Electromagnetic Spallation of 6.4-TeV ^{32}S Nuclei

P. B. Price, Ren Guoxiao,[a] and W. T. Williams
Physics Department, University of California, Berkeley, California 94720
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We have studied the fragmentation of 6.4-TeV ^{32}S nuclei in Pb, Cu, and Al targets. For Pb, the electromagnetic spallation cross sections are larger than the nuclear cross sections. For Pb and Cu the electromagnetic cross sections decrease with projectile charge loss ΔZ as $\sim\exp(0.6\Delta Z)$ and show a dependence on target charge consistent with $\sim Z_T^{1.8}$ as predicted by theory.

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In central nucleus-nucleus collisions at ultrarelativistic energies, now available at Brookhaven and CERN, one expects to see interesting effects when an ultrarelativistic nucleus experiences a very strong electromagnetic field as it passes a target nucleus at distances outside the range of the nuclear force.[1] We report here experiments showing that some of the partial cross sections for projectile fragmentation, due to the long-range electromagnetic field of a heavy target nucleus, are an order of magnitude higher than for fragmentation due to short-range nuclear forces. Thus, if one is searching for exotic forms of nuclear matter in ultrarelativistic collisions, one must recognize that the majority of fragments may constitute a background of normal matter that did not originate in the overlap of two nuclei.

Electromagnetic dissociation, with the removal of one or two neutrons or a proton from the *projectile,* has been seen in interactions of 2.1-GeV/N ^{12}C and ^{16}O (Ref. 2), 1.7-GeV/N ^{18}O (Ref. 3), and 1.88-GeV/N Fe (Ref. 4) with heavy targets; and electromagnetic dissociation, with the removal of one neutron from the *target,* has been studied in interactions of $\sim$2-GeV/N C, Ne, Ar, and Fe nuclei with ^{59}Co, ^{89}Y, and ^{197}Au targets,[5] and in interactions of 1.26-GeV/N La nuclei and of ^{16}O nuclei at energies up to 200 GeV/N with a ^{197}Au target.[6] In the classical model of Weiszacker and Williams,[7] the rapidly time-varying electromagnetic field seen by a projectile and because of a point target nucleus is represented by a spectrum of virtual photons whose number per unit energy interval depends on photon energy E_γ and projectile Lorentz factor γ approximately as

$$dN/dE_\gamma \approx 2Z_T^2\alpha/(\pi E_\gamma \beta^2) \times [\ln(1.123E_{\gamma,\max}/E_\gamma) - \beta^2/2] , \qquad (1)$$

out to an adiabatic cutoff energy $E_{\gamma,\max} \approx \hbar c\beta\gamma/R$, where R is the sum of touching radii of target and projectile. Beyond the cutoff energy, dN/dE_γ falls off as $\sim\exp(-2E_\gamma/E_{\gamma,\max})$. (To estimate the spectrum of virtual photons seen by the target nucleus, replace Z_T by Z_P, the projectile charge.) When one takes into account the mild dependence of $\ln E_{\gamma,\max}$ on Z_T through the radius R, the intensity of virtual photons should go as $\sim Z_T^{1.8}$, as shown in Ref. 3. To calculate the cross section for a particular mode of electromagnetic dissociation, one integrates the energy-dependent cross section for that mode of photodissociation over dN/dE_γ. At Bevalac energies, $\sim$2 GeV/N, $E_{\gamma,\max} \approx 40$ MeV. Photons with energies below 40 MeV interact with nuclei mainly through the giant dipole resonance; heavy nuclei decay mainly by emission of one neutron whereas lighter nuclei, with lower Coulomb barriers, may also emit a proton. The virtual-photon description fits most of the observations at 2 GeV/N rather well.

At 200 GeV/N, the maximum energy available for heavy ions at CERN, $E_{\gamma,\max} \approx 4$ GeV, is far above the photomeson threshold. A large fraction of the virtual photons have a wavelength $\lesssim 1$ fm and can thus interact with a single nucleon, exciting a Δ resonance, which decays into a nucleon and a pion, either of which can initiate a two-step process of intranuclear cascade plus evaporation similar to that seen in proton interactions. Photospallation of nuclei in the bremsstrahlung beams of electron accelerators has been studied for nearly 30 yr.[8-12]

We have used track-recording sheets of CR-39 plastic ($H_{18}C_{12}O_7$) to measure the charges of nuclear fragments produced in the CERN superproton synchrotron in interactions of 200-GeV/N ^{32}S with Pb, Cu, and Al. The target thicknesses, as a fraction of a total interaction length, were 0.15 for Cu, 0.34 for Pb, and 0.3 for Al. One sheet placed in front of a target was used to select tracks of beam particles; these tracks were followed by a computer-controlled, automated scanning and measuring system into the sheets in a stack in back of the target.[13] We studied interactions in the target that led to projectile fragments, i.e., fragments with almost exactly the rapidity and direction of the beam. The plastic sheets, $\sim$740 μm thick, were etched in NaOH solution to produce conical etch pits at the points of intersection of the trajectories of highly charged particles with the top and bottom surfaces. The charge was determined from the average of measurements of four etch-pit diameters, with a standard deviation less than 0.1 charge unit. Figure 1 shows the charge distribution for fragmentation of ^{32}S in the Pb target.

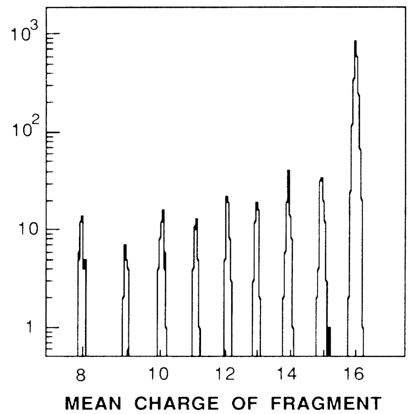

FIG. 1. Distribution of charges of fragments of 6.4-TeV ^{32}S nuclei with about the same rapidity and direction as the beam produced in a Pb target. For method, see Ref. 13.

Table I gives $\sigma(^{32}\mathrm{S},T)$, the total cross section for loss of one or more charge units in collisions of ^{32}S with a target T, and the partial cross sections $\sigma(^{32}\mathrm{S},T,Z_F)$ for fragmentation of ^{32}S into nuclei with $Z_F=8$ to 15. The values of $\sigma(^{32}\mathrm{S},T,Z_F)$ for a hydrogen target come from the semiempirical expressions of Silberberg, Tsao, and Letaw[14] (given for a Lorentz frame in which protons interact with various target nuclei), which fit all measured cross-section data to within $\sim$20%. To correct partial cross sections for loss of fragments within the target, we used the expression for cross section in a thick target given by

$$\sigma(^{32}\mathrm{S},T,Z_F)=N(Z_F,y)A/N(^{32}\mathrm{S},y)N_{\mathrm{A}}\rho y\,, \qquad (2)$$

where $N(^{32}\mathrm{S},y)$ and $N(Z_F,y)$ are the number of surviving ^{32}S nuclei and of fragments Z_F at depth y, N_{A} is Avogadro's number, and ρ and A are the density and atomic number of the target. This expression differs from the simple exponential relation for production in a thin target; it is valid for a thick target when the total charge-changing cross sections for ^{32}S and Z_F are equal. We estimate that even if they differed by as much as 50%, Eq. (2) would be correct to within 10%. For total cross section in a thick target the usual exponential absorption equation is valid.

We find that the total and partial cross sections for projectile fragmentation in heavy targets are much higher at 200 GeV/N than at Bevalac energies ($\sim$1 to 2 GeV/N), and we attribute the increase to electromagnetic spallation.

Following the same procedure carried out by others,[2-6] we assume the cross section for electromagnetic spallation (ES) to a fragment Z_F to be the difference between our measured partial cross section to Z_F and the cross section for nuclear spallation (NS) to Z_F. This procedure assumes that nuclear spallation occurs at impact parameters less than R and that electromagnetic spallation occurs at impact parameters greater than R, with no interference. We will briefly discuss the ES contribution to the total charge-changing cross section and discuss in more detail the ES contribution to partial cross sections. To calculate the NS contribution to the total charge-changing cross section, we start with the semiempirical expression as a result of Westfall *et al.*,[4] which fitted data obtained at 1 to 2 GeV/N for projectiles and targets of mass $A_P \gtrsim 12$ and $A_T \gtrsim 12$:

$$\sigma_{\mathrm{NS}}(P,T)=\pi[r_0(A_P^{1/3}+A_T^{1/3}-b)]^2\,, \qquad (3)$$

where $r_0=1.35$ fm and $b=0.83$. In order for this same expression to be valid for a hydrogen target, they had to choose $A_T=0.089$. According to Karol's soft-spheres

TABLE I. Experimental total charge-changing $[\sigma(^{32}\mathrm{S},T)]$ and partial $[\sigma(^{32}\mathrm{S},T,Z_F)]$ cross sections (mb) for breakup of 200-GeV/N ^{32}S into fragments with $Z_F=8$ to 15.

Cross section	Z_F	$T=$Pb	Cu	Al	H [a]	$\gamma_{\mathrm{Al}}/\gamma_{\mathrm{H}}$
$\sigma(^{32}\mathrm{S},T)$	≤ 15	8770 ± 110	3250 ± 150	2000 ± 50	...	...
σ_{NS}[Eq. (3)]	≤ 15	3950	2400	1800	450	...
$\sigma_{\mathrm{ES}}=\sigma-\sigma_{\mathrm{NS}}$	≤ 15	4820	850	200	...	...
σ_{ES}(if $\propto Z_T^{1.8}$)	≤ 15	$\equiv 4820$	742	175	...	...
$\sigma(^{32}\mathrm{S},T,Z_F)$	8	218 ± 19	93 ± 7	110 ± 10	24 ± 5	4.6 ± 1.0 [c]
	9	120 ± 13	73 ± 9	38 ± 8	20 ± 4	1.9 ± 0.6 [c]
	10	253 ± 20	114 ± 12	84 ± 10	28 ± 6	3 ± 0.7 [c]
	11	251 ± 20	104 ± 15	82 ± 10	29 ± 6	2.83 ± 0.7 [c]
	12	520 ± 29	238 ± 20	128 ± 13	44 ± 9	2.9 ± 0.7 [c]
	13	511 ± 29	187 ± 18	105 ± 12	36 ± 7	2.9 ± 0.6 [c]
	14	1530 ± 50	363 ± 30	191 ± 16	68 ± 14	2.8 ± 0.6 [c]
	15	2400 ± 60	500 ± 34	218 ± 18	39 ± 8	$[5.6\pm1.2]$
γ_T [b]		4.27	3.31	2.82	$\equiv 1.0$	

[a]From Ref. 14.
[b]See text.
[c]Average of just these quantities $=2.82\pm0.2$.

model,[15] this expression should also apply at higher energies when corrected for the slight energy dependence of the nucleon-nucleon scattering cross section. Since the resulting values of $\sigma_{NS}(P,T)$ at 200 GeV/N are only $\sim$1% to 2% lower than at 2 GeV/N for ^{32}S on Pb, Cu, and Al targets, we have ignored this correction. Table I lists both $\sigma_{NS}(P,T)$ and $\sigma_{ES}(P,T)=\sigma(P,T)-\sigma_{NS}(P,T)$. Without attempting to calculate σ_{ES} directly from an integration of the virtual-photon spectrum over photonuclear cross sections for ^{32}S (which have not been measured at all relevant energies), we note that the values of σ_{ES} in Table I scale quite as well as $Z_T^{1.8}$.

To calculate the nuclear contribution to the partial cross sections for fragmentation of ^{32}S into nuclei with $8\le Z\le 15$, we draw on extensive data[16] which have shown that nuclear fragmentation of a projectile into a large residual fragment ($Z_F \gtrsim Z_P/2$) is a *peripheral* process with a cross section proportional to the sum of the radii of projectile plus target nucleus, reduced by a small overlap. These experiments showed that the partial cross sections for products of grazing nuclear collisions are factorable,

$$\sigma_{NS}(P,T,Z_F)=\gamma_{PF}\gamma_T\,, \quad (4)$$

where γ_{PF} depends on projectile and fragment only, and γ_T is the target factor,

$$\gamma_T=A_P^{1/3}+A_T^{1/3}-c\,. \quad (5)$$

Note that factorization does not hold for total cross sections, only for products of grazing collisions. Note also that Eq. (5) fits the data well for a limited range of values of A_T, from $A_T\approx 9$ to 238, but does not usually fit the data for $A_T=1$. In Ref. 16 the overlap parameter, c, was found to be $\sim$0.65, $\sim$0.16, $\sim$0.1, and $\sim$1.13 for fragmentation of ^{12}C, ^{16}O, ^{18}O, and ^{56}Fe, respectively, in targets $A_T\gtrsim 9$. We used $c=0.5$ to calculate the nuclear target factors γ_T for our ^{32}S data in Pb, Cu, and Al; the results are essentially the same for values of c between 0.2 and 1. To determine γ_T for hydrogen [which cannot be obtained from Eq. (5)] and γ_{PF} for the various fragments, we assumed that, because of its steep dependence on Z_T, $\sigma_{ES}(^{32}\text{S},T,Z_F)$ in both Al and H are negligible, except for one-proton removal in Al. The last column of Table I shows the resulting ratio γ_{Al}/γ_H obtained from the ratio of values in the Al and H columns. This ratio is around 2.8 to 3 for most of the fragments. Since we expect the ES contribution for one-proton removal to be significant in Al, it is not surprising that γ_{Al}/γ_H is larger for $Z_F=15$. We chose to define the value of γ_{Al}/γ_H as the average of the values in the last column of Table I except that for $Z_F=15$. The result is 2.82 ± 0.2. With γ_H normalized to 1.00, the resulting values of γ_T are listed in the bottom row of Table I.

Table II gives the values of

$$\sigma_{ES}(^{32}\text{S},T,Z_F)\equiv\sigma(^{32}\text{S},T,Z_F)-\sigma_{NS}(^{32}\text{S},T,Z_F)\,,$$

TABLE II. Electromagnetic spallation cross sections (mb).

Z_F	$\sigma_{ES}(^{32}\text{S},T,Z_F)$ Pb	Cu	Al
8	116 ± 24	14 ± 13	42 ± 10
9	35 ± 15	7 ± 6	-18 ± 8
10	133 ± 25	21 ± 17	5 ± 10
11	127 ± 25	8 ± 7	0 ± 10
12	332 ± 35	92 ± 25	4 ± 13
13	357 ± 34	68 ± 23	3 ± 12
14	1240 ± 55	138 ± 35	-1 ± 16
15	2233 ± 66	371 ± 40	108 ± 18
8–15	4573	719	143
8–15	$\equiv$4573[a]	704[a]	166[a]

[a]Expected if $\sigma_{ES}(^{32}\text{S},T,Z_F)\propto Z_T^{1.8}$.

where $\sigma_{NS}(^{32}\text{S},T,Z_F)$ is obtained from the product of γ_T and the NS cross section for H in Table I. We also list the values of $\sigma_{ES}(^{32}\text{S},T,Z_F)$ summed over fragments $8\le Z_F\le 15$ and show in the bottom row that the sum is consistent with a $Z_T^{1.8}$ dependence.

Figure 2 displays the values of σ_{ES} for Pb and Cu targets as functions of charge loss, $\Delta Z=Z_P-Z_F$. The trends, as indicated by the best-fit straight lines, are similar to those observed in photospallation of stationary targets with bremsstrahlung at $E_{max}\gtrsim 1$ GeV (reviewed in Ref. 17), and are much steeper than the dependence of $\sigma_{NS}(^{32}\text{S},T,Z_F)$ on ΔZ, shown at the bottom of Fig. 2. Both $\sigma_{ES}(^{32}\text{S},T,Z_F)$ and $\sigma_{NS}(^{32}\text{S},T,Z_F)$ fall off roughly exponentially with ΔZ, but with very different slopes. The dashed lines above and below the best-fit line for

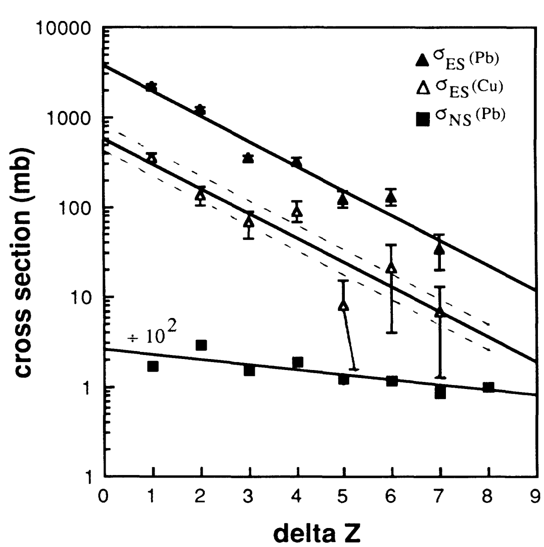

FIG. 2. Cross sections for electromagnetic spallation in Pb and Cu and for nuclear spallation in Pb as functions of $\Delta Z\equiv Z_P-Z_F$. Straight lines are least-squares fits to exponentials. Dashed lines for Cu are for a $Z_T^{1.5}$ and $Z_T^{2.1}$ dependence; solid line for Cu is for $Z_T^{1.83}$ dependence.

$\sigma_{ES}(^{32}S, CU, Z_F)$ are for a $Z_T^{1.5}$ and a $Z_T^{2.1}$ dependence, respectively. The best-fit line corresponds to a $Z_T^{1.83}$ dependence.

All but one of the previous studies of electromagnetic dissociation in heavy-ion reactions have been at energies such that almost all of the virtual photons had an energy far below the photomeson threshold; in the one study at high energy (3.2-TeV ^{16}O nuclei), only the cross section for one-neutron removal was measured.[6] Our work is the first to report the spallation of 200-GeV/N heavy ions into many different fragments by the intense electromagnetic field felt in the rest frame of the projectile as it passes near a heavy target nucleus. The ratio of ES cross sections for a Pb and for a Cu target is consistent with the expected $Z_T^{1.8}$ dependence[3] as contrasted with the shallower $\sim Z_P^{1.43}$ dependence of the one-neutron removal cross section for ^{197}Au reported by Mercier *et al.*[5]

A recent preprint by Brechtmann and Heinrich[18] also reports a study of electromagnetic spallation of 6.4-TeV ^{32}S.

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[(a)]Permanent address: Institute of High-Energy Physics, Academia Sinica, Beijing, China.

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