light fragment ^{37}Ar, from 25-GeV ^{12}C + Au, while the distribution for ^{127}Xe is strongly forward peaked. Conflicts of these observations and other existing data with predictions of models for the fragmentation process are discussed.

PACS numbers: 25.70.Np, 25.40.Sc

Although it has long been known that light fragments ($A_f \lesssim 50$) are produced copiously in high-energy hadron interactions with heavy nuclei, the underlying mechanism or mechanisms remain poorly understood. Multiplicity data[1] show that these fragments are produced in very violent events. Models for the process range from a hot nuclear fireball[2] to a cold "cleavage" mechanism.[3] Hydrodynamical calculations[4] indicate different origins for the very light products (^{1}H, . . . , ^{4}He) and the heavier fragments. The latter are identified as residues of relatively undisturbed, spectator parts of the target.

Increased interest in fragment production has been stimulated by the observation of Hirsch *et al.*[5] that fragment yields from 80–350-GeV ^{1}H interactions with Kr and Xe follow a power-law dependence on fragment mass. This was interpreted as the characteristic signature of a mechanism involving a liquid-gas phase transition near a critical point in nuclear matter. Although differing in details, similar models[6,7] retain the idea of a phase transition under conditions of thermal and chemical equilibrium. An identical power-law dependence has been reported for fragment production by relativistic heavy ions (RHI).[8]

Proponents of phase transitions have focused on yields and energy spectra, largely ignoring angular distributions which provide important clues to reaction mechanisms. An interesting feature of the data for incident ^{1}H is the transition from forward to sideward peaking at energies $\gtrsim 10$ GeV.[9–11] For some products, intensities at $\sim 0°$ become lower than those at $\sim 180°$.[12,13] Analyses of double-differential cross sections indicate that there is no clean temporal separation of the fragment-formation process from the initial excitation step.[9,14–16]

Angular-distribution data for RHI projectiles are very limited, particularly for heavier fragments. The counter study of Warwick *et al.*[1] included angular distributions for $Z = 8$ fragments for ^{1}H, ^{4}He, ^{20}Ne incident on Au. Morita *et al.*[17] reported angular distributions for some heavier products from the interaction of ^{12}C with Au and U; however, there were experimental problems due to low beam intensities. This Letter reports the first definitive angular distributions for heavy fragments from RHI interactions. The new measurements employed techniques developed for the assay of low levels of radioactivity in lunar samples.[18] Amenable species are ^{37}Ar, a typical light fragment, and ^{127}Xe, a deep spallation product. The experiment utilized an evacuated cylindrical scattering chamber (38.6 cm long, 19.7 cm diam) at the Lawrence Berkeley Laboratory Bevalac. The 25-GeV ^{12}C beam passed along the axis of the cylinder, entering and exiting through 6.1-cm-diam Mylar windows. A 200-μg/cm^2 Au target inclined at 45° to the beam was supported at the center of the chamber which was lined with two layers of 21 mg/cm^2 Al foil. The primary catcher was sufficiently thick to stop recoils $\leqslant 7$ MeV/u. The second was used to evaluate blanks. Au, vacuum deposited on Al foils downstream from the exit window, served as a beam monitor. Relative to the (17.1 ± 2.7) mb cross section[19] for ^{127}Xe, the cross section for ^{37}Ar is (6.6 ± 1.0) mb and we infer that $(4.4 \pm 0.7) \times 10^{13}$ ^{12}C ions passed through the chamber during the ~ 30 h irradiation. The ^{37}Ar-to-^{127}Xe cross-section ratio is twice as large as that reported[20] for 28-GeV ^{1}H confirming that ^{12}C is relatively more effective in producing lighter fragments.[19,21]

After irradiation, the catchers were cut to sample the angular distribution at nine angles from 18° to 162° with $\pm 9°$ resolution. Azimuthal angles were limited such that mean recoil paths in the target were $\leqslant 150$ μg/cm^2. Two samples were obtained at 90°, one from the backward catchers, the other from the forward ones. Assay methods for ^{37}Ar and ^{127}Xe have been described.[18] Each foil was vacuum melted in the presence of Ar, Kr, and Xe carriers, and the noble gases were separated chromatographically on charcoal columns using He as a carrier. After cleanup over hot V, the Ar and Xe fractions were transformed with added P-10 into small proportional counters. Earliest assays started ~ 5 d after the end of irradiation and continued for about four months. While not all samples could be counted for this full period, sufficient data were acquired to examine decay and background effects in detail. Rates varied from a low of 38 counts/d for the 18° ^{37}Ar sample to a high of 309 counts/d for ^{127}Xe at 72°. ^{127}Xe was assayed with an energy window encompassing the K and L Auger and conversion-electron peaks giving $\sim 70\%$ efficiency and backgrounds of ~ 2–3 counts/d. ^{37}Ar was assayed with $\sim 54\%$ efficiency and ~ 1 count/d background with a window on its K Auger peak. Data were analyzed to give end-of-irradiation activities which were corrected for chemical yields, counting efficiencies, and solid angles determined from catcher areas and chamber geometry. Single-differential cross sections are shown as filled points in Fig. 1. The relatively larger errors for ^{37}Ar reflect the lower cross section and counting efficiency as well as corrections for activation of impurities in the catchers. Blanks were 12% and 7%, respectively, for 18° and 162° catchers which were closest to the beam. Uncertainties equal to 50% of the blank corrections are included in the error bars. No significant blanks were observed for ^{127}Xe. The open points for each nuclide at 54° are for a part of the catcher which sampled long recoil paths in the target (a mean of 294 μg/cm^2 compared to 125 μg/cm^2 in the normal sample). Agreement between open and filled points and the agreement at 90° indicate no major distortion due to scattering or absorption. Improper evaluation of such effects may be one source of serious errors in the results of Morita *et al.*[17] We see no evidence for the more than a factor of two rise in $d\sigma/d\Omega$ between 72 and 23° which they reported for products comparable to ^{37}Ar and ^{127}Xe.

Figure 1 gives the first clear evidence for the occurrence of sideward peaking in RHI-induced fragmentation. The data for ^{37}Ar also suggest a slight preference for backward emission. At 18°, $d\sigma/d\Omega$ is 0.88 ± 0.09 of that at 162° and the integrated forward-to-backward ratio is $F/B = 0.98 \pm 0.02$. Sideward peaking is not apparent for lower-mass ($Z = 8$) fragments from ^{20}Ne + Au at 42 GeV.[1] However, an onset or enhancement of sideward peaking between $Z = 8$ and 18 is consistent with the trend observed for 28-GeV ^{1}H.[9] Such parallelisms between ^{1}H and RHI-induced fragmentation suggest that the mechanism is not sensitive to projectile size.

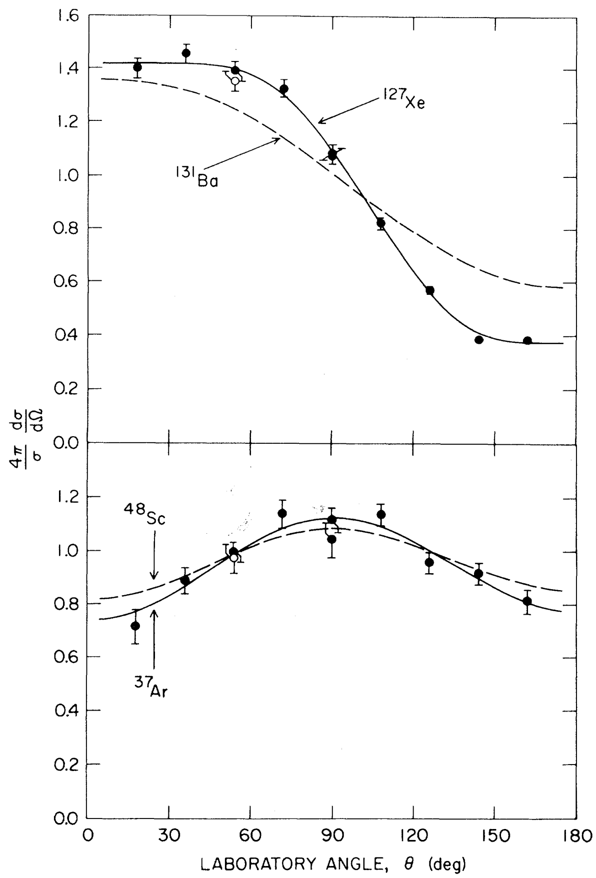

FIG. 1. Angular distributions of fragments from the interaction of energetic projectiles with Au. Points for ^{37}Ar and ^{127}Xe are from the present study with 25-GeV ^{12}C ions. The solid curves show general trends. For comparison, results from Ref. 13 for incident 28-GeV ^{1}H are shown as dashed curves.

The angular distribution of the deep-spallation product ^{127}Xe is strongly forward peaked. Its F/B ratio, 2.02 ± 0.04, is greater than the 1.53 ± 0.02 of the comparison product ^{131}Ba, suggesting a larger momentum transfer from ^{12}C. The very different angular distributions of ^{37}Ar and ^{127}Xe confirm the conclusion of Warwick *et al.*[1] that light fragments and deep-spallation products are not complementary; the light fragments are formed in the most violent events (as measured by associated charged-particle multiplicities) while the deep-spallation products are formed in less violent processes with about one-half the associated multiplicity. The seeming paradox that the higher-multiplicity product, ^{37}Ar, appears to arise from a nearly stationary source is discussed below.

The present results and related data serve to constrain various models of fragmentation. In hydrodynamic models, "bounce off" of projectile remnants and collective flow of the participating nucleons to one side for nonzero impact parameters cause the relatively undisturbed parts of the target to move in the opposite direction at angles slightly forward of, or near, 90°. One-fluid calculations[4] for ^{20}Ne + U at 400 MeV/u indicate sideward peaking for a wide range of residue masses. The present results for ^{37}Ar are consistent with such predictions; those for ^{127}Xe are definitely not, suggesting a failure of the hydrodynamic assumptions for large impact parameters. Another problem for hydrodynamics is the strong similarity of results for ^{1}H and ^{12}C ions. It seems unlikely that a projectile as small as a ^{1}H will initiate the same sort of collective flow as a ^{12}C or ^{20}Ne ion.

In the cold "cleavage" model,[3] impact parameter, size, and opening angle of the hole bored through a heavy nucleus by a projectile determine the course of the fragmentation process. Sideward peaking is the result of the dominance of Coulomb repulsion between a light fragment and a heavy residue over forward-momentum transfer and an isotropic component due to Fermi motion. The lack of complementarity between light and heavy fragments observed in the present work and in counter experiments[1] conflicts with the implicit binary nature of cleavage. Furthermore, one might expect the opening angle of the hole to increase with decreasing energy, moving fragments to angles further behind 90°, but this is the reverse of the observed trend.[10]

Production of an extended region of hot nuclear matter in thermal and chemical equilibrium is a requisite of phase-transition pictures of fragment formation.[5-7] Our angular distribution for ^{37}Ar gives no evidence for the forward-momentum transfer expected in the excitation step of such a process. However, forward-momentum transfer is inferred from counter[1] and thick-target thick-catcher experiments.[19] This conflict between angular distributions and velocity or multiplicity measurements is indicative of a fast-reaction mechanism as has been discussed for incident ^{1}H.[9, 14-16] It casts doubts on whether sufficient time is available to achieve equilibrium conditions prior to a phase transition. Boal[22] has questioned the uniqueness of the power-law signature and has shown that this mass dependence of yields can be reproduced by a fast-coalescence mechanism on a time scale of $\sim 4\times10^{-23}$ sec. He concluded that the nuclear-interaction region involved in intermediate-mass fragment emission is too small and too short lived to support a sharp phase transiton.

In conclusion, this paper has reported the first definitive angular distributions of massive fragments formed in RHI interactions. The sideward peaking observed for ^{37}Ar supports the idea that fragmentation is a global process not strongly dependent on projectile mass. Theories which focus on one type of projectile or a single aspect of the process often fail to reproduce others. A more comprehensive approach is needed.

We acknowledge with thanks the assistance of F. Lothrop and the Bevalac staff during the irradiation. This research was performed at Brookhaven National Laboratory under contract DE-AC02-76CH00016 with the U. S. Department of Energy.

[1] A. I. Warwick *et al.*, Phys. Rev. C **27** 1083 (1983).
[2] G. D. Westfall *et al.*, Phys. Rev. Lett. **37**, 1202 (1976); J. Gosset *et al.*, Phys. Rev. C **16**, 629 (1977).
[3] S. Bohrmann, J. Hüfner, and M. C. Nemes, Phys. Lett. **120B**, 59 (1983); J. Hüfner and H. M. Sommermann, Phys. Rev. C **27**, 2090 (1983).
[4] L. P. Csernai *et al.*, Phys. Rev. C **28**, 2001 (1983).
[5] A. S. Hirsch *et al.*, Phys. Rev. C **29**, 508 (1984).
[6] P. J. Siemens, Nature **305**, 410 (1983).
[7] A. D. Panagiotou *et al.*, Phys. Rev. Lett. **52**, 496 (1984).
[8] H. H. Gutbrod, A. I. Warwick, and H. Wieman, Nucl. Phys. **A387**, 177C (1982).
[9] L. P. Remsberg and D. G. Perry, Phys. Rev. Lett. **35**, 361 (1975), and unpublished.
[10] D. R. Fortney and N. T. Porile, Phys. Lett. **76B**, 553 (1978).
[11] J. A. Urbon *et al.*, Phys. Rev. C **21**, 1048 (1980).
[12] N. T. Porile *et al.*, Phys. Rev. Lett. **43**, 918 (1979).
[13] R. L. Klobuchar, G. J. Virtes, and J. B. Cumming, unpublished.
[14] J. B. Cumming *et al.*, Phys. Rev. B **167**, 134 (1964).
[15] A. M. Poskanzer, G. W. Butler, and E. K. Hyde, Phys. Rev. C **3**, 882 (1971); G. D. Westfall *et al.*, Phys. Rev. C **17**, 1368 (1978).
[16] D. R. Fortney and N. T. Porile, Phys. Rev. C **22**, 670 (1980).
[17] Y. Morita *et al.*, Phys. Rev. C **26**, 511 (1982); Y. Morita, W. Loveland, and G. T. Seaborg, Phys. Rev. C **28**, 2519 (1983).
[18] R. W. Stoenner, W. J. Lyman, and R. Davis, Jr., Geochim. Cosmochim. Acta., Suppl. 1, **2**, 1583 (1970).
[19] S. B. Kaufman *et al.*, Phys. Rev. C **22**, 1897 (1980).
[20] J. Hudis *et al.*, Phys. Rev. C **1**, 2019 (1970).
[21] G. D. Cole and N. T. Porile, Phys. Rev. C **24**, 2038 (1981).
[22] D. Boal, Phys. Rev. C **28**, 2568 (1983).