Enhanced fragment emission in the interaction of 18.5 GeV ^{12}C ions with complex nuclei

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(Received 26 May 1981)

Cross sections for the formation of seven fragments ranging from ^{24}Na to ^{52}Mn in the interaction of 18.5 GeV ^{12}C ions and 400 GeV protons with Cu, Ag, Gd, Ta, Au, and U have been measured. After correction for the difference in bombarding energy, the results were used to test the factorization hypothesis. Enhanced fragment emission in ^{12}C reactions was observed for all targets excepting copper. The magnitude of the enhancement and its dependence on target and product A are described. The variation of fragment yields with target A is examined. The neutron excess products obey modified Qgg systematics while the neutron deficient ones do not. The implications of these results for the reaction mechanism are considered.

[NUCLEAR REACTIONS Cu, Ag, Gd, Ta, Au, U [^{12}C and p, fragments (A =24−52)] $T_{^{12}C}$=18.5 GeV, Tp =400 GeV. Measured cross sections. Test of factorization, yield systematics. Gross γ-ray assay [Ge (Li)].]

I. INTRODUCTION

The interaction of relativistic heavy ions (RHI) with nuclei can be broadly categorized as involving either peripheral interactions or central collisions. Peripheral interactions lead to projectile and target fragmentation, processes in which the residual nuclei have only modest excitation energies and are fairly close in mass number, atomic number, and velocity to those of the projectile and target, respectively. The final result of target fragmentation is the formation of spallation products, although fission is of importance for heavy elements.

A characteristic feature of projectile and target fragmentation is that these processes obey the factorization hypothesis.[1] As applied to target fragmentation, this hypothesis states that the cross sections for the formation of specific products depend on the identity of the projectile only via a factorable total cross section term. To be valid, the comparison should be made at high enough energies that limiting fragmentation[1] is applicable, i.e., the regime at which cross sections becomes independent of bombarding energy. However, evidence has been obtained which indicates that factorization holds at somewhat lower energies provided the comparison is made at the same projectile kinetic energy.[2–4] The factorization hypothesis has usually been tested by comparison of the yields of products formed in RHI interactions with those produced in proton induced reactions with the same target. For such a comparison, the hypothesis can be formulated as

$$\frac{\sigma(^{A}Z,\mathrm{RHI},T_{\mathrm{RHI}})/\sigma_R(\mathrm{RHI},T_{\mathrm{RHI}})}{\sigma(^{A}Z,p,Tp)/\sigma_R(p,Tp)}=1, \qquad (1)$$

where $\sigma(^{A}Z,\mathrm{RHI},T_{\mathrm{RHI}})$ is the cross section for the formation of nuclide ^{A}Z in the interaction of some RHI of kinetic energy T_{RHI} with a certain target, and $\sigma_R(\mathrm{RHI},T_{\mathrm{RHI}})$ is the corresponding total reaction cross section. The quantities in the denominator are the corresponding cross sections for protons with kinetic energy Tp.

Equation (1) has been tested for targets of copper,[2,5,6] silver,[7] tantalum,[3] and gold,[3,4] and found to be valid for most reaction products. The only significant discrepancy has been found in the case of light fragments, whose yields are enhanced in RHI interactions. In the case of copper, the only enhancement is observed for ^{7}Be while for silver, higher yields are obtained in 25 GeV ^{12}C interactions for products with A up to 40. Significant enhancements up to $A \sim 60$ are observed for gold[4] but only for 25 GeV ^{12}C ions. At energies below 10 GeV the RHI enhancements are either small or absent. The one exception to this otherwise reasonably consistent picture of factorization has been presented in a preliminary report on the interaction of 25 GeV ^{12}C ions with uranium.[8] A large enhancement in the yield of products in the $A = 160-190$ mass region was obtained in reactions induced by ^{12}C. On the other hand, no apparent enhancement was noted for light products, in contrast to the behavior observed for lower mass targets.

It appears that light fragments having yields inconsistent with factorization are the result of a central collision process. Such a process results in the near total destruction of both projectile and target and the resulting fragments cannot be identified with either nucleus but result instead from a system moving with an intermediate velocity.[9–11] The enhancement in the fragment yield presumably reflects the fact that such a violent interaction is more likely for a heavy projectile than for a proton. Central collisions have attracted considerable interest since they may involve the formation of nuclear matter at abnormally high temperature or density. Although such effects have not as yet been observed, the study of fragment emission in RHI reactions continues to attract considerable interest.[12]

The present work focuses on the magnitude of the enhancement in fragment emission observed in RHI interactions. Although some information on this point has been obtained for several targets and projectiles at various energies,[2–8] no systematic measurements have as yet been performed. It would thus be of interest to determine how the enhancement varies with the mass of both target and fragment for a given RHI at a particular bombarding energy. If fragment emission is indeed indicative of central collisions, such measurements will show which target-fragment combinations are the most effective measures of such collisions. We present in this study comparative results on the yields of fragments ranging from ^{24}Na to ^{52}Mn emitted in the interaction of Cu, Ag, Gd, Ta, Au, and U with relativistic ^{12}C ions and protons. The data also give a coherent picture of the dependence of fragment yield on target A and the systematics of this dependence are examined.

II. EXPERIMENTAL

The experiments involved the irradiation of metallic foils of the various target elements with 18.5 GeV ^{12}C ions at the Bevalac and with 400 GeV protons at Fermilab. The products of interest were detected after bombardment by γ-ray spectrometry. The experimental procedure was essentially the same as that described in a previous report from our laboratory,[7] which may be consulted for a complete description.

The targets ranged in surface density from 10 mg/cm^2 (Ag) to 80 mg/cm^2 (U). The foils were surrounded by Mylar catcher foils and individually encapsulated in evacuated plastic bags along with three Al beam monitor foils placed on the upstream side. All six targets were simultaneously irradiated at the Bevalac. In order to minimize secondary effects, the targets were arranged in order of increasing atomic number and separated from each other by 5 cm. The beam intensity was determined with a calibrated ion chamber[13] mounted just upstream of the target holder, as well as by assay of the ^{24}Na activity induced in the Al monitor foils. The cross section of the ^{27}Al(^{12}C,x)^{24}Na reaction was assumed to be 19.4 mb.[7] Replicate irradiations lasting ~ 10 h were performed. Because of these relatively long irradiation periods, the data were corrected for fluctuations in beam intensity, as determined from the ion chamber readout.

In the case of the proton irradiations, two targets were irradiated at a time. The stack consisted of three aluminum foils for beam intensity determination, followed in order of increasing Z by the two separately encapsulated target-catcher combinations. The beam intensity was determined by means of the ^{27}Al(p,$3pn$)^{24}Na cross section whose value was taken as 8.6 mb.[14] Since the irradiation time was usually less than one hour, fluctuations in beam intensity could be neglected. Replicate irradiations were performed for each target.

Following irradiation, the targets were assayed with Ge(Li) γ-ray spectrometers. The spectra were analyzed with the code SAMPO (Ref. 15) in order to obtain the desired γ-ray intensities. The disintegration rates at end of bombardment were obtained with the code CLSQ (Ref. 16), and the cross sections were obtained from these results and the beam intensity monitor data after correction for recoil loss. Since the experiment was designed to obtain results for specific products, the measured γ-ray energy interval as well as the counting times were optimized for the nuclides of interest. Table I

TABLE I. Decay properties of product nuclides.

Nuclide	$t_{1/2}$	E_γ (keV)	Branching ratio
^{24}Na	15.0 h	1368.6	1.00
		2754.0	0.999
^{28}Mg	21.3 h	941.7	0.359
		1779.0	1.00[a]
^{42}K	12.4 h	1524.7	0.179
^{44}Sc^m	2.44 d	1157.0	0.998[b]
^{48}Sc	1.82 d	983.3	1.00
		1037.4	0.98
		1311.7	1.00
^{48}V	16.1 d	983.3	1.00
		1311.7	0.98
^{52}Mn	5.6 d	744.2	0.85
		935.5	0.93
		1434.3	1.00

[a]Emitted in the decay of ^{28}Al daughter.
[b]Emitted in the decay of ^{44}Sc daughter.

summarizes the relevant decay properties of these nuclides.[17] The list is comprised of those light fragments for which reliable results could be obtained by gross γ-ray assay of the targets.

III. RESULTS

The results obtained for ^{12}C ions and protons are summarized in Tables II and III, respectively. The designations C and I indicate whether the tabulated cross sections constitute cumulative or independent yields, respectively. The results have been corrected for a number of factors. Corrections for reduced photopeak intensities resulting from γ-γ coincidences were made on the basis of the analysis by McCallum and Coote[18] and varied between 0 and 12% depending on the complexity of the level scheme and the counting geometry. While the cross sections for the production of fragments are not sensitive to low-energy secondaries because of their high effective threshold, the activity of ^{24}Na in the Al monitor foils must be corrected for this effect. The secondary correction in high-energy proton reactions has been investigated for a variety of targets [5,7,14,19,20] in which the monitor foil was placed upstream of the target, as in the present experiment. Based on these data, the monitor activities were reduced by a Z dependent factor which ranged from $<1\%$ for Cu and Ag to 10% for U. Since the secondary effect appears to be comparable for ^{12}C and protons,[5-7] similar corrections were made to the ^{12}C data. The disintegration rates of the various Al monitor foils from a given ^{12}C bombardment were in close agreement after this correction was made and were in accord with the ion chamber results. Finally, the ^{12}C data were corrected by up to 2% for fluctuations in beam intensity during bombardment.

The uncertainties associated with the tabulated cross sections are the larger of the internal and external error. The former is based on the uncertainty in the SAMPO and CLSQ fits and includes an additional $5-10\%$ uncertainty in the magnitude of the various correction factors. The external error is based on the agreement between the results obtained on the basis of the various γ-rays assayed for a given nuclide in the replicate determinations. Any inconsistencies in branching ratios will thus manifest themselves in corresponding differences in cross section. No systematic differences were seen, as expected from the fact that the level schemes of the nuclides in question are well known. The uncertainties in the monitor reaction cross sections and ion chamber calibration have not been incorporated in the cross sections. While these uncertainties do not affect the relative cross sections ob-

TABLE II. Cross sections (mb) for the formation of fragments in the interaction of 18.5 GeV ^{12}C ions with the listed targets.

Product \ Target	Cu	Ag	Gd	Ta	Au	U
^{24}Na(C)	9.73±0.27	13.1 ±0.4	27.3 ±0.7	34.1 ±0.8	41.0 ±1.0	61.4 ±2.4
^{28}Mg(C)	1.04±0.07	1.88±0.24	5.00±0.15	6.55±0.24	7.63±0.44	17.3 ±0.5
^{42}K(I)	6.1 ±0.7	6.5 ±2.0	5.9 ±0.9	8.0 ±1.0	9.9 ±1.9	14.3 ±2.6
^{44}Sc^m(I)	8.60±0.32	4.36±0.37	3.81±0.17	4.23±0.23	4.65±0.23	5.00±0.27
^{48}Sc(I)	1.21±0.09	0.93±0.15	2.16±0.12	3.01±0.12	3.84±0.17	7.90±0.28
^{48}V(C)	16.2 ±1.0	6.18±0.47	4.14±0.43	4.44±0.33	4.49±0.37	3.99±0.65
^{52}Mn(I)	10.8 ±0.3	4.12±0.16	2.39±0.12	2.33±0.19	2.65±0.12	2.46±0.25

TABLE III. Cross sections (mb) for the formation of fragments in the interaction of 400 GeV protons with the listed targets.

Product \ Target	Cu	Ag	Gd	Ta	Au	U
^{24}Na(*C*)	3.75±0.09	5.15±0.23	7.19±0.45	8.98±0.59	12.3 ±0.3	19.3 ±0.5
^{28}Mg(*C*)	0.47±0.03	0.70±0.02	1.61±0.10	2.11±0.18	2.94±0.14	5.80±0.18
^{42}K(*I*)	3.01±0.11	2.36±0.10	2.07±0.56	2.22±0.18	3.50±0.37	6.31±0.50
^{44}Sc^{m}(*I*)	3.94±0.14	2.22±0.13	1.39±0.05	1.42±0.08	1.60±0.19	1.66±0.10
^{48}Sc(*I*)	0.53±0.04	0.49±0.04	0.87±0.03	1.13±0.04	1.66±0.10	3.08±0.26
^{48}V(*C*)	8.25±0.29	3.31±0.16	1.61±0.13	1.92±0.20		2.1 ±1.3
^{52}Mn(*I*)	4.64±0.10	2.34±0.10	0.88±0.04	0.93±0.07	1.18±0.09	0.86±0.07

tained for a given projectile, they will uniformly affect the ratio of ^{12}C to proton cross sections by as much as 15%.

The results are displayed in graphical form in Figs. 1 and 2 as plots of the production cross sections versus target *A*. Generally speaking, the cross sections for the formation of neutron excess fragments increase with target *A* while those of the neutron deficient ones show an initial decrease followed by a leveling off or a slight increase. Similar results have been previously obtained at lower energies in the case of proton induced reactions.[21–26] Some comparisons are presented in the next section.

Although the present results for ^{12}C ions constitute the first set of measurements in the vicinity of 18 GeV, a number of comparable results for 300–400 GeV protons have been reported previously.[7,14,27,28] The accord with the present results is generally good, as illustrated in Fig. 2, where some of the previously determined cross sections are included.

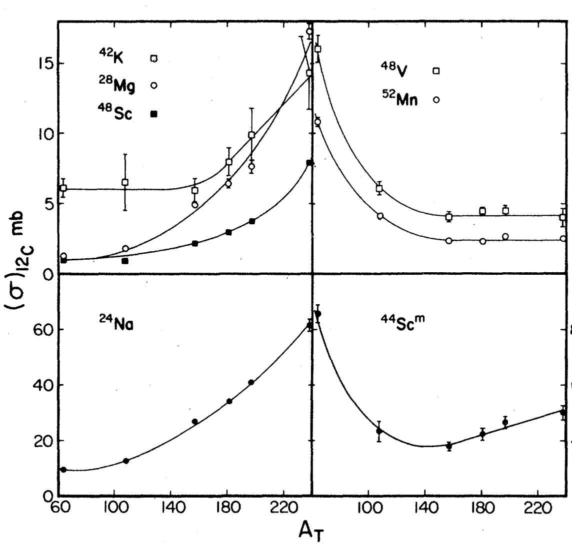

FIG. 1. Target *A* dependence of the cross sections for the formation of fragments in 18.5 GeV ^{12}C reactions.

IV. DISCUSSION

A. Test of factorization

The applicability of the factorization hypothesis may be tested by means of Eq. (1). The proton cross sections must first be adjusted for the difference in bombarding energy between the two projectiles. Although this difference is seemingly large, the adjustments are fortunately small. This is due

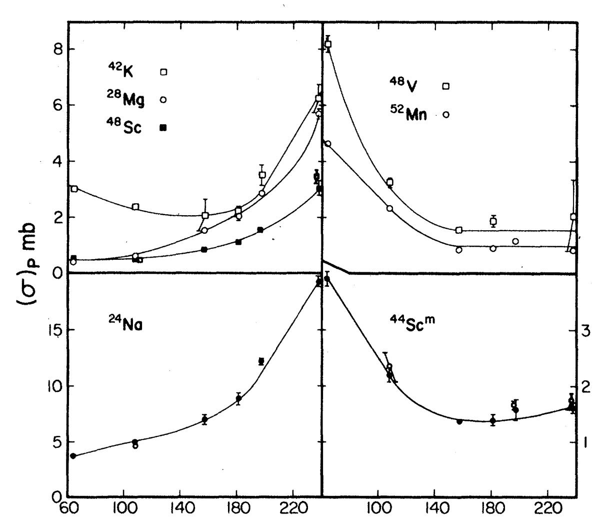

FIG. 2. Target *A* dependence of the cross sections for the formation of fragments in 400 GeV proton reactions. The open points near some of the closed data points for ^{24}Na, ^{44}Sc^{m}, and ^{48}Sc are the results of previous determinations (Refs. 14, 27, and 28).

to the fact that the regime of limiting fragmentation is nearly attained by 18 GeV protons and cross sections change to only a minor extent above this energy. We have used the relatively large body of proton cross sections available at energies of 11.5 GeV and above to obtain correction factors. (Refs 5, 14, 25, 27–35). The experimental cross sections were reduced by 0–25%, depending on the target and product, in order to correct for this effect.

The total reaction cross sections for 18 GeV ^{12}C ions were obtained from Karol's soft-sphere model[36] and those for 18 GeV protons from the parametrization by Ashmore *et al.*[37] The relative cross sections of the various products are displayed as a function of target A in Fig. 3. It is seen that factorization, which demands a cross section ratio of unity, is generally not obeyed. For a given fragment, the enhancement of the ^{12}C production cross section tends to increase with target A up to $A \sim 160$, at which point the effect appears to saturate. The enhancement is most noticeable for the lightest fragments and practically disappears for the heaviest products studied. For instance, the ^{24}Na cross section is enhanced by about a factor of 2 for heavy target elements, an effect that constitutes a significant departure from factorization.

A somewhat different perspective of the results is given in Fig. 4, which shows the variation of the cross section ratios with product A for the various targets. It is apparent that factorization is obeyed for all products formed from Cu, in agreement with the results of Cumming and collaborators.[2,5,6] A 40–50% enhancement is obtained for ^{24}Na and ^{28}Mg from Ag, while the heavier products from this target are consistent with factorization. This result is qualitatively similar to that previously reported for 25 GeV ^{12}C ions by Porile, Cole, and Rudy.[7] Within the limits of error, the behavior of the cross section ratios is the same for all heavier targets. The enhancement decreases from about a factor of 2 for ^{24}Na to approximately 30% for ^{52}Mn. The present results for uranium constitute the first indication that the yields of light fragments formed in RHI bombardment are enhanced for a highly fissile target in approximately the same way as for the less fissile heavy elements.

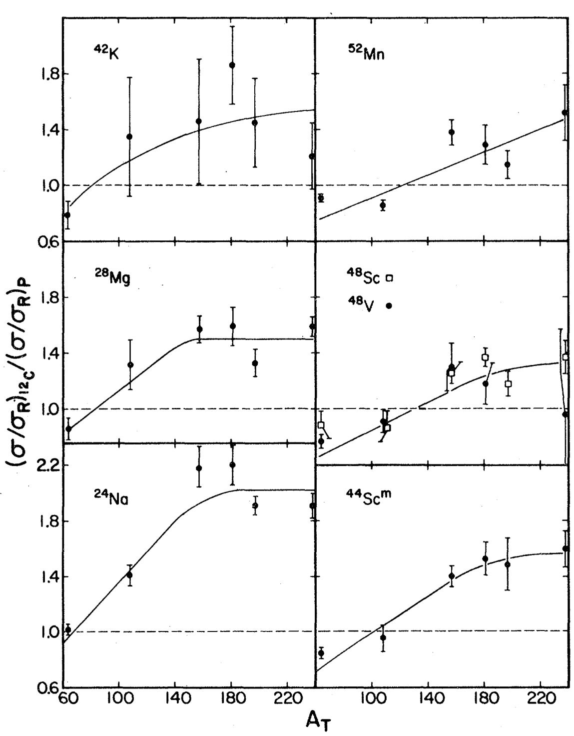

FIG. 3. Test of factorization for fragments produced in ^{12}C and proton reactions at 18.5 GeV. The curves show the trends in the cross section ratios. The dashed lines through unity are the expected values if factorization is obeyed.

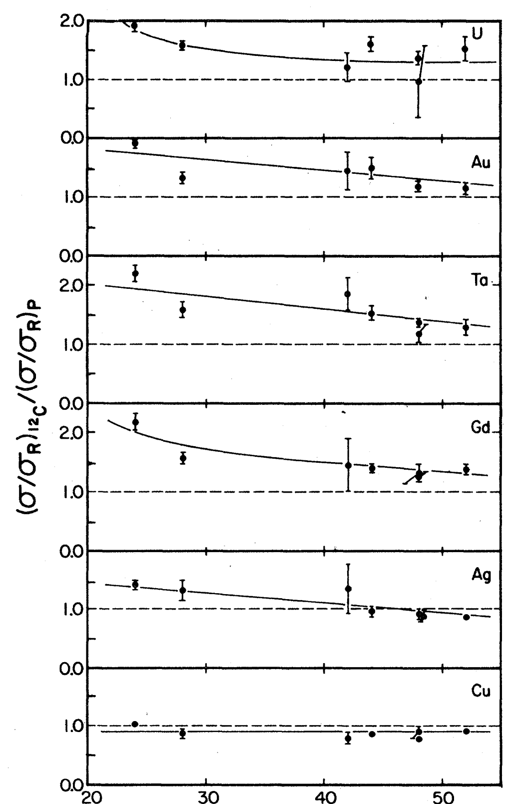

FIG. 4. Test of factorization as a function of product A for the various targets of interest.

These, then, are the results of the comparison at 18.5 GeV. It turns out, however, that the magnitude of the enhancement factors, particularly for heavy element targets, also depends on the bombarding energy. Figure 5 displays the data available for ^{24}Na from gold,[4] silver,[7] and copper.[2,5] The enhancement factor for the Au target increases from unity at 5 GeV to three at 25 GeV. In the case of silver, the enhancement factor is both smaller and less energy dependent while the results for copper suggest that ^{24}Na production is not enhanced in ^{12}C reactions over the energy range of interest. It is apparent that there is a systematic increase in energy dependence of the enhancement factor with increasing target A.

The trend in the dependence of the fragment enhancement factors on target A is, at least in part, suggestive of a geometric interpretation. Calculations based on the abrasion-ablation model have shown a correlation between the impact parameter of the collision of projectile with target and the mass difference between target and resulting product.[6,7,38] With decreasing impact parameter, the mass of the observed products decreases. This trend continues until impact parameters are reached at which there is complete overlap between target and projectile, at which point the target fragmentation cross section is exhausted. This point appears to be reached at a mass loss of perhaps 40 to 100 nucleons, depending on the target. Lighter products are presumably the result of central collisions. These considerations suggest that factorization should not be applicable in collisions in which there is complete overlap between the projectile and the dense core of the target.

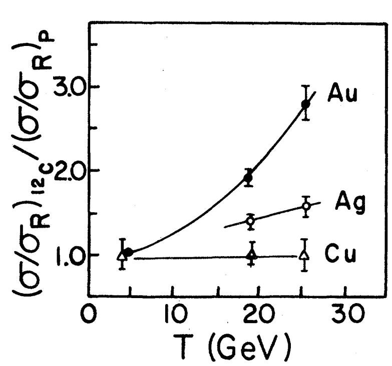

FIG. 5. Energy dependence of the ^{24}Na cross section enhancement in ^{12}C induced reactions. Data from Refs. 2, 4, 5, and 7 are included along with the present results.

Figure 6 shows the overlap between a ^{12}C ion and various targets for a collision at zero impact parameter. The radial density distributions of the target nuclei are based on the usual Fermi distribution obtained from electron scattering data.[39] The linear interval corresponding to the ^{12}C ion encompasses 90% of its mass.[39] It is seen that the core of the Cu nucleus is sufficiently small that complete overlap with a ^{12}C projectile is not possible. If such overlap is indeed required to observe the violent kind of breakup characteristic of a central collision, this process must be unlikely for a target as light as copper. The validity of factorization for copper, displayed in Fig. 4, is consistent with this view.

Virtually complete overlap between ^{12}C and the nuclear core is obtainable for silver. Central collisions are thus possible and some enhancement in the RHI yields of light fragments is expected, in accord with the results displayed in Figs. 3 and 4. For heavier targets, complete overlap becomes possible for an increasing range of impact parameters and the enhancement in fragment yields would be expected to increase continuously with target A. We have already remarked that such an increase is, in fact, observed up to Gd at which point the enhancement factor becomes independent of target A. In view of the significant energy dependence of the enhancement factors displayed in Fig. 5, it appears that the bombarding energy used in the present study is not sufficiently high to permit the applicability of a geometric model. Since the data

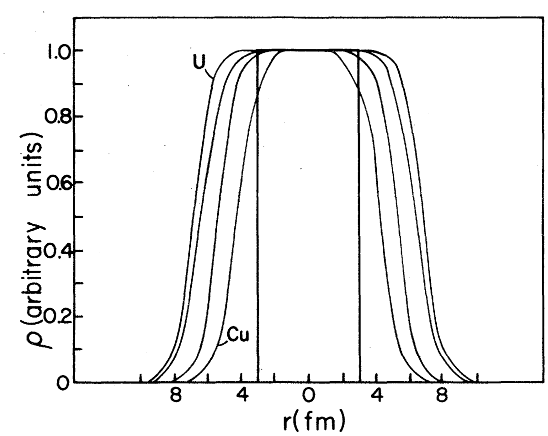

FIG. 6. Radial density distributions of Cu, Ag, Ta, and U displaying the overlap with a ^{12}C projectile in a $b=0$ collision. The vertical lines representing ^{12}C are drawn at a radius of 3.1 fm, corresponding to the distance at which 90% of the mass is encompassed.

in Fig. 5 suggest that limiting fragmentation may be attained at a different rate for different targets, the comparison should actually be made at a sufficiently high energy to ensure invariant cross sections for all targets.

B. Systematics of fragment yields

The variation of fragment production cross sections with target A has been investigated as increasingly higher proton bombarding energies have become available. The present results constitute the first systematic set of data for 400 GeV protons. It is thus pertinent to examine how the trends observed at lower energies evolve in the regime of present interest. The most complete set of data at lower energies is available for ^{24}Na formation. We have therefore chosen to examine the systematics of the yields of this particular fragment.

Figure 7 displays the variation with target A of the ^{24}Na production cross section at proton energies of 1, 3, 30, and 400 GeV.[21,25] The trends observed up to 30 GeV have been previously commented upon.[21,25] The general increase in ^{24}Na yields obtained with increasing proton energy clearly shows that fragmentation is a high energy process. The double branched shape of the curve obtained at the lower energies has generally been attributed to the fact that ^{24}Na is a spallation residue from copper.[30,40] While the spallation yield appears to become nearly independent of energy by 3 GeV, the fragmentation yield continues to increase. Consequently, the double branched curve eventually gives way to a monotonic increase of σ with A_T. The fact that silver lies on the left branch of the curve at the lower energies probably reflects the contribution of binary fission to ^{24}Na production.[41] The fission cross section of the less fissile elements has a broad peak in the vicinity of 3 GeV.[42] The increase in the yield of ^{24}Na from silver observed above this energy presumably reflects the increasing fragmentation cross section, the same as for the heavier target elements.

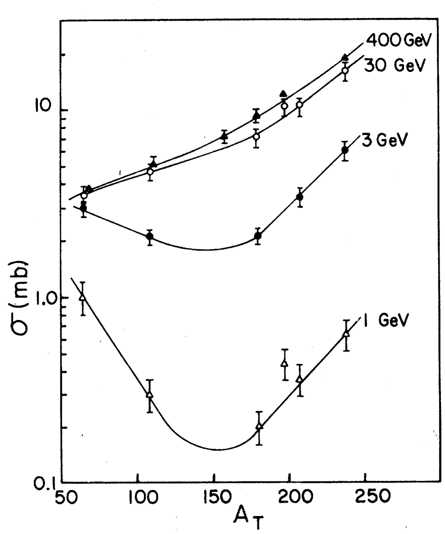

FIG. 7. Dependence of the ^{24}Na production cross section on target A at the indicated proton bombarding energies. The data for 1–30 GeV protons are from Refs. 21 and 25.

The present results closely resemble the 30 GeV data. However, while the cross section for ^{24}Na production from copper is essentially equal at the two energies, the yield from the heavier elements increases by an additional 20% between 30 and 400 GeV. Evidently, the limiting fragmentation regime has not as yet been attained by 30 GeV for light fragment production. This fact bears on the previously discussed enhancement in fragment yields observed in ^{12}C induced reactions. Since product yields in RHI reactions depend on the total projectile energy rather than on the energy per nucleon,[2,4] the proton results suggest that the fragment yields from the heavier target elements should continue to increase with ^{12}C bombarding energy, in accord with the trend displayed in Fig. 5.

Although the emission of fragments in high energy reactions has been extensively studied for over two decades, the reaction mechanism is still not well understood. The angular distributions of fragments in the moving system defined by the Doppler shift in the energy spectra have been found to be asymmetric,[43–46] an indication of a fast process. On the other hand, fragment yields are consistent with evaporation calculations,[22,24,47] showing that the process is sufficiently slow to permit at least partial statistical equilibration. Similar features have more recently been exhibited by the products of deep inelastic transfer reactions induced by heavy ions.[48] The statistical features of the isotopic yields are displayed by the Qgg systematics.[49] A modified version of this analysis has recently been applied to the yields of fragments emitted in high energy proton reactions.[50] It is of interest to explore the applicability of this approach to the present data.

The isotopic yields have been fitted by the relation

$$\sigma = C \exp(Qgg/T), \qquad (2)$$

where $Qgg = M_F - M_1 - M_2$ and C is a constant. The subscripts on the masses defining Qgg refer to the fragmenting nucleus (F), the observed fragment (1), and the complementary fragment (2). We are interested here in the variation of the yield of a particular fragment with target A. This makes it necessary to reduce Qgg by the value of the effective Coulomb barrier, $kB = kZ_1Z_2e^2/(R_1+R_2)$, which exhibits a strong dependence on target A. The constant k is a barrier reduction factor which takes into account the fact that the classical barrier overestimates the minimum energy of the fragments.[44,45,51] If the nuclear temperature is assumed to be the same for all targets, an assumption that is supported by fragment spectra,[45,52] the cross section is given by the expression

$$\sigma = CA_T{}^{2/3}\exp[(Qgg - kB)/T], \qquad (3)$$

where the $A_T{}^{2/3}$ factor accounts for the variation of the total reaction cross section with target A.

In order to evaluate Qgg the identity of the emitting nucleus must be known. While little is known about the distribution of emitting nuclei in high energy reactions, the results turn out to be moderately insensitive to the assumed values provided that N/Z is kept essentially constant. This is not surprising in view of the fact that the fragment separation energies depend strongly on the composition of the emitting nucleus while varying relatively slowly with its mass number. The results presented below are based on the assumption of a 20% loss in charge and mass prior to fragmentation, a value that is consistant with estimates based on spectral measurements.[52] The assumed value of k is coupled to the choice of emitting nucleus. To first order, it is possible to obtain comparable fits to fragment spectra with evaporation calculations that assume either a light emitting nucleus and a large k, or a heavier emitter and smaller k.[45,51] We have chosen a fairly large value, $k = 0.7$, consistent with the rather light emitting nuclei suggested by the Fermilab data.[52] The Coulomb barrier was evaluated for $r_0 = 1.44$ fm.

The cross sections of ^{48}Sc and ^{52}Mn are plotted in the form of Eq. (3) in Fig. 8. We have chosen these particular fragments because their yields represent independent formation and thus permit an unambiguous evaluation of Qgg and kB. Qualitatively similar results are obtained for the cumulatively formed products indicating, perhaps, that the changes in isobaric yield distribution with increasing target A are not severe.[53] The data for the copper target are not included in the plot. The

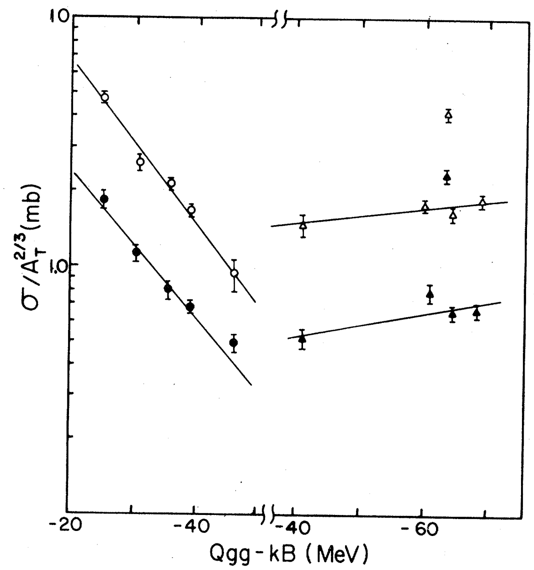

FIG. 8. Modified Qgg systematics for the formation of ^{48}Sc (circles) and ^{52}Mn (triangles) in the interaction of 400 GeV protons (closed points) and 18.5 GeV ^{12}C ions (open points) with Ag-U. The values of $A_T{}^{2/3}$ have been normalized to unity for Ag.

small mass difference between the products in question and copper indicates that they are formed as spallation residues, a fact supported by their much higher production cross sections from this target.

The results for neutron excess ^{48}Sc are consistent with the modified Qgg systematics for both ^{12}C and proton bombardment. Both sets of data lead to a temperature of approximately 14 MeV. Perhaps fortuitously, this value is in agreement with that extracted from the energy spectra of fragments emitted in high energy reactions.[45,51,52] The other neutron-excess fragments observed in this study yield generally similar results. We have also examined the correlation between σ and Qgg, that is, without the barrier modification. We were motivated by the fact that the spectra of Sc fragments from 400 GeV proton interactions with uranium suggest that there may be practically no barrier to the emission of these fragments.[51] It is found that the cross sections maintain their exponential decrease with Qgg but the temperature is now much higher, approximately 35 MeV.

The results for neutron deficient ^{52}Mn are in sharp contrast to those obtained for ^{48}Sc. It is seen that the Qgg systematics are not obeyed at all for this fragment. The other neutron deficient fragments observed in this study, ^{44}Sc^m, and ^{48}V, display a similar behavior. We have explored whether various changes in the nature of the assumed emitting nuclei, e.g., neutron deficient emitters, can improve the situation. This does not appear to be possible as long as all targets are treated uniformly with respect to the dissipation of mass and charge prior to breakup. It appears that another mechanism must be of importance in the formation of neutron deficient fragments. The high ^{52}Mn yield from silver suggests that this product is formed as a spallation residue and this may to some extent also be the case for the heavier targets.

If the neutron deficient products in the $A \sim 40-50$ mass range are formed by a different mechanism than the neutron excess ones, some differences in kinematic properties should presumably be observable. For instance, the kinetic energy of the neutron deficient products should be smaller. The extensive body of data reported for scandium nuclides formed in the interaction of ^{238}U with high-energy protons suggests that such differences, while in the correct direction, are minor.[28,46,51,54] Unfortunately, the information available for lighter targets at high energies is too sparse to permit any firm conclusions to be drawn.

V. CONCLUSIONS

The applicability of the factorization hypothesis to the emission of fragments with $A = 24-52$ in the interaction of 18.5 GeV ^{12}C ions and protons with target nuclei ranging from copper to uranium has been tested. It is found that factorization holds only for copper, enhanced fragment yields as high as 100% being observed in ^{12}C reactions with the heavier targets. The enhancement increases with decreasing fragment mass and with increasing target mass up to $A \sim 160$, at which point the effect appears to saturate. It is postulated that this saturation arises from the fact that fragment yields from the interaction of ^{12}C with the heavier elements are still increasing with bombarding energy in this regime. A geometrical estimate based on complete target-projectile overlap in central collisions suggests that the enhancement factor should continue to increase with target A. It would be of interest to determine whether this is indeed the case at sufficiently high energies for limiting fragmentation to be applicable.

The variation of fragment yield with target A has been examined. The neutron excess fragments obey modified Qgg systematics, suggesting that partial statistical equilibrium may occur prior to fragment emission. On the other hand, the neutron deficient fragments do not show this behavior indicating that a different mechanism must be involved. It is suggested that these fragments are, at least in part, formed as spallation residues.

ACKNOWLEDGEMENTS

The assistance of Dr. W. Everette with the operation of the ion chamber at the Bevalac, and that of Dr. S. Baker with the radioactivity measurements at Fermilab are gratefully acknowledged. This work was supported financially by the Department of Energy.

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*Present adress: Central Radioanalytical Facility, Commonwealth Edison Company, Maywood, Ill. 60153.

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