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Multiple Nucleon Knockout by Coulomb Dissociation in Relativistic Heavy-Ion Collisions

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Summary

The Coulomb dissociation contributions to fragmentation cross sections in relativistic heavy-ion collisions, in which more than 1 nucleon is removed, are estimated using the Weizsäcker-Williams method of virtual quanta. Photonuclear cross sections taken from experimental results are folded into target photon-number spectra calculated with the Weizsäcker-Williams method. Calculations for several projectile-target combinations are reported over a wide range of charge numbers and a wide range of incident projectile energies. These results suggest that a multiple nucleon emission process (knockout) by the Coulomb field is of negligible importance in galactic heavy-ion studies for projectiles lighter than ^{56}Fe.

Introduction

In order to assess the radiobiological effects of galactic cosmic rays on astronauts, a theoretical description of the transport of heavy ions through spacecraft structures is being developed (ref. 1). Essential inputs to this theory are accurate values for total fragmentation cross sections for heavy-ion collisions. Previous studies (refs. 2 and 3) using the Weizsäcker-Williams method (refs. 4 and 5) have shown that the electromagnetic interaction, as compared with the nuclear interaction, provides an important contribution to the cross section for the knockout of 1 nucleon from projectiles as light as ^{12}C incident at relativistic velocities. In the present work, the method of reference 2 is extended to estimate fragmentation cross sections for multiple nucleon emission processes (knockouts) caused by the electromagnetic interaction. Estimates, which are based only on the giant electric dipole contribution to the virtual photon-number spectrum, are made for several nuclear pairs covering a large charge range at incident projectile energies extending from 350 MeV/nucleon to 100 GeV/nucleon.

Method of Evaluation

The electromagnetic dissociation cross section is written (ref. 2) as

$$\sigma_{\mathrm{EM}} = \int_{E_o} \sigma_\nu(E,X)\, N(E)\, dE \qquad (1)$$

where E is the photon energy, E_o is the threshold energy for the reaction, $N(E)$ is the virtual photon-number spectrum of the target, and $\sigma_\nu(E,X)$ is the total photonuclear reaction cross section for the production of particle or particles X. The virtual photon spectrum is calculated using the Weizsäcker-Williams (WW) method of virtual quanta (refs. 2, 4, and 5) and is given by

$$N(E) = \frac{2}{\pi E}\frac{Z_T^2 \alpha}{\beta^2}\left\{ x\, K_0(x)\, K_1(x) - \frac{x^2 \beta^2}{2}\left[K_1^2(x) - K_0^2(x)\right]\right\} \qquad (2)$$

where $N(E)$ is the number of virtual photons per unit entry E, Z_T is the target charge number, β is the relative projectile-target velocity in units of c, α is the fine-structure constant, and K_0 and K_1 are modified Bessel functions of the second kind. The parameter x is defined as

$$x = \frac{E b_{\mathrm{min}}}{\gamma\beta(\hbar c)} \qquad (3)$$

where $\gamma = (1 - \beta^2)^{-1/2}$, and the minimum impact parameter b_{min} is taken as (ref. 2)

$$b_{\mathrm{min}} = R_{0.1}(p) + R_{0.1}(t) \qquad (4)$$

where $R_{0.1}(p)$ and $R_{0.1}(t)$ are the 10-percent-charge density radii of the projectile and target nuclei, respectively.

For a single nucleon emission, theoretical models of $\sigma_\nu(E,X)$ have been developed and a large experimental data base exists for verification of these models. For multiple emission processes, this is not true. An extensive data search reveals that very few experimental measurements have been made for $\sigma_\nu(E,X)$ for multiple emissions, especially for mass numbers $A \leq 56$. Since theoretical models for $\sigma_\nu(E,X)$ cannot be substantiated for the reactions under consideration, we will use the available experimental data as input to our calculations. This severely limits our study because few such data exist for the abundant nuclei that make up the largest percentage of the cosmic rays (99 percent). Furthermore, results for nearby nuclei cannot be used as reliable estimates because the photonuclear cross sections are largely dependent on the neutron excess and shell structure of the nucleus in question.

Results and Discussion

The results are shown in tables I through VI. From tables I, IV, and V we see that the 2-neutron knockout cross section increases with projectile mass number, but it is negligible for ^{16}O for all targets and energies. We also find a negligible cross section for the $^{27}\mathrm{Al} \rightarrow {}^{24}\mathrm{Na}$ for all targets except ^{208}Pb. The results of tables I and IV can be compared with those of references 3 and 6 to see the relative unimportance of the Coulomb field to the nuclear field for the reactions being studied. The results of tables V and VI are of more interest from a fundamental physics standpoint, as they suggest that the Coulomb field will dominate the nuclear field in Pb-Pb collisions at energies as low as 2 GeV/nucleon. For the Pb-Pb collision, we found a substantial overlap between the photonuclear spectrum and the target spectrum for photons with energies as high as 100 MeV. This overlap is well past the peak of the giant dipole resonance and possibly beyond where we should expect the WW method to hold. (The reference for the input photonuclear data (refs. 7 through 11) is listed with the corresponding table.)

From the results of this limited study, we conclude that multiple nucleon emission (knockout) through Coulomb dissociation is of minor importance for most collision pairs of interest in galactic heavy-ion shielding studies, except for projectiles with $A > 56$ which may warrant further study. However, further studies should include estimates of the contribution of higher multipoles to the virtual photon spectrum, specifically the contribution from the giant electric quadrupole resonance which may be important for multiple nucleon emission.

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Table I. Coulomb Dissociation Cross Sections for ^{16}O + Target → ^{14}O + Anything
[Input photonuclear data taken from reference 7]

Projectile kinetic energy, GeV/nucleon	Values of σ, mb, for elements—				
	^{12}C	^{27}Al	^{40}Ca	^{56}Fe	^{208}Pb
5.0	<0.5	<0.5	<0.5	<0.5	2.0
20.0	<.5	<.5	.5	.8	6.5
100.0	<.5	.5	.9	1.5	13.6

Table II. Coulomb Dissociation Cross Sections for ^{27}Al + Target → ^{24}Na + Anything
[Input photonuclear data taken from reference 8]

Projectile kinetic energy, GeV/nucleon	Values of σ, mb, for elements—				
	^{12}C	^{27}Al	^{40}Ca	^{56}Fe	^{208}Pb
2.0	<0.5	<0.5	<0.5	<0.5	0.6
5.0	<.5	<.5	<.5	<.5	2.4
20.0	<.5	<.5	.6	1.0	8.2
100.0	<.5	.5	1.1	1.9	17.4

Table III. Coulomb Dissociation Cross Sections for ^{40}Ar + Target → ^{36}Cl + Anything
[Input photonuclear data taken from reference 9]

Projectile kinetic energy, GeV/nucleon	Values of σ, mb, for elements—				
	^{12}C	^{27}Al	^{40}Ca	^{56}Fe	^{208}Pb
0.35	<0.5	1.1	2.2	3.2	15.2
.6	<.5	1.6	3.4	5.1	29.1
1.0	.6	2.3	4.9	7.6	49.1
2.0	.9	3.6	7.9	12.5	92.6
5.0	1.4	6.2	14.0	22.8	189.0
20.0	2.6	11.7	27.0	44.8	403.8

Table IV. Coulomb Dissociation Cross Sections for ^{64}Cu + Target → ^{62}Cu + Anything
[Input photonuclear data taken from reference 10]

Projectile kinetic energy, GeV/nucleon	Values of σ, mb, for elements—				
	^{12}C	^{27}Al	^{40}Ca	^{56}Fe	^{208}Pb
0.35	<0.5	1.1	2.2	3.3	17.3
.6	<.5	1.6	3.3	5.0	30.5
1.0	.5	2.1	4.5	7.1	48.6
2.0	.7	3.1	7.0	11.2	86.0
5.0	1.2	5.3	12.0	19.6	165.9
20.0	2.1	9.7	22.5	37.3	339.9

Table V. Coulomb Dissociation Cross Sections for ^{208}Pb + Target → ^{206}Pb + Anything
[Input photonuclear data taken from reference 11]

Projectile kinetic energy, GeV/nucleon	Values of σ, mb, for elements—				
	^{12}C	^{27}Al	^{40}Ca	^{56}Fe	^{208}Pb
0.35	1.9	7.5	15.7	24.1	143.9
.6	2.6	10.4	22.6	35.4	238.6
1.0	3.3	14.0	30.8	49.1	362.3
2.0	4.8	20.8	46.9	76.1	614.3
5.0	7.8	34.8	79.7	131.3	1145.6
20.0	14.0	63.9	148.6	247.5	2290.4

Table VI. Coulomb Dissociation Cross Sections for ^{208}Pb + Target → ^{205}Pb + Anything
[Input photonuclear data taken from reference 11]

Projectile kinetic energy, GeV/nucleon	Values of σ, mb, for elements—				
	^{12}C	^{27}Al	^{40}Ca	^{56}Fe	^{208}Pb
0.35	<0.5	<0.5	0.6	0.9	4.1
.6	<.5	.7	1.4	2.1	11.2
1.0	<.5	1.2	2.5	3.9	24.4
2.0	.5	2.3	5.1	8.1	59.2
5.0	1.1	4.8	11.0	17.9	149.0
20.0	2.3	10.5	24.4	40.5	369.0