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BRIEF REPORTS

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Recoil properties of target fragments from the interaction of silver with 218 GeV ^{16}O ions

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Thick-target recoil ranges and forward-to-backward ratios of some thirty target fragments from the interaction of Ag with 218 GeV ^{16}O ions have been measured. The results were analyzed by means of the two-step model and compared with similar data for 18.5 GeV ^{12}C ions and 400 GeV protons in order to test the applicability of factorization and limiting fragmentation.

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This work is one of a series of studies of target fragments formed in the interaction of ~ 14 GeV/nucleon heavy ions with nuclear targets. Previous studies have shown that the mass yield distributions obtained for the interaction of gold [1] and silver [2] with ^{28}Si or ^{16}O ions of this energy are similar to those obtained with 2 GeV/nucleon heavy ions or with 300 GeV protons, confirming the applicability of factorization and limiting fragmentation [3] at these energies. However, the forward-to-backward (F/B) emission ratios of ^{24}Na produced from various targets by 14 GeV/nucleon ^{16}O and, to a lesser extent, the ranges of this product where found to be significantly lower than those from the interaction of 400 GeV protons or 2 GeV/nucleon heavy ions, in disagreement with these hypotheses [4]. We have examined this possible difference in further detail and present here the results of a thick-target recoil study of target fragments from the interaction of silver with 218 GeV ^{16}O ions.

Recoil properties were determined in the same experiments used to determine cross sections, as described previously [2,5]. The recoil properties of interest are the experimental range, $2W(F+B)$, where W is the target thickness and F and B are the fractions of the total activity of a given nuclide collected in the forward and backward catcher foils, respectively, and F/B. The results for some 30 products are summarized in Table I, where the uncertainties are the larger of the standard deviation in the mean of as many as eight replicate determinations and the estimated uncertainty in single determinations, as based on decay curve analysis. Results are reported only for products for which at least two separate determinations were made.

The variation of the range and F/B with product mass is shown in Fig. 1. The ranges decrease monotonically with increasing product mass while the F/B ratios show relatively little variation within the limits of uncertainty. As discussed below, these trends can be understood in terms of the recoil parameters derived from these data. Also included in Fig. 1 are smooth curves representing similar data for the interaction of silver with 18.5 GeV ^{12}C ions [6] and with 400 GeV protons [7]. The present F/B ratios are substantially lower than those obtained

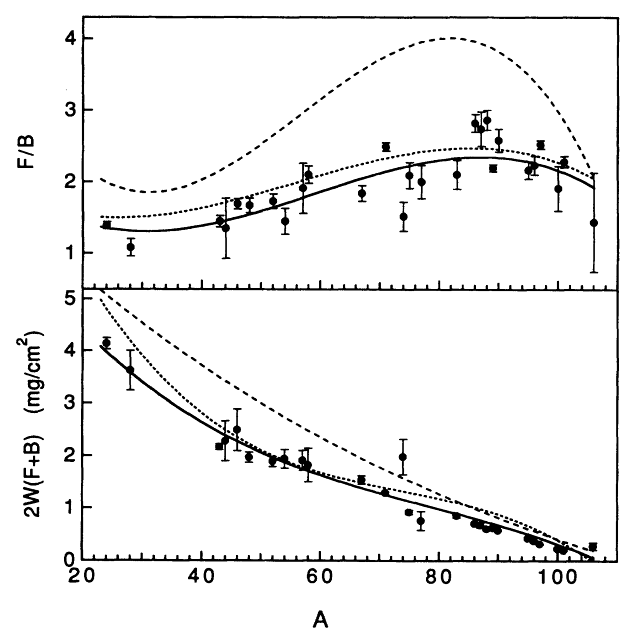

FIG. 1. Product mass dependence of the experimental range and F/B of target fragments of the interaction of silver with 218 GeV ^{16}O ions. The solid curves show the trends of the data points. Long- and short-dashed curves show trends in similar data for the interaction of silver with 18.5 GeV ^{12}C [6] and 400 GeV protons [7], respectively.

with the lower-energy ^{12}C and slightly lower than those obtained with 400 GeV protons. The weighted averages of the ratios of F/B for individual products are 0.63 ± 0.01 and 0.90 ± 0.02, respectively. Figure 1 also shows the behavior of the ranges obtained in these other experiments. A similar though less pronounced difference as that seen for the F/B may be noted, the weighted average of the ratios of individual ranges being 0.73 ± 0.02 for ^{16}O and ^{12}C and 0.91 ± 0.03 for ^{16}O and protons. Thus, our more complete data confirm the earlier results reported for ^{24}Na, namely, that recoil properties are not consistent with limiting fragmentation for ~2 GeV/nucleon heavy ions. Furthermore, the differences in the recoil properties of ^{24}Na reported for ^{16}O and 400 GeV protons, particularly for a gold target [4], are also exhibited by the products detected in the present work, but to a smaller extent.

The mean velocity along the beam direction of the remnant of the initial projectile-target interaction, $\beta_\parallel = v_\parallel / c$, and the kinetic energy of the observed products in the moving system, T, may be obtained from the tabulated data by means of equations based on the two-step model of high-energy reactions [8–10]. The exact procedure used has been described elsewhere [11]. Figure 2 shows the dependence of $\beta_\parallel$ and T on fractional mass loss, $\Delta A / A_T$, where A_T is the target mass. Owing to the proportionality between longitudinal momentum and excitation energy of the remnant in the spallation regime [12], $\beta_\parallel$ should increase linearly with $\Delta A / A_T$ in this regime. Similarly, T of spallation products is also expected to increase linearly with $\Delta A / A_T$ because of the random direction in which succeeding evaporated particles are emitted [13,14]. Our data are consistent with these expectations for fractional mass loss up to ~0.5–0.6. Greater mass losses from silver lead to multifragmentation products [15], for which the above relationships are not expected to be valid. The slope of the line in the T vs $\Delta A / A_T$ plot is an approximate measure of the mean kinetic energy of particles emitted in the deexcitation step. The present result is 16.6 ± 0.2 MeV, a value that lies in the range of of Winsberg's systematics [16] for high-energy reactions.

The present values of $\beta_\parallel$ and T are compared with those derived in an identical analysis of the ^{12}C and proton data in Figs. 3 and 4, respectively. These figures show the ratios of $\beta_\parallel$ and T for individual products. Within the limits of error, the ratios are virtually independent of product mass, with the possible exception of the $^{16}O/^{12}C$ $\beta_\parallel$ ratios for the lightest products, which appear to be lower than average. While both T and $\beta_\parallel$ values for 218 GeV ^{16}O are lower, on average, than the corresponding values for 18.5 GeV ^{12}C or 400 GeV protons, the difference is particularly large for the $\beta_\parallel$ from ^{16}O and ^{12}C.

The decrease in $\beta_\parallel$ with increasing heavy ion energy is

TABLE I. Recoil properties of products of the interaction of silver with 218 GeV ^{16}O ions.

Nuclide	$2W(F+B)$ (mg/cm^2)	F/B
^{24}Na	4.14±0.11	1.39±0.05
^{28}Mg	3.62±0.38	1.08±0.12
^{43}K	2.17±0.06	1.45±0.08
^{44}Sc^m	2.28±0.38	1.35±0.42
^{46}Sc	2.49±0.40	1.69±0.07
^{48}Sc	2.53±0.29	1.85±0.40
^{48}V	1.88±0.07	1.64±0.07
^{52}Mn	1.89±0.10	1.73±0.10
^{54}Mn	1.94±0.18	1.45±0.18
^{57}Co	1.91±0.19	1.91±0.35
^{58}Co	1.82±0.32	2.10±0.12
^{67}Ga	1.54±0.08	1.84±0.11
^{71}As	1.29±0.02	2.50±0.06
^{72}Se	1.20±0.33	1.48±0.36
^{74}As	1.98±0.34	1.52±0.20
^{75}Se	0.935±0.039	2.09±0.18
^{77}Br	0.757±0.181	2.00±0.23
^{83}Rb	0.796±0.020	2.17±0.23
^{83}Sr	0.952±0.057	2.02±0.31
^{86}Zr	0.714±0.015	2.82±0.12
^{87}Y^m	0.678±0.046	2.74±0.24
^{88}Zr	0.606±0.034	2.86±0.14
^{89}Zr	0.627±0.008	2.19±0.05
^{90}Nb	0.576±0.014	2.58±0.16
^{95}Tc	0.430±0.011	2.16±0.12
^{96}Tc	0.377±0.012	2.23±0.13
^{97}Ru	0.324±0.012	2.52±0.06
^{100}Rh	0.195±0.031	1.74±0.39
^{100}Pd	0.280±0.054	2.17±0.25
^{101}Rh^m	0.200±0.007	2.28±0.08
^{106}Ag^m	0.275±0.066	1.44±0.69

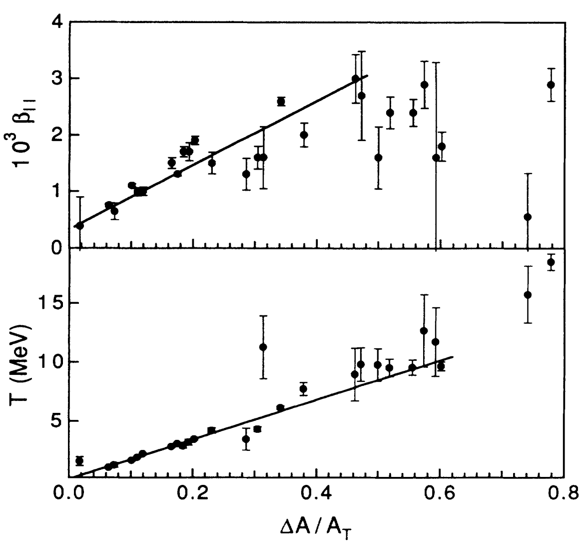

FIG. 2. Dependence of $\beta_\parallel$ and T on fractional mass loss. The solid lines represent linear fits extending to $\Delta A / A_T$ of 0.5 and 0.6, respectively.

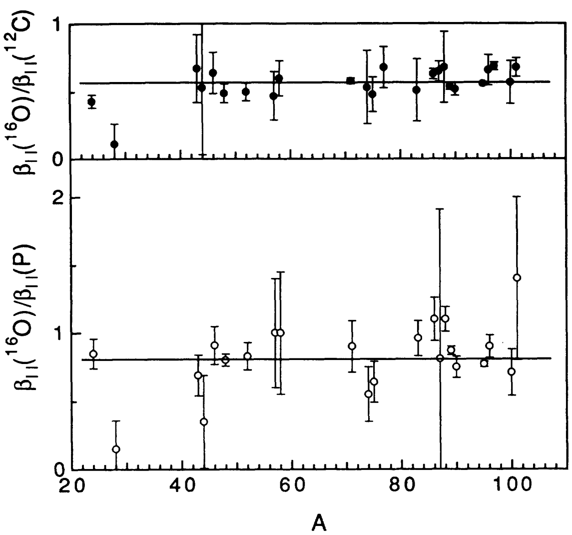

FIG. 3. Product mass dependence of ratios of $\beta_{\parallel}$ from 218 GeV ^{16}O and 18.5 GeV ^{12}C bombardment of silver (top) and ^{16}O and 400 GeV protons (bottom). The horizontal lines represent the weighted average of the ratios, 0.57±0.01 (top) and 0.81±0.02 (bottom).

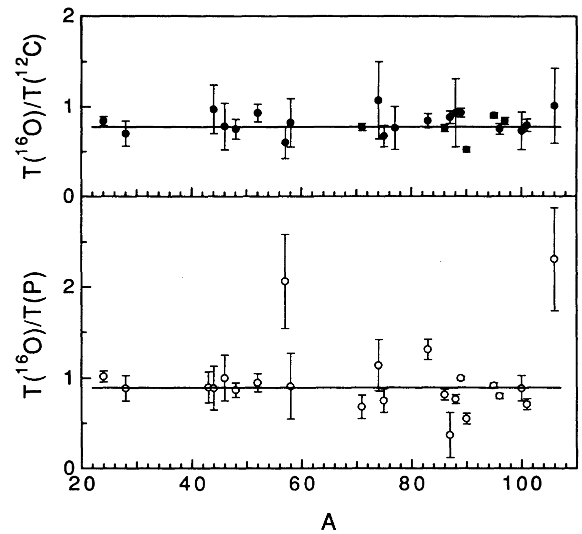

FIG. 4. Product mass dependence of ratios of T. See Fig. 3 for details. The weighted averages are 0.77±0.03 (top) and 0.89±0.03 (bottom).

consistent with that observed for light fragments produced in the interaction of gold with 5–42 GeV ^{20}Ne ions [17], and appears to continue at even higher energies. This decrease has been attributed [17] to a change in the direction of the momentum transferred in the initial interaction from forward to sideward angles, an effect reported previously for high-energy proton-induced reactions [18].

In summary, our comparison of recoil properties and cross sections [2] of target fragments of the interaction of silver with 218 GeV ^{16}O ions with similar data for comparable energy protons and lower-energy heavy ions indicates that the production cross sections attain the regime of limiting fragmentation at substantially lower energies than recoil properties do. Furthermore, the $\beta_{\parallel}$ values derived from the ^{16}O data are significantly lower than those from the 400 GeV proton data, indicating that, in contrast to the cross sections, recoil properties may not be consistent with factorization at even the highest energies.

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