Fragmentation cross sections of ^{28}Si at 14.5 GeV/nucleon

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We used CR39 plastic nuclear track detectors ($C_{12}H_{18}O_7$) in combination with automatic track measurement techniques to determine total charge changing and partial cross sections for the production of fragments of charge $Z_F=6$ to $Z_F=13$ in collisions of ^{28}Si beam nuclei at 14.5 GeV/nucleon in targets H, C, CR39, ($C_{18}H_{38}O$), Al, Cu, Ag, and Pb. By application of factorization rules, measured partial cross sections are separated into pure nuclear and electromagnetic components. The cross sections for electromagnetic dissociation agree with theoretical models. The results are consistent with a Z^2 dependence of virtual photon spectra.

INTRODUCTION

The results presented in this paper are part of an investigation of interactions of heavy-ion projectiles at different energies in various targets. After an analysis of ^{32}S fragmentation at 0.7, 1.2, and 200 GeV/nucleon[1,2] and of ^{16}O fragmentation of 60 and 200 GeV/nucleon[3] we investigated fragmentation of ^{28}Si at 14.5 GeV/nucleon. These results are presented and discussed in this paper. In comparison to the recent experiments of Hill *et al.*,[4] our experiments are sensitive not only to the increasing intensity but also to the harder quality of the virtual photon spectra at ultrarelativistic energies. This is shown by the detection of electromagnetic dissociation (ED) events with $\Delta Z \geq 3$. Details of our experimental method are given in Ref. 1.

RESULTS

Total charge changing cross sections and elemental fragmentation cross sections for the production of fragments of charge $Z_F=6$ to $Z_F=13$ from ^{28}Si projectiles in the targets H, C, ($C_{18}H_{38}O$), CR39, Al, Cu, Ag, and Pb at 14.5 GeV/nucleon are listed in Table I. The cross sections for hydrogen targets are determined using the measurements in ($C_{18}H_{38}O$) and C.

Total charge changing cross sections

The contribution by ED to the experimentally measured total charge changing cross section σ^{tot} (Table I) can be determined by subtracting the pure nuclear component $\sigma_{em}^{tot}=\sigma^{tot}-\sigma_{nuc}^{tot}$. Experimental results of σ^{tot} for ^{28}Si at lower energies where the ED contribution is negligible are not available. To determine σ_{nuc}^{tot} for ^{28}Si projectiles in collisions on different targets we applied a model similar to the soft-sphere model of Karol[5] which was adjusted to fit total pure nuclear cross sections obtained from our experiments with ^{16}O and ^{32}S projectiles.[2,3]

For this purpose we selected measured cross sections with only a small electromagnetic contribution, i.e., low-energy data at 0.7 or 1.2 GeV/nucleon with targets C, Al, Cu, and Ag for ^{32}S beam nuclei and data measured with small target charges (C or Al) at higher energies for ^{16}O and ^{32}S beam nuclei. By subtraction (not negligence) of the electromagnetic contribution which we calculated for these cases, pure nuclear cross sections σ_{nuc}^{tot} could be obtained. The model assumes that there is no energy dependence of the nuclear component of the total cross sections for energies above our lowest-measured energy 0.7 GeV/nucleon. This assumption can be justified by comparison of the pure nuclear cross sections obtained for ^{32}S projectiles colliding on C target at 0.7 and 200 GeV/nucleon. These cross sections agree within the statistical error of less than 2%. For Al target a similar comparison at 1.2 and 200 GeV/Nucleon gives agreement within 3%. For ^{16}O projectiles at 60 and 200 GeV/nucleon colliding with C or Al targets, total nuclear cross sections agree within 2%. An independence from energy in these limits in the energy range from 0.7 up to 200 GeV/nucleon is also predicted by the Karol model,[5] which incorporates the energy dependence of nucleon-nucleon cross sections.

The next step was the calibration of the model so that our pure nuclear cross sections for ^{16}O and ^{32}S were reproduced and to use this model for the prediction of unknown cross sections of ^{28}Si. The total nuclear cross section was calculated as

$$\sigma_{nuc}^{tot}=2\pi\int_0^\infty [1-T(r)]r\,dr \ ,$$

$T(r)$ being the probability that at impact parameter r the projectile will pass through the target without interaction. It is calculated by numerical integration of the overlap, assuming for projectile and target nuclei a spherical shape of radius $R=r_0 A^{1/3}$, a homogeneous nuclear density, and a constant mean free path λ of nucleons in nuclear matter. The Karol model is similar to our calculation but uses Gaussian shaped nuclear densities. The Karol model may be more realistic but our simple model is easy to use. We adjusted the two parameters r_0 and λ of our model to fit our data for ^{16}O and ^{32}S. The subsequent prediction of pure nuclear cross sections for ^{28}Si using this model is in fact only a slight scaling of our data for ^{32}S projectiles. Calculated total pure nuclear cross sections $\sigma_{\rm nuc}^{\rm tot}$ and total ED cross sections determined by $\sigma_{\rm em}^{\rm tot}=\sigma^{\rm tot}-\sigma_{\rm nuc}^{\rm tot}$ are listed in the second column of Table II for ^{28}Si projectiles.

We calculated total charge changing ED cross sections $\sigma_{\rm emc}^{\rm tot}$ based on the theoretical model of Bertulani and Baur[6] using their virtual photon spectra[7] and the relation

$$\sigma_{\rm emc}^{\rm tot}=\int_0^{\infty} n(E_\gamma)\sigma_\gamma(E_\gamma)dE_\gamma \ .$$

In practice, we used an upper limit of the integration which is significantly beyond the onset of the exponential decrease of the virtual-photon spectrum at about $E_\gamma=350$ MeV for 14.5 GeV/nucleon projectile energy.

The photon spectrum weighted according to an estimation for the relative strength of the giant dipole and quadrupole resonance is $n=0.96n_{E1}+0.04n_{E2}$.[8] The only adjustable parameter is the minimum impact parameter at which ED can occur without interference by strong nuclear interaction. We derive it from the total charge changing pure nuclear cross section (Table II): $b_{\rm min}=(\sigma_{\rm nuc}^{\rm tot}/\pi)^{1/2}$.

$\sigma_\gamma(E_\gamma)$ is the cross section for the absorption of a photon of energy E_γ by a ^{28}Si nucleus and subsequent decay by emission of at least one particle of positive charge. Photo cross sections σ_γ were measured in different experiments using beams of real photons. We determined the charge changing photo cross section as the difference between total photon absorption cross section[9–14] and the cross section for the emission of only neutrons[15–17] (Fig. 1). p and α emission cross sections[18,19] were found to be consistent with this difference in the giant resonance region. Details of the calculation of $\sigma_{\rm emc}^{\rm tot}$ are given in Ref. 3.

The resulting total charge changing ED cross sections obtained by calculation $\sigma_{\rm emc}^{\rm tot}$ are included in the third column of Table II. We estimate the error due to uncertainties in σ_γ to be $\Delta\sigma_{\rm emc}/\sigma_{emc}\approx 8\%$. An increase of the relative strength of the giant quadrupole resonance from 0.04 to 0.05 would increase $\sigma_{\rm emc}^{\rm tot}$ by 0.5%.

Partial cross sections

For a more detailed understanding of how the strong nuclear and the electromagnetic interaction contribute to the process of fragmentation, we tried to separate the measured partial cross sections $\sigma(P,T,F)$ for the production of a fragment F in a collision of a projectile P on a target T into a pure nuclear and an ED component:

$$\sigma(P,T,F)=\sigma_{\rm nuc}(P,T,F)+\sigma_{\rm em}(P,T,F) \ .$$

For this purpose, we assumed that both cross-section components factorize so that

$$\sigma_{\rm nuc}(P,T,F)=\gamma_{PT}\gamma_P^F$$

and

TABLE I. Experimental total charge changing and elemental fragmentation cross sections (mb) for the production of fragments of charge $Z_F=6$ to $Z_F=13$ from ^{28}Si projectiles at 14.5 GeV/nucleon for different targets.

Fragment charge	Target							
	H	$C_{18}H_{38}O$	$C_{12}H_{18}O_7$	C	Al	Cu	Ag	Pb
6	40.1±7.2	48.8±2.9	58.5±4.2	65.7±11.4	88.3±6.0	116.1±9.3	135.0±13.0	178.0±18.0
7	23.5±4.2	33.9±2.3	41.1±2.9	54.2±5.2	55.1±4.1	82.0±7.7	73.0±11.0	108.0±15.0
8	30.0±4.9	45.8±2.7	51.2±2.9	76.8±5.6	74.6±4.7	104.0±8.1	133.0±12.0	138.0±16.0
9	8.5±3.4	19.8±1.8	24.8±2.0	42.0±4.1	39.7±3.3	53.9±5.5	48.0±8.0	96.0±13.0
10	30.5±4.7	42.2±2.6	49.1±2.8	65.1±5.1	73.2±4.5	81.3±6.9	113.0±10.0	126.0±15.0
11	28.5±4.6	37.9±2.6	48.5±2.8	56.2±4.7	67.6±4.4	79.2±6.9	116.0±11.0	125.0±16.0
12	58.0±6.5	77.9±3.7	83.2±3.6	116.7±6.9	137.8±6.2	190.2±10.5	237.0±15.0	441.0±28.0
13	62.8±6.3	77.8±3.6	83.1±3.4	107.0±7.4	142.5±6.2	288.4±14.3	489.0±20.0	1039.0±41.0
$\sigma^{\rm tot}$	388.0±24.0	657.0±13.0	823.0±16.0	1185.0±30.0	1620.0±25.0	2457.0±59.0	3121.0±52.0	4992.0±99.0

TABLE II. Total charge changing pure nuclear cross section $\sigma_{\text{nuc}}^{\text{tot}}$, calculated ED cross section $\sigma_{\text{emc}}^{\text{tot}}$, and measured ED cross section $\sigma_{\text{em}}^{\text{tot}}$ at 14.5 GeV/nucleon. All cross sections are given in mb. For details see text.

Target	$\sigma_{\text{nuc}}^{\text{tot}}$	$\sigma_{\text{em}}^{\text{tot}}$	$\sigma_{\text{emc}}^{\text{tot}}$
C	1173±36	12±47	10
Al	1581±47	39±53	41
Cu	2243±63	216±86	185
Ag	2817±91	300±110	455
Pb	3800±140	1190±170	1265

$$\sigma_{\text{em}}(P,T,F)=\epsilon_{PT}\epsilon_P^F .$$

γ_P^F and ϵ_P^F are proportional to the probability for the production of a fragment F in collisions induced by strong and electromagnetic interaction. They reflect intrinsic properties of the projectile P, which are not known *a priori* and have to be extracted by the following analysis. γ_{PT} and ϵ_{PT} are factors which scale the cross section according to the target T. Detailed arguments for the concept of factorization of σ_{nuc} and σ_{em} are given in Ref. 2, and only the conclusions are repeated here.

In pure nuclear interactions as a prediction of a simple geometrical model γ_{PT} should be proportional to the impact parameter b_p for peripheral collisions.[20] We take the square root of the total nuclear cross section $(\sigma_{\text{nuc}}^{\text{tot}}/\pi)^{1/2}$ from Table II as a suitable value for b_p and normalize arbitrarily on C target

$$\gamma_{PT}=[\sigma_{\text{nuc}}^{\text{tot}}(P,T)]^{1/2}/[\sigma_{\text{nuc}}^{\text{tot}}(P,T=C)]^{1/2} .$$

Since in a good approximation virtual photon spectra for different targets do not differ in shape but only in intensity, the fragmentation probabilities and therefore ϵ_P^F should not change from target to target. ED cross sections σ_{em} should scale with the intensity of the virtual photons. We assume that the calculated total ED cross sections provide the best estimation for the relative intensities from target to target and define the normalized target factor

$$\epsilon_{PT}=\sigma_{\text{emc}}^{\text{tot}}(P,T)/\sigma_{\text{emc}}^{\text{tot}}(P,T=C) .$$

γ_{PT} and ϵ_{PT} are given in Table III.

A least-squares fit of

$$\sigma_{\text{nuc}}(P,T,F)+\sigma_{\text{em}}(P,T,F)=\gamma_{PT}\gamma_P^F+\epsilon_{PT}\epsilon_P^F$$

to the measured cross sections $\sigma(P,T,F)$ (Table I), with γ_P^F and ϵ_P^F as adjustable parameters and fixed γ_{PT} and ϵ_{PT}, is possible with a value of $\chi^2=28.7$ for 24 degrees of freedom. Data for C, Al, Cu, Ag, and Pb targets were used for the fit. Similar to the analysis of the fragmentation of ^{32}S at 200 GeV/nucleon,[2] also in this experiment the concept of double factorization is not in contradiction with our data. γ_P^F and ϵ_P^F as obtained by the fit are given in Table IV.

Figure 2 shows partial cross sections σ_{nuc} and σ_{em} vs fragment charge Z_F. Similarly to the ^{32}S projectile, production of fragments with $\Delta Z \geq 3$ by ED is observed. ED cross sections for $Z_F=12$ and 13 exhaust 93% of $\sigma_{\text{em}}^{\text{tot}}$, while photons of energy $E_\gamma \leq 70$ MeV exhaust 92% of $\sigma_{\text{emc}}^{\text{tot}}$ by excitation and decay of giant resonances. This may indicate that photons of $E_\gamma \geq 70$ MeV are preferably responsible for fragmentations of ^{28}Si with $\Delta Z \geq 3$ due to ED.

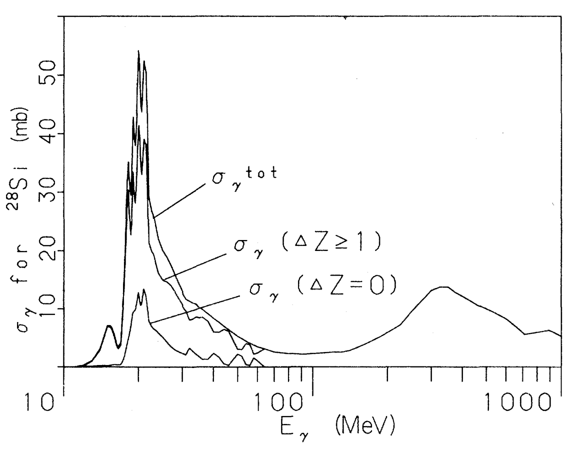

FIG. 1. Photonuclear cross sections σ_γ for ^{28}Si as a function of photon energy E_γ used in our calculation of $\sigma_{\text{emc}}^{\text{tot}}$. Data are sampled and combined from experiments referenced in the text. The upper curve shows $\sigma_\gamma^{\text{tot}}$. The lower curve for $\sigma_\gamma(\Delta Z=0)$ was obtained as a mean of three experiments referenced in the text which were sensitive to neutrons. The charge changing photo cross section $\sigma_\gamma(\Delta Z\geq 1)$ that was used in our calculations is plotted as the difference $\sigma_\gamma^{\text{tot}}-\sigma_\gamma(\Delta Z=0)$.

TABLE III. Pure nuclear target factor γ_{PT} and ED target factor ϵ_{PT} for ^{28}Si projectiles at 14.5 GeV/nucleon for different targets.

Target	γ_{PT}	ϵ_{PT}
C	1.00	1.0
Al	1.16	4.2
Cu	1.38	19.3
Ag	1.55	47.5
Pb	1.80	132.2

Cross sections in hydrogen

Cross sections in hydrogen target are a special point of astrophysical interest, since they are responsible for the

TABLE IV. Pure nuclear fragment factor γ_P^F and ED fragment factor ϵ_P^F at 14.5 GeV/nucleon for fragment charges $Z_F=6$ to $Z_F=13$. All fragment factors are given in mb.

Fragment charge	γ_P^F	ϵ_P^F
6	75.0±4.3	0.36±0.15
7	50.4±2.8	0.11±0.12
8	70.1±3.1	0.17±0.13
9	35.7±2.2	0.14±0.10
10	62.6±2.9	0.12±0.12
11	57.0±2.8	0.24±0.12
12	112.7±4.1	1.66±0.20
13	101.4±4.4	6.73±0.27

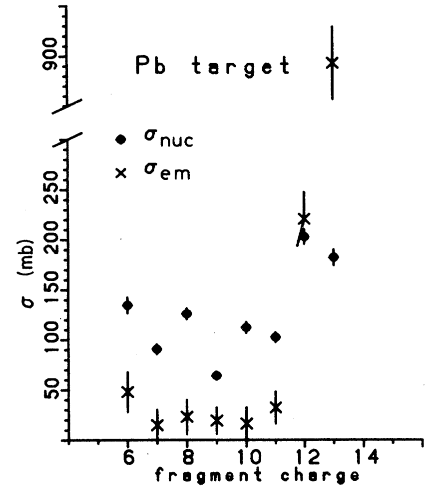

FIG. 2. Partial pure nuclear cross sections $\sigma_{\rm nuc}(P,T,F)=\gamma_{PT}\gamma_P^F$ (crosses) and partial ED cross sections $\sigma_{\rm em}(P,T,F)=\epsilon_{PT}\epsilon_P^F$ (circles) for the production of a fragment of charge Z_F in a collision of ^{28}Si projectile nuclei on Pb target. The measured cross sections were separated into $\sigma_{\rm nuc}$ and $\sigma_{\rm em}$ based on the assumption that both components follow factorization (see text).

change of the elemental composition of the cosmic radiation on their way from the sources to earth. ED effects are not significant for hydrogen target. We tested the partial cross sections for hydrogen target for factorization. Figure 3 (upper part) shows the ratio $R_1=\sigma(P,T=H,F)/\gamma_P^F$ which should give $\gamma_{P,T=H}$ as a constant value if factorization is also valid for this target. We obtained $\gamma_{P,T=H}=0.49$ ($\chi^2=11.7$ at 7 degrees of freedom). Obviously, deviations from factorization remain still at 14.5 GeV/nucleon for hydrogen target.

Partial cross sections in hydrogen obtained using the

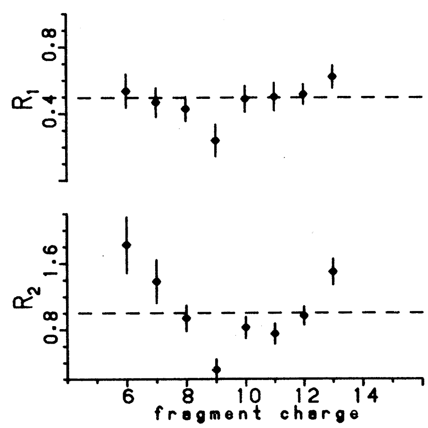

FIG. 3. Ratio $R_1=\sigma(P,T=H,F)/\gamma_P^F$ vs fragment charge Z_F (upper part). $\sigma(P,T=H,F)$ is the partial cross section measured for hydrogen target (Table I); γ_P^F is the pure nuclear fragment factor (Table III). Ratio $R_2=\sigma(P,T=H,F)/\sigma_{ST}(P,T=H,F)$ vs fragment charge Z_F (lower part). σ_{ST} is the prediction from the semiempirical formulas of Silberberg and Tsao (Ref. 21).

semiempirical formula of Silberberg and Tsao[21] are calculated for 14.5 GeV. Figure 3 (lower part) shows the ratio R_2 of these values with our experimental ones, which exhibits significant discrepancies up to 60%.

Total charge changing cross sections of 385 to 411 mb measured by Webber[23] at 503 to 1296 MeV/nucleon are in agreement with our value of 388±24 mb. The semiempirical formula of Letaw *et al.*[22] gives total mass changing cross sections. By subtraction of the $\Delta Z=0$ cross section[21] a total charge changing cross section of 434 mb beyond 2 GeV/nucleon was evaluated, which is too large by 10% compared to the experimental data.

CONCLUDING REMARKS

A recent investigation of Hill *et al.*[4] gave reason to believe that essentials of the electromagnetic interaction in relativistic heavy-ion collisions are not yet fully understood. Therefore we will concentrate in this conclusion on a comparison of experimental results for the electromagnetic dissociation cross section with calculations based on the virtual-photon method. In addition to the results published in this paper, we considered our earlier experiments with ^{32}S projectiles at 200 GeV/nucleon (Ref. 3) and ^{16}O projectiles at 60 and 200 GeV/nucleon (Ref. 2). Figure 4 shows the comparison of the experimental total charge changing electromagnetic cross section $\sigma_{\rm em}^{\rm tot}$ with calculated values $\sigma_{\rm emc}^{\rm tot}$. We considered only data for Pb targets, which have the greatest significance. We can exclude discrepancies in the order of about 30% as observed by Hill *et al.*[4] A general agreement between experiment and calculation is found.

Encouraged by these results, we tried to resolve the

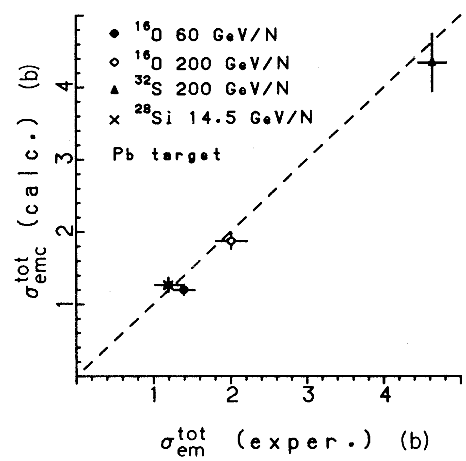

FIG. 4. Comparison of total charge changing electromagnetic dissociation cross sections. Abscissa: $\sigma_{\rm em}^{\rm tot}$ derived from our experimental cross sections by subtraction of the nuclear component. Uncertainties of the experimental values and of the nuclear component are considered by the horizontal error bars. Ordinate: $\sigma_{\rm emc}^{\rm tot}$ calculated by the virtual photon method using experimental measurements of photonuclear cross sections σ_γ. The errors shown as vertical bars are mainly caused by uncertainties of σ_γ. A dashed line is shown at $\sigma_{\rm em}^{\rm tot}=\sigma_{\rm emc}^{\rm tot}$. For details see text and Refs. 2 and 3.

discrepancies between calculation and experiment reported by Hill *et al.*,[4] who investigated the electromagnetic dissociation $^{197}Au \rightarrow {}^{196}Au$ by relativistic heavy ions. These authors reported an experimental value

$$\sigma_{em}[{}^{197}Au({}^{139}La \text{ at } 1.26 \text{ GeV/nucleon}, X){}^{196}Au] ,$$

which is significantly smaller, and a value

$$\sigma_{em}[{}^{197}Au({}^{16}O \text{ at } 200 \text{ GeV/nucleon}, X){}^{196}Au] ,$$

which is significantly greater than expected by calculation. We confirmed the calculation made by Hill *et al.* When applying some refinements as recoil corrections, contribution of photons at distances smaller than the minimum-impact parameter b_{min}, contribution of $E2$ excitations, multiple excitation in one collision, and the possibility that the emission of one neutron can also be caused by excitation of nucleon resonances and not only by giant resonances, we calculated results different from Ref. 4, but none of these points could explain both of the discrepancies in the observed magnitude.

It should be noted that our results are not necessarily in contradiction to those of Hill *et al.* There may be an unknown effect which increases the electromagnetic dissociation cross section for very high energies and decreases it for large photon generating charges. Such an effect could be responsible for the observations of Hill *et al.*[4] The consequences of this effect could, possibly, mutually cancel so that our results for high energy and Pb target agree with the calculation based on the usual model. For energies in the order of only a few GeV/nucleon or for smaller target charges our results for σ_{em}^{tot} have insufficient significance. Furthermore, it should be considered that we cannot compare calculated and experimental electromagnetic cross sections for a special reaction channel (e.g., $\Delta Z = 1$) since experimental $\sigma_\gamma(E_\gamma)$ for these channels are not available throughout the whole range of expected photon energies. This is also true for the experiments of Hill *et al.* at 60 and 200 GeV/nucleon, but probably not very important for the emission of only one neutron by a heavy nucleus such as ^{197}Au, since the contribution of the giant dipole resonance is dominating.

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