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Comparisons of Cross-Section Predictions for Relativistic Iron and Argon Beams With Semiempirical Fragmentation Models

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Symbols

A	nuclear mass number
b	impact parameter, fm
NRL	Naval Research Laboratory
Z	nuclear charge number
ΔA	total number of abraded and ablated nucleons
Δ_{abl}	number of ablated nucleons
Δ_{abr}	number of abraded nucleons
σ	cross section, mb
σ_o, Ω, η	parameters in Silberberg-Tsao theory (eq. (10))
Subscripts:	
F	fragment
FSI	frictional spectator interaction
nuc	nuclear
P	projectile
T	target

Abstract

Cross-section predictions with semiempirical nuclear fragmentation models from the Langley Research Center and the Naval Research Laboratory are compared with experimental data for the breakup of relativistic iron and argon projectile nuclei in various targets. Both these models are commonly used to provide fragmentation cross-section inputs into galactic cosmic ray transport codes for shielding and exposure analyses. Overall, the Langley model appears to yield better agreement with the experimental data.

Introduction

In the approaching era of career astronauts and space workers who will man Space Station *Freedom*, establish lunar bases, and explore the solar system, concern is mounting over possible deleterious effects to crews from the heavy ion component of solar and galactic cosmic rays (refs. 1 and 2). To properly assess these risks, knowledge of cosmic ray interaction and transport in bulk matter is required to accurately determine shielding requirements and to adequately assess radiobiological damage to the astronauts. A major source of uncertainty in these risk assessments is the input fragmentation cross-section data base (ref. 3). At present, the experimental data base is inadequate, and accurate theories of nuclear fragmentation are hampered by the paucity of experimental data. Two nuclear fragmentation models currently used for galactic cosmic ray shielding studies are semiempirical formalisms developed at the Naval Research Laboratory (refs. 4, 5, and 6) and at the Langley Research Center (ref. 7).

The NRL model involves extrapolations to heavy targets of a modified form of a parameterization originally developed by Rudstam for hydrogen targets (ref. 8). Numerous adjustable parameters have been chosen by comparisons with available experimental data. The Langley model is based upon a two-step abrasion-ablation collision formalism. It has one adjustable parameter, a second-order correction to the excitation energy used as input into the ablation stage of the reaction.

In the present work, cross-section predictions from each semiempirical model are made and compared with available data from recent experiments using iron (ref. 9) and argon beams (ref. 10). Comparisons with earlier measurements (ref. 11) for iron beams at energies different from those used in reference 9 are also made. The agreement between model predictions and experimental measurements is assessed by analyzing the distribution of cross-section differences.

Semiempirical Models

Formulation of Langley Research Center Model

In the Langley semiempirical model, the classical, geometric abrasion-ablation model of Bowman, Swiatecki, and Tsang (ref. 12) is modified to include frictional spectator interactions through the use of higher order corrections to the abraded prefragment excitation energies. In this method, the nuclear fragmentation cross sections are given by

$$\sigma_{\text{nuc}}(Z_F, A_F) = F_1 \exp\left(-R|Z_F - SA_F + TA_F^2|^{3/2}\right) \sigma(\Delta A) \tag{1}$$

where according to Rudstam (ref. 8), $R = 11.8A_F^{-0.45}$, $S = 0.486$, $T = 3.8 \times 10^{-4}$, and F_1 is a normalizing factor such that

$$\sum_{Z_F} \sigma_{\text{nuc}}(Z_F, A_F) = \sigma(\Delta A) \tag{2}$$

which ensures charge and mass conservation. The Rudstam formula for $\sigma(\Delta A)$ is not used because the ΔA dependence is too simple and breaks down for heavy targets. Instead, the cross section for removal of ΔA nucleons is estimated by using

$$\sigma(\Delta A) = \pi b_2^2 - \pi b_1^2 \tag{3}$$

where b_2 is the impact parameter at which Δ_{abr} nucleons are abraded by the collision and Δ_{abl} nucleons are ablated in the subsequent prefragment deexcitation, such that

$$\Delta_{\text{abr}}(b_2) + \Delta_{\text{abl}}(b_2) = \Delta A - \frac{1}{2} \tag{4}$$

and similarly for b_1

$$\Delta_{\text{abr}}(b_1) + \Delta_{\text{abl}}(b_1) = \Delta A + \frac{1}{2} \tag{5}$$

The number of abraded nucleons is estimated from the geometric overlap volume and the mean-free path in nuclear matter λ as

$$\Delta_{\text{abr}} = F A_P \left[1 - 0.5 \exp\left(-\frac{C_P}{\lambda}\right) - 0.5 \exp\left(-\frac{C_T}{\lambda}\right)\right] \tag{6}$$

where F is the fraction of the volume in the geometric overlap region between the colliding nuclei and C_P and C_T are the maximum chord lengths of the intersecting surfaces in the projectile (P) and target (T). Expressions for F given elsewhere (ref. 7) differ because of the relative sizes of the colliding nuclei and the nature of the collision (central versus peripheral). The number of ablated nucleons Δ_{abl} is computed from

$$\Delta_{\text{abl}} = \frac{E_s + E_{\text{FSI}}}{10 \text{ MeV}} \tag{7}$$

which assumes that a nucleon is ablated (evaporated) for every 10 MeV of excitation energy. In equation (7), E_s represents excitation energy associated with the surface energy contribution from abrasion, and E_{FSI} represents the contributions resulting from frictional spectator interactions. The only arbitrarily adjusted parameter in this model is a second-order correction to the expression for the surface energy term.

Because the dissociation of projectile and target nuclei by their interacting Coulomb fields may be important for some heavier nuclei at high energies, the electromagnetic dissociation contributions σ_{em} must be added to the nuclear fragmentation cross section σ_{nuc} to yield the total fragmentation cross section

$$\sigma_F = \sigma_{\text{nuc}} + \sigma_{\text{em}} \tag{8}$$

Methods for estimating σ_{em} have been developed and parameterized for use with this fragmentation model (refs. 7 and 13).

Formulation of Naval Research Laboratory Model

The fragmentation cross sections for nucleus-nucleus collisions with the NRL model are calculated from nucleus-nucleon collisions by

$$\sigma_F(A_P - A_T) = \sigma_F(A_P - \text{H}) S_c \varepsilon_n \varepsilon_L \varepsilon_1 \varepsilon_\Delta \tag{9}$$

where $\sigma_F(A_P - \text{H})$ is the fragmentation cross section for nuclear breakup by hydrogen targets. In equation (9), S_c is a scaling factor obtained by empirically fitting nuclear skin thicknesses. The factors ε_n, ε_L, ε_1, and ε_Δ, respectively, represent adjustable correction factors for neutron-deficient fragments, for light mass products, for single-nucleon stripping, and for large ΔA removal. Parameterized expressions for these factors and their appropriate limits of applicability can be found in references 4, 5, and 6.

From reference 4, the cross sections for fragmentation by hydrogen targets are given by

$$\sigma_F(A_P - \text{H}) = \sigma_o f(A_F) f(E) \exp(-P\Delta A) \times \exp\left(-R|Z - SA_F + TA_F^2|^v\right) \Omega \eta \xi \tag{10}$$

Equation (10) is applicable to projectile nuclei with mass numbers between 9 and 209 and fragments with mass numbers A_F between 6 and 200, except for peripheral interactions where $\Delta A (= A_P - A_F)$ is small. Parameterizations of the various factors in equation (10) are given elsewhere (refs. 4 and 5).

Cross-Section Predictions

With the Langley and NRL semiempirical models, elemental production cross sections for iron beams at 1.88A GeV and 1.55A GeV fragmenting in various targets are presented in tables 1 and 2. The experimental data are taken from Westfall et al. (ref. 11) and Cummings et al. (ref. 9). From tables 1 and 2, generally good agreement exists between the Langley model predictions and the experimental measurements. The NRL model predictions, however, typically overestimate the experimental data, especially for heavier mass fragments. Detailed analyses of the distributions of cross-section differences are presented in the next section.

Recently, Tull reported measurements of fragment production cross sections for 1.65A GeV argon beams fragmenting in carbon and potassium chloride (KCl) targets. (See ref. 10.) Figures 1 and 2 display predictions of elemental production cross sections obtained with the Langley and the NRL models compared with the measured values of Tull. Unlike the previous comparisons involving iron beams, the agreement between theory and experiment is good for both the Langley and the NRL models. Although not displayed here, comparisons between theory and experiment were also made for fragment isotope production cross sections. Detailed analyses of the distributions of both elemental and isotopic cross-section differences are presented in the next section.

Distributions of Cross-Section Differences

Quantitative agreement between theory and experiment is evaluated by investigating the

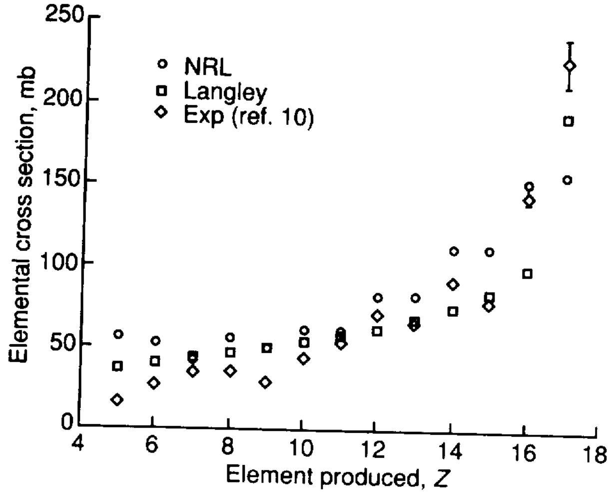

Figure 1. Elemental production cross sections for 1.65*A* GeV argon beams fragmenting in carbon targets.

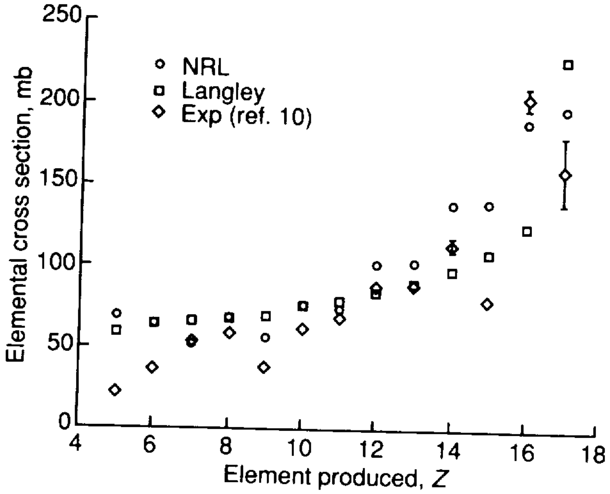

Figure 2. Elemental production cross sections for 1.65*A* GeV argon beams fragmenting in KCl targets.

distribution of cross-section differences. Deciding whether theory and experiment agree or disagree is actually a subjective interpretation of the results of the evaluation process. For example, in some applications, differences of up to 50 percent may be considered acceptable. For other applications, differences greater than 25 percent may not be acceptable.

In tables 3 and 4, the target-averaged distributions of elemental cross-section differences are tabulated for each incident beam-energy combination. The table entries are the percentage of cross-section differences within the experimental uncertainties; the percentages outside the error bars but within 10, 25, 50, and 100 percent; and the percentages which differ by more than 100 percent.

From table 3, for 1.88*A* GeV iron beams, 62 percent of the Langley cross-section predictions fall within the experimental uncertainties, 77 percent of the predictions fall within 25 percent of the experimental data, and 95 percent fall within 50 percent of the data. None of the Langley cross-section predictions differ by more than 100 percent from the data. For the NRL model, 17 percent of the predictions fall within the experimental error, 25 percent within 25 percent of the data, 47 percent within 50 percent of the data, and 15 percent differ from the data by more than 100 percent.

The 1.55*A* GeV iron-beam comparisons, also presented in table 3, indicate that both models predict 5 percent of the cross sections falling within the experimental errors. For the Langley model, 24 percent fall within 10 percent of the data, 59 percent within 25 percent of the data, and 95 percent within 50 percent of the data. None of the Langley predictions differ from the data by more than 100 percent. For the NRL model, 7 percent of the cross-section predictions fall within 10 percent of the data, 14 percent agree within 25 percent, 45 percent agree within 50 percent, and 21 percent differ by more than 100 percent. Overall, the Langley model appears to give much better agreement with experiment for these iron beams fragmenting in various heavy targets.

In table 4, results for elemental and isotopic cross-section differences are presented for 1.65*A* GeV argon beams fragmenting in carbon and KCl targets. For the Langley model, 8 percent of the elemental cross-section predictions fall within the experimental uncertainties, 20 percent are within 10 percent of the data, 54 percent are within 25 percent, 81 percent are within 50 percent, and 92 percent are within 100 percent of the experimental data. For the NRL model, 4 percent of the elemental cross-section predictions fall within the experimental uncertainties, 16 percent are within 10 percent of the data, 58 percent are within 25 percent, 73 percent are within 50 percent, and 92 percent are within 100 percent of the experimental data.

Comparing isotopic cross sections, 35 percent of the Langley model predictions fall within the error bars, 40 percent are within 25 percent of the data, 53 percent are within 50 percent, and 89 percent are within 100 percent of the experimental values. For the NRL model, 34 percent of the isotopic cross sections are within the error bars, 41 percent are within 25 percent of the data, 59 percent are within 50 percent, and 81 percent are within 100 percent of the experimental data. Overall, these two models appear to yield essentially the same agreement with experiment for these argon data.

Concluding Remarks

The cross-section predictions of two semi-empirical fragmentation models have been compared with experimental measurements for relativistic beams of iron and argon colliding with various targets. Overall, the Langley Research Center model appears to yield better agreement with these data. Incorporating the Langley model into cosmic ray transport codes should provide improved accuracy in predictions of radiation exposures and concomitant shield requirements for spacecraft crews. For elemental production, the Langley model typically predicted cross sections which were within 25 percent of the experimental values for over 80 percent of these cross sections. For isotopic production, the Langley model had a 53-percent success rate for predicting cross sections within 50 percent of the data and an 89-percent success rate for predicting cross sections within 100 percent of the data. Further comparisons with experiment require additional experimental data.

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Table 1. Element Production Cross Sections for 1.88A GeV Iron Beams Fragmenting in Various Targets

Element produced	Cross section, mb		
	NRL	Langley	Experiment[a]
Carbon target			
Mn	237	184	181 ± 27
Cr	182	123	124 ± 13
V	115	101	100 ± 11
Ti	157	87	87 ± 11
Sc	116	78	54 ± 9
Ca	111	71	78 ± 11
K	81	65	52 ± 7
Ar	82	61	55 ± 9
Cl	55	57	53 ± 7
S	62	53	54 ± 10
P	40	50	59 ± 10
Si	39	47	57 ± 10
Al	31	44	83 ± 11
Sulphur target			
Mn	402	217	250 ± 22
Cr	213	139	128 ± 16
V	135	115	86 ± 12
Ti	184	100	64 ± 10
Sc	136	90	91 ± 13
Ca	130	82	97 ± 14
K	95	76	55 ± 21
Ar	96	71	74 ± 13
Cl	64	66	66 ± 14
S	72	62	74 ± 12
P	47	59	50 ± 8
Si	46	56	106 ± 14
Al	36	53	78 ± 13
Copper target			
Mn	648	266	219 ± 20
Cr	250	158	149 ± 16
V	158	132	121 ± 15
Ti	216	117	101 ± 14
Sc	160	106	100 ± 15
Ca	153	98	98 ± 14
K	112	91	88 ± 14
Ar	112	86	95 ± 15
Cl	75	82	86 ± 13
S	85	78	56 ± 11
P	55	74	88 ± 15
Si	54	72	72 ± 11
Al	42	69	179 ± 27

[a] Data from reference 11.

Table 1. Concluded

Element produced	Cross section, mb		
	NRL	Langley	Experiment[a]
Silver target			
Mn	906	338	280 ± 23
Cr	293	171	218 ± 21
V	186	143	117 ± 15
Ti	253	126	124 ± 16
Sc	188	115	104 ± 13
Ca	179	106	118 ± 14
K	131	100	79 ± 11
Ar	132	94	84 ± 14
Cl	88	90	79 ± 14
S	99	86	96 ± 13
P	65	82	64 ± 13
Si	63	79	158 ± 20
Al	50	76	112 ± 19
Lead target			
Mn	1042	514	509 ± 40
Cr	375	190	242 ± 25
V	237	160	142 ± 20
Ti	323	142	148 ± 22
Sc	240	129	111 ± 17
Ca	229	120	144 ± 22
K	168	113	90 ± 19
Ar	169	107	73 ± 15
Cl	112	102	90 ± 19
S	127	98	116 ± 19
P	93	94	78 ± 16
Si	81	91	119 ± 22
Al	64	88	191 ± 34

[a] Data from reference 11.

Table 2. Element Production Cross Sections for $1.55A$ GeV Iron Beams Fragmenting in Various Targets

Element produced	Cross section, mb		
	NRL	Langley	Experiment[a]
	Carbon target		
Mn	243	185	140.73 ± 3.36
Cr	196	124	105.33 ± 2.69
V	121	101	79.32 ± 2.31
Ti	162	87	75.17 ± 2.23
Sc	118	78	57.29 ± 1.92
Ca	111	71	63.37 ± 2.01
K	80	65	43.62 ± 1.64
Ar	79	60	47.65 ± 1.72
Cl	52	56	41.45 ± 1.59
S	58	53	46.47 ± 1.68
P	38	49	39.45 ± 1.53
Si	36	47	50.99 ± 1.75
Al	27	44	41.23 ± 1.55
Mg	29	42	45.45 ± 1.62
Na	24	40	35.83 ± 1.42
Ne	25	37	44.79 ± 1.59
	Aluminum target		
Mn	359	208	174.04 ± 4.46
Cr	223	137	127.60 ± 3.23
V	137	113	91.05 ± 2.70
Ti	184	98	84.12 ± 2.58
Sc	134	87	73.41 ± 2.40
Ca	126	79	68.92 ± 2.31
K	91	74	52.89 ± 2.01
Ar	90	68	52.72 ± 2.01
Cl	59	64	45.24 ± 1.85
S	66	60	52.27 ± 1.98
P	43	57	43.47 ± 1.80
Si	41	54	58.21 ± 2.08
Al	31	51	45.37 ± 1.82
Mg	33	49	51.76 ± 1.94
Na	27	46	45.23 ± 1.81
Ne	29	44	49.11 ± 1.88

[a] Data from reference 9.

Table 2. Concluded

Element produced	Cross section, mb		
	NRL	Langley	Experiment[a]
Copper target			
Mn	670	263	238.96 ± 6.78
Cr	270	159	147.44 ± 3.73
V	167	133	98.89 ± 3.00
Ti	223	117	98.45 ± 2.97
Sc	163	106	73.64 ± 2.57
Ca	153	98	80.32 ± 2.67
K	110	91	59.98 ± 2.31
Ar	109	86	61.18 ± 2.32
Cl	72	82	49.41 ± 2.09
S	80	78	59.58 ± 2.27
P	52	74	49.82 ± 2.08
Si	50	71	72.20 ± 2.48
Al	38	69	51.47 ± 2.10
Mg	40	67	61.03 ± 2.27
Na	33	65	50.17 ± 2.06
Ne	35	63	54.55 ± 2.14
Lead target			
Mn	1082	484	500.52 ± 13.42
Cr	405	190	223.00 ± 6.18
V	250	160	130.18 ± 4.64
Ti	335	142	135.00 ± 4.67
Sc	244	129	104.01 ± 4.11
Ca	230	120	98.20 ± 3.98
K	165	112	79.76 ± 3.60
Ar	163	107	77.23 ± 3.54
Cl	107	102	59.97 ± 3.14
S	120	98	75.75 ± 3.47
P	78	94	63.66 ± 3.19
Si	75	91	86.28 ± 3.65
Al	56	88	61.90 ± 3.12
Mg	60	86	74.14 ± 3.38
Na	49	84	66.19 ± 3.20

[a] Data from reference 9.

Table 3. Distribution of Element Production Cross-Section Differences Between Theory and Experiment for Beams Fragmenting in Various Targets

[Experimental data used in comparisons are from ref. 11 for 1.88*A* GeV beams and from ref. 9 for 1.55*A* GeV beams]

Difference, percent	Cross sections, percent	
	Langley	NRL
1.88*A* GeV iron beams		
Within error bars	62	17
≤25	15	8
26–50	18	22
51–100	5	38
>100	0	15
1.55*A* GeV iron beams		
Within error bars	5	5
≤10	19	2
11–25	35	7
26–50	37	31
51–100	5	34
>100	0	21

Table 4. Distribution of Elemental and Isotopic Cross-Section Differences Between Theory and Experiment for 1.65*A* GeV Argon Beams Fragmenting in Carbon and KCl Targets

[Experimental data used in comparisons are from ref. 10]

Difference, percent	Cross sections, percent			
	Elemental		Isotopic	
	Langley	NRL	Langley	NRL
Within error bars	8	4	35	34
≤10	12	12		
11–25	34	42	5	7
26–50	27	15	13	18
51–100	11	19	36	22
>100	8	8	11	19

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