BRIEF REPORTS

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Interactions of 13.6-GeV/nucleon ^{16}O and ^{28}Si with carbon, aluminum, and copper

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(Received 25 May 1993)

Cross sections for forming ^{24}Na and ^{18}F by the interactions of 13.6-GeV/nucleon ^{16}O and ^{28}Si ions with Al and for forming ^{24}Na in ^{16}O interactions with Cu have been measured relative to the cross section for forming ^{11}C from carbon. The results are generally consistent with energy-independent inclusive cross sections (limiting fragmentation) for heavy ions between $\sim$ 2 and 13.6 GeV/nucleon. However, comparison of the heavy-ion data with those for high-energy protons indicates a significantly weaker dependence on projectile size than that predicted by the factorization hypothesis for $\sigma_{\rm C}(^{11}{\rm C})$, $\sigma_{\rm Al}(^{18}{\rm F})$, and $\sigma_{\rm Al}(^{24}{\rm Na})$. The dependence is slightly stronger in the case of $\sigma_{\rm Cu}(^{24}{\rm Na})$.

PACS number(s): 25.75.+r, 25.70.Mn

Experiment-825 at the Brookhaven AGS was intended to survey target fragmentation reactions induced by the 13.6-GeV kinetic energy per nucleon ^{16}O and ^{28}Si ions which are available at that facility. Fragment cross sections [1, 2] and kinetic properties [3–5] have been reported for Cu, Ag, and Au targets. Two hypotheses, *limiting fragmentation* and *factorization*, provide a convenient framework for comparisons between these results and similar data for heavy ions at lower energies per nucleon and for high-energy protons. Limiting fragmentation asserts that cross sections and recoil properties of target fragmentation reactions will become independent of bombarding energy at a sufficiently high energy. Factorization, as commonly applied, states that the cross section for forming an individual fragment [6] will be proportional to the inelastic cross section σ_R for the particular projectile-target pair. It follows that the shape of the mass-yield distribution should be independent of the projectile except for this scaling factor. These hypotheses have been tested by comparing cross sections and kinetic properties of products of fragmentation by heavy ions at Bevalac energies ($\sim$ 2 GeV/nucleon) with similar data for high-energy protons [7–11]. Both appear to be approximately valid for a variety of reactions. A notable exception is that light fragment production from medium- to heavy-mass targets by heavy projectiles is significantly higher than expected from σ_R. Shapes of the mass-yield curves from interactions of 13.6-GeV/nucleon projectiles with Ag [1] and with Au [2] are generally similar to those reported at Bevalac energies. There is no further enhancement of light fragment production as energies increase from $\sim$ 2 to 13.6 GeV/nucleon. There is, however, a significant change in kinetic properties of these fragments over that range. Light fragments from ^{28}Si + Au interactions at 13.6 GeV/nucleon are emitted preferentially into the backward hemisphere [5] with a forward to backward ratio, $F/B = 0.81 \pm 0.05$, significantly below those reported for heavy ions at lower energies per nucleon or for high-energy protons. Some reductions of mean longitudinal momenta of fragments are also noted in the interactions of 13.6-GeV/nucleon ^{16}O ions with Cu [3] and with Ag [4].

During a number of the E-825 irradiations, stacks containing aluminum and polyethylene (PE) were irradiated with 13.6-GeV/nucleon ^{16}O or ^{28}Si ions, or with 28-GeV protons. This Brief Report presents cross section ratios obtained from these exposures and discusses the derived cross sections in the context of factorization and limiting fragmentation. Experimental techniques were the same as those used to measure cross section ratios for incident protons [12]. Aluminum and PE foil stacks consisting of (in the order traversed by the beam) a 7-mg/cm^2 Al guard foil, one or more 21-mg/cm^2 Al foils, another Al guard, then a 5-mg/cm^2 PE guard foil, one or more 10-mg/cm^2 PE foils, and a final PE guard foil were irradiated in air in external beam lines at the AGS for periods up to 20 min. They were positioned 50 cm downstream of beam exit windows and > 30 cm upstream of other targets to minimize the influence of secondary particles. After each irradiation, the ^{18}F and ^{24}Na in the Al and ^{11}C in the PE were assayed using the same well-type NaI(Tl) scintillation detectors which had been calibrated for the previous measurements [12]. The standard 54-mg/cm^2 Al-PE stacks for ^{16}O exposures contained only single central Al and PE foils. However, the influence of secondary particles was examined in one irradiation of a thick stack containing five each central Al and PE foils (total thickness 174 mg/cm^2). Single irradiations of stacks containing two central Al and PE foils (total thickness 82 mg/cm^2) were performed with 13.6-GeV/nucleon

^{28}Si ions and with 28-GeV protons.

Results from the present measurements are presented in the form of three cross section ratios in Table I. These were selected from the various possible combinations of cross sections to illustrate specific points. Tabulated ratios include, where needed, corrections for the $(12 \pm 2)\%$ loss of ^{11}C in the form of gaseous compounds from PE, for the 3% electron capture branch of ^{18}F, and for beam intensity fluctuations on the basis of periodic readings of an ion chamber. No correction was made for the 1.1% natural abundance ^{13}C in the PE.

The $\sigma_{Al}(^{18}F)/\sigma_C(^{11}C)$ ratio is expected to be independent of target thickness as the individual cross sections are insensitive to secondary particles. This is confirmed by measured ratios of 0.221 ± 0.003 and 0.218 ± 0.003 for the thin- and thick-target irradiations with 13.6-GeV/nucleon ^{16}O ions, respectively. The mean value is shown for 218-GeV ^{16}O ions in Table I. This ratio is also independent of counting efficiencies and their errors as the ^{18}F and the ^{11}C are assayed via the same radiation, 511-keV photons from β^+ annihilation.

The ratio $\sigma_{Al}(^{24}Na)/\sigma_{Al}(^{18}F)$ compares different products from the same target. Any projectile dependence will reflect changes in the shape of the fragmentation mass-yield distribution from Al, independent of the absolute cross section scale. This ratio is sensitive to secondary reactions because ^{24}Na can be produced readily from Al by low-energy particles. It was observed to increase from 1.197 ± 0.019 to 1.347 ± 0.010 in going from the 54- to the 174-mg/cm^2 target, corresponding to a rise of $(11.0 \pm 2.0)\%$ per 100 mg/cm^2. The value of $\sigma_{Al}(^{24}Na)/\sigma_{Al}(^{18}F)$ for ^{16}O in Table I is a linear extrapolation to zero thickness. Its error includes $\pm 50\%$ of the correction from the value for the 54-mg/cm^2 targets as well as systematic uncertainties of $\pm 1.5\%$ on each of the counting efficiencies. A comparable secondary effect, $(9.7 \pm 2.0)\%$ per 100 mg/cm^2, was observed for the $\sigma_{Al}(^{24}Na)/\sigma_C(^{11}C)$ ratio. The contribution of secondaries to ^{24}Na production from Al by 13.6-GeV/nucleon ^{16}O ions is larger than the 3.6% per 100 mg/cm^2 for ^{40}Ar on Al-Cu targets [7] or the 4% for ^{12}C on Al-Cu stacks [9] reported at Bevalac energies. It is much larger than the 1.5% per 100 mg/cm^2 of target thickness observed for 300-GeV protons incident on similar Al-PE stacks [13]. The secondary correction to $\sigma_{Al}(^{24}Na)/\sigma_{Al}(^{18}F)$ was not measured for incident ^{28}Si. It is expected to be at least as large as that observed for ^{16}O, and might plausibly increase by as much as the mass ratio, $28/16 = 1.75$, to $(19.2 \pm 3.5)\%$ per 100 mg/cm^2. We have used the midvalue, $(15.1 \pm 4.1)\%$ per 100 mg/cm^2, to correct the ratio, 1.275 ± 0.040, observed for the 82-mg/cm^2 target to the zero-thickness value shown in Table I. The indicated error again includes $\pm 50\%$ of the correction. The ratio shown for 28-GeV protons includes a small correction for secondaries based on the $(1.4 \pm 0.4)\%$ per 100 mg/cm^2 measured at that energy [12].

The $\sigma_{Cu}(^{24}Na)/\sigma_{Al}(^{24}Na)$ ratio compares the production of the same product from different targets. It was determined in two longer irradiations with ^{16}O ions by comparing production rates of ^{24}Na from Al in standard 54-mg/cm^2 Al-PE stacks with those from Cu in 198-mg/cm^2 Cu-Mylar stacks located 60 cm downstream. Since the comparisons were based on the assay of the 1368- and 2754-keV gamma rays from ^{24}Na with Ge(Li) detectors, this ratio is independent of counting efficiencies and their errors. It is also independent of the substantial beam fluctuations during the long irradiations. The value reported in Table I has been corrected for secondaries using the same $(11.0 \pm 2.0)\%$ per 100 mg/cm^2 which had been applied to the $\sigma_{Al}(^{24}Na)/\sigma_{Al}(^{18}F)$ ratio.

Some existing experimental ratios for incident protons [12–15] are included in Table I to illustrate the agreement between the present results for $\sigma_{Al}(^{18}F)/\sigma_C(^{11}C)$ and $\sigma_{Al}(^{24}Na)/\sigma_{Al}(^{18}F)$ and the previous values at 28 GeV, and the energy independence of the ratios for protons between 28 and 300 GeV. This limiting fragmentation behavior is a consequence of the energy independence of the separate reactions whose cross sections are known to vary by $\lesssim 5\%$ over this range [13, 16–19].

It has been noted [7] that total kinetic energy, rather than energy per nucleon, is a better variable for the parametrization of target fragmentation cross sections. If limiting fragmentation and factorization were valid, ratios for 218-GeV ^{16}O and 381-GeV ^{28}Si ions should be

TABLE I. Experimental cross section ratios for the interaction of high-energy heavy ions and protons with C, Al, and Cu.

Projectile	Cross section ratio $\sigma_{Al}(^{18}F)/\sigma_C(^{11}C)$	$\sigma_{Al}(^{24}Na)/\sigma_{Al}(^{18}F)$	$\sigma_{Cu}(^{24}Na)/\sigma_{Al}(^{24}Na)$
28-GeV ^{1}H	0.235 ± 0.006	1.38 ± 0.04	
	0.232 ± 0.009^a	1.39 ± 0.07^a	0.450 ± 0.005^b
300-GeV ^{1}H	0.227 ± 0.009^c	1.44 ± 0.07^c	0.436 ± 0.010^d
218-GeV ^{16}O	0.220 ± 0.005	1.13 ± 0.05	0.629 ± 0.020
381-GeV ^{28}Si	0.209 ± 0.006	1.13 ± 0.08	

[a] From Ref. [12].
[b] From Ref. [14].
[c] From Ref. [13].
[d] From Ref. [15].

the same as those for 300-GeV protons. Some significant differences are apparent in Table I. It is informative to discuss these in terms of the individual cross sections rather than the ratios. For the conversion of ratios into cross sections, we make use of the extensive body of data on ^{11}C production from carbon by a wide range of projectiles: 28- and 300-GeV protons [16, 17], heavy ions from ^{4}He to ^{139}La at Bevalac energies [20], and 13.4-GeV/nucleon ^{28}Si ions [21]. These values of $\sigma_C(^{11}C)$ are plotted as a function of the inelastic cross section [22] for the appropriate projectile-target combination in Fig. 1. The choice of the log-log form with σ_R as the abscissa emphasizes the role of factorization which, in its strong form, would require unit slope. The experimental $\sigma_C(^{11}C)$ are consistent with a power-law dependence on σ_R, but the exponent, $\alpha = 0.68 \pm 0.03$, is significantly less than unity. The least-squares fit which generated the solid line did not include the rightmost point, that for ^{139}La, as the cross section for $Z = 57$ is expected to include a substantial contribution, 24 mb, from electromagnetic dissociation [20]. The root-mean-square deviation of points from the fitted line is 5%, typical of uncertainties on such absolute cross section measurements. That the solid point for ^{28}Si at AGS energies falls within $\sim 5\%$ of the line which is defined primarily by measurements at Bevalac energies, is evidence that there is no significant energy dependence, a feature that is consistent with limiting fragmentation.

Values of $\sigma_C(^{11}C)$ from the least-squares line in Fig. 1, 65.1 mb for ^{16}O and 77.5 mb for ^{28}Si, were used to obtain the $\sigma_{Al}(^{24}Na)$, $\sigma_{Al}(^{18}F)$, and $\sigma_{Cu}(^{24}Na)$ from the experimental data. Errors assigned to each derived cross section in Table II include a 5% uncertainty in $\sigma_C(^{11}C)$ combined with those from the ratio measurements. These cross sections are plotted as solid symbols in Fig. 1. Values for high-energy protons are shown as the open leftmost points for each reaction. The crosshatched points indicate $\sigma_{Al}(^{24}Na)$ and $\sigma_{Cu}(^{24}Na)$ values obtained for ^{12}C [9, 15] and ^{40}Ar [7, 23] projectiles at Bevalac energies. The value of $\sigma_{Al}(^{24}Na) = 26 \pm 6$ mb reported [1] for 13.6-GeV/nucleon ^{16}O ions has not been shown in the figure as it was not corrected for secondary production. The large errors on $\sigma_{Cu}(^{24}Na)$ reflect 15–20 % uncertainties on the absolute determinations of $\sigma_{Al}(^{24}Na)$ at Bevalac energies. Considering these errors, the data are in reasonable agreement with the present results and they point to the absence of any strong energy dependence.

The data for $\sigma_{Al}(^{24}Na)$, $\sigma_{Al}(^{18}F)$, and $\sigma_{Cu}(^{24}Na)$ in Fig. 1 are too limited to prove a power-law dependence on σ_R. However, they can be used to obtain apparent power-law exponents. The value of α (0.67 ± 0.04) for $\sigma_{Al}(^{24}Na)$ is essentially identical to that for $\sigma_C(^{11}C)$, and the strong form of factorization which requires proportionality between cross sections and σ_R is violated for both reactions. Such violations can be understood qualitatively in terms of a simple geometrical picture: As projectile size increases, an increasingly large fraction of σ_R leads to central events at the expense of peripheral ones. If the dependence of the cross section on σ_R were the same for all or some class of peripheral reactions, a weaker form of factorization might be considered as applicable. Values of α for $\sigma_C(^{11}C)$ and $\sigma_{Al}(^{24}Na)$ which involve the removal of one and three target nucleons, respectively, are indeed consistent with the same dependence: The value of α (0.81 ± 0.05) for $\sigma_{Al}(^{18}F)$, where nine nucleons are removed, is clearly not. The ratios in Table I indicate that the pattern of fragmentation yields

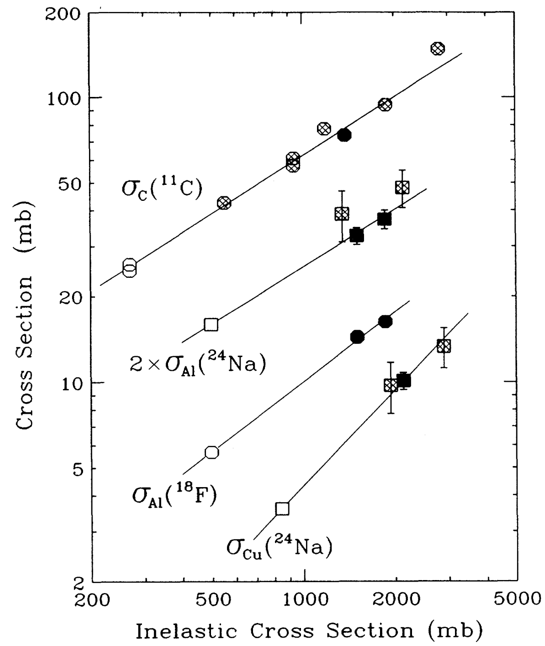

FIG. 1. Dependence of selected target fragmentation cross sections on inelastic cross sections for the appropriate projectile-target pairs. Solid points are from this work and Ref. [21] for $\sim$ 13.6-GeV/nucleon ^{16}O or ^{28}Si projectiles, open points for high-energy protons, and crosshatched ones for ^{4}He or heavy-ion induced fragmentation at $\sim$ 2 GeV/nucleon (see text for references). Results for $\sigma_{Al}(^{24}Na)$ are offset vertically by a factor of 2 to simplify the display. Solid lines suggest an approximate power-law variation for each reaction.

TABLE II. Derived cross sections for the interaction of high-energy heavy ions with C, Al, and Cu.

	Cross section (mb)			
Projectile	$\sigma_C(^{11}C)$	$\sigma_{Al}(^{18}F)$	$\sigma_{Al}(^{24}Na)$	$\sigma_{Cu}(^{24}Na)$
218-GeV ^{16}O	65.1 ± 3.3[a]	14.3 ± 0.8	16.4 ± 1.1	10.2 ± 0.6
381-GeV ^{28}Si	77.5 ± 3.9[a]	16.2 ± 0.9	18.6 ± 1.6	

[a] Adopted values from the least-squares line through the points shown in Fig. 1.

from an Al target is shifted to favor the lower mass product, ^{18}F, as projectile size increases. The applicability of a weaker form of factorization is limited then to at most small mass losses. It is reasonable to expect that values of α will rise above unity for products still further removed from Al than ^{18}F since σ_R must be conserved.

The $\sigma_{\mathrm{Cu}}(^{24}\mathrm{Na})$ exhibits a much stronger dependence, $\alpha = 1.11 \pm 0.07$, on σ_R than those for the three reactions in C and Al. It has been inferred that Cu fragmentation cross sections leading to products in the range $37 \leq A \leq 61$ are consistent with strong factorization, i.e., $\alpha \sim 1$. Hence, the relative shape of the fragmentation mass-yield distribution is independent of projectile type at lower energies. The production of ^{24}Na from Cu at ~ 2 GeV per nucleon exhibited at most a small enhancement consistent with the value of α from the present work. The extensive data on light fragment production by 400-GeV protons and 18.5-GeV ^{12}C ions [15] suggest that ^{24}Na production from Cu falls in a transitional region between peripheral mechanisms ($\alpha < 1$) in the case of the Al target and central processes for Gd and heavier targets for which $\alpha \sim 2$.

In summary, from the comparison of data for high-energy protons and heavy ions, it is concluded that a general feature of peripheral target fragmentation reactions in light nuclei is their weak dependence on inelastic cross section. The cross section for an individual fragment increases less rapidly with projectile size than does σ_R. A difference of the dependence for $\sigma_{\mathrm{Al}}(^{24}\mathrm{Na})$ from that for $\sigma_{\mathrm{Al}}(^{18}\mathrm{F})$ suggests a favoring of more complex reactions when the projectile is a heavy ion. Both observations are inconsistent with factorization which predicts the proportionality between cross sections and σ_R, a behavior observed for many fragmentation reactions in medium- and heavy-mass targets. Comparison of $\sigma_{\mathrm{C}}(^{11}\mathrm{C})$, $\sigma_{\mathrm{Al}}(^{24}\mathrm{Na})$, and $\sigma_{\mathrm{Cu}}(^{24}\mathrm{Na})$ values indicates no significant changes in cross sections between Bevalac and AGS energies, which is consistent with limiting fragmentation.

We wish to acknowledge the cooperation of the other members of the E825 collaboration: K. Aleklett, M. Bronikowski, S. Katcoff, W. Loveland, N.T. Porile, and L. Sihver. Special thanks are due D. Beavis for his assistance during the irradiations. This research was performed at Brookhaven National Laboratory under Contract No. DE-AC02-76CH00016 with the U.S. Department of Energy and supported by its Office of High Energy and Nuclear Physics.

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[1] M. Bronikowski and N. T. Porile, Phys. Rev. C **44**, 1661 (1991).

[2] W. Loveland, M. Hellström, L. Sihver, and K. Aleklett, Phys. Rev. C **42**, 1753 (1990).

[3] J. B. Cumming, Y. Y. Chu, and P. E. Haustein, Phys. Rev. C **46**, 2042 (1992).

[4] M. Bronikowski and N. T. Porile, Phys. Rev. C. **45**, 1389 (1992).

[5] W. Loveland, K. Aleklett, M. Bronikowski, Y. Y. Chu, J. B. Cumming, P. E. Haustein, S. Katcoff, N. T. Porile, and L. Sihver, Phys. Rev. C **37**, 1311 (1988).

[6] We will use $\sigma_t(f)$ to denote the cross section for forming fragment f from target t. The projectile will be identified in the text as needed.

[7] J. B. Cumming, P. E. Haustein, T. J. Ruth, and G. J. Virtes, Phys. Rev. C **17**, 1632 (1978).

[8] J. B. Cumming, P. E. Haustein, and H.-C. Hseuh, Phys. Rev. C **24**, 2162 (1981).

[9] N. T. Porile, G. D. Cole, and C. R. Rudy, Phys. Rev. C **19**, 2288 (1979).

[10] G. D. Cole and N. T. Porile, Phys. Rev. C **25**, 244 (1982).

[11] S. B. Kaufman, E. P. Steinberg, B. D. Wilkins, and D. J. Henderson, Phys. Rev. C **22**, 1897 (1980).

[12] J. B. Cumming, G. Friedlander, J. Hudis, and A. M. Poskanzer, Phys. Rev. **127**, 950 (1962); J. B. Cumming, J. Hudis, A. M. Poskanzer, and S. Kaufman, *ibid.* **128**, 2392 (1962).

[13] S. B. Kaufman, M. W. Weisfield, E. P. Steinberg, B. D. Wilkins, and D. J. Henderson, Phys. Rev. C **19**, 962 (1979).

[14] J. B. Cumming, R. W. Stoenner, and P. E. Haustein, Phys. Rev. C **14**, 1554 (1976).

[15] G. D. Cole and N. T. Porile, Phys. Rev. C **24**, 2038 (1981).

[16] J. B. Cumming, G. Friedlander, and S. Katcoff, Phys. Rev. **125**, 2078 (1962).

[17] S. B. Kaufman, M. W. Weisfield, B. D. Wilkins, D. Henderson, and E. P. Steinberg, Phys. Rev. C **13**, 253 (1976).

[18] J. B. Cumming, V. Agoritsas, and R. Witkover, Nucl. Instrum. Methods **180**, 37 (1981).

[19] S. I. Baker, R. A. Allen, P. Yurista, V. Agoritsas, and J. B. Cumming, Phys. Rev. C **43**, 2862 (1991).

[20] A. R. Smith, J. C. Hill, J. A. Winger, and P. J. Karol, *ibid.* **38**, 210 (1988). This work provides references and corrections to earlier heavy-ion measurements.

[21] J. A. Winger, J. C. Hill, J. B. Cumming, and D. Beavis, Phys. Rev. C **41**, 2931 (1990).

[22] S. Barshay, C. B. Dover, and J. P. Vary, Phys. Rev. C **11**, 360 (1975); P. J. Karol, *ibid.* **11**, 1203 (1975).

[23] S. Katcoff (private communication) has reported $\sigma_{\mathrm{Al}}(^{24}\mathrm{Na}) = 27 \pm 4$ mb for 76-GeV ^{40}Ar ions. The value plotted in Fig. 1 has been reduced by 11% to account for the contribution of secondary reactions in the 380-mg/cm^2 Lexan-mica-Al target used in that measurement. The same correction is also appropriate for the Ar + Cu cross sections reported in Ref. [7].