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ELECTROMAGNETIC INTERACTIONS OF COSMIC RAYS WITH NUCLEI

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ABSTRACT

Parameterizations of single nucleon emission from the electromagnetic interactions of cosmic rays with nuclei are presented. These parameterizations are based upon the most accurate theoretical calculations available today. When coupled with Strong interaction parameterizations, they should be very suitable for use in cosmic ray propagation through interstellar space, the Earth's atmosphere, lunar samples, meteorites and spacecraft walls.

Introduction

Galactic cosmic rays are very high energy particles confined to the region of our Milky Way galaxy. They consist of about 98% bare nuclei (stripped of all electrons) and about 2% electrons and protons (Simpson 1983). Of the nuclear component about 87% is hydrogen, about 12% is helium and the other 1% consists of heavier nuclei. Fe is the most abundant of these nuclei with a typical energy of about 1 GeV/N. Even though these heavy nuclei are not very abundant, they are very penetrating due to their large mass and high speed.

An understanding of the interactions of galactic cosmic ray nuclei is important for several reasons:

1) Knowledge of the cosmic ray spectrum at the top of the Earth's atmosphere and knowledge of the composition of the interstellar medium enables us to determine the cosmic ray spectrum at the source (Simpson 1983).

2) Knowledge of the spectrum at the surface of the Earth and knowledge of the composition of the Earth's atmosphere enables us to determine the cosmic ray spectrum at the top of the atmosphere (Wilson, Townsend and Badavi 1987).

3) The radiation environment inside a spacecraft, due to solar and galactic cosmic rays may be determined (Wilson and Townsend 1988).

4) Studies of the history of extraterrestrial matter (such as lunar samples, meteorites and cosmic spherules and dust found in deep sea sediments) and also of the history of cosmic rays themselves can be made with knowledge of the production rate of various nuclides (Reedy 1987; Reedy, Arnold and Lal 1983).

The basic nucleus-nucleus interaction that a cosmic ray undergoes can occur mainly via the Strong or Electromagnetic force. Strong interaction processes (Gyulassy 1981) have been studied extensively and quite recently the study of Electromagnetic processes in high energy nuclear collisions has begun (Bertulani and Baur 1988).

In order to study the propagation of cosmic rays through interstellar space, the Earth's atmosphere or a spacecraft wall it is not enough to have only a good understanding of the nucleus-

nucleus interaction mechanism. One must have an accurate theory of transport as well. Generally one uses a nucleus-nucleus interaction cross section as input to a transport computer code. These codes however can be very complex and therefore require simple expressions for the cross sections rather than the use of data bases or complicated theoretical expressions (Wilson and Townsend 1988). Thus there has been a considerable effort to parameterize the cross section expressions so that the only required inputs are the nuclear energies and charge and mass numbers (Letaw, Silberberg and Tsao 1983; Silberberg and Tsao 1973; Townsend and Wilson 1986; Norbury, Cucinotta, Townsend and Wilson 1988; Wilson, Townsend and Badavi 1987).

One approach to the parameterization of cross sections is to simply take all the available experimental data and fit a curve through it (Letaw, Silberberg and Tsao 1983; Silberberg and Tsao 1973). Such an approach has certainly been useful and successful, but a much more satisfying parameterization would be one tied more directly to theory. It is the aim of the present work to obtain such a parameterization for the Electromagnetic (EM) part of the nucleus-nucleus interaction. One can then couple this with a similar theoretical parameterization of the Strong interaction process (Wilson, Townsend and Badavi 1987) to obtain a complete theoretical parameterization of the complete cross section.

A preliminary parameterization of the EM process has already been presented (Norbury, Cucinotta, Townsend and Badavi 1988), which utilizes the Weizsäcker-Williams (WW) method of virtual quanta (Bertulani and Baur 1988; Jackson 1975). However, since then the theory has been improved to include the effects of both electric dipole (E1) and electric quadrupole (E2) interactions (Bertulani and Baur 1988; Norbury 1989a), which will henceforth be referred to as multipole theory in contrast to WW theory. These E1 and E2 effects modify the parameterization considerably. Also in the present work several different parameterizations are presented differing in degree of complexity. In addition much more data has become available with which to compare the parameterizations (Heckman and Lindstrom 1976; Olson, Berman, Greiner, Heckman, Lindstrom, Westfall and Crawford 1981; Mercier, Hill, Wohn, McCullough, Nieland, Winger, Howard, Renwick, Matheis and Smith 1986; Hill, Wohn, Winger and Smith 1988; Smith, Hill, Winger and Karol 1988; Hill, Wohn, Winger, Khayat, Leininger and Smith 1988; Hill, Wohn, Winger, Khayat, Mercier and Smith 1989; Norbury 1989b; Hill and Wohn 1989). The parameterizations to be presented below can then be combined with Strong interaction parameterizations such as the excellent parameterization by Wilson, Townsend and Badavi (1987). This combination should provide for much more accurate models of cosmic ray propagation through interstellar space, the Earth's atmosphere and spacecraft walls.

The present work will only consider single nucleon emission from cosmic ray nuclei. This has been shown to be the dominant electromagnetic process. Other particle emission processes such as two-neutron emission have much smaller probability (Hill, Wohn, Winger, Khayat, Mercier and Smith 1989), and will be studied in future work.

ELECTROMAGNETIC THEORY

The EM theory has already been discussed extensively (Bertulani and Baur 1988; Norbury 1989a) and only a few relevant details will be given here. The total nucleus-nucleus EM cross section is written as

$$\sigma = \sigma_{E1} + \sigma_{E2}$$
$$= \int [N_{E1}(E)\, \sigma_{E1}(E) + N_{E2}(E)\, \sigma_{E2}(E)]\, dE \tag{1}$$

where $N_{E1}(E)$ is the virtual photon spectrum (of energy E) of a particular multipolarity due to the projectile nucleus and $\sigma_{E1}(E) + \sigma_{E2}(E)$ is the photonuclear reaction cross section of the target nucleus. (In principle the above equation should include other EM multipoles, but their effect is much less important.) A less exact expression is given by WW theory as

$$\sigma_{WW}(E) = \int N_{WW}(E)\, [\sigma_{E1}(E) + \sigma_{E2}(E)]\, dE \tag{2}$$

where $N_{WW}(E)$ is the WW virtual photon spectrum. Bertulani and Baur (1988) have shown that

$$N_{WW}(E) = N_{E1}(E) = \frac{1}{E}\frac{2}{\pi} Z^2 \alpha \frac{1}{\beta^2} [\xi K_0 K_1 - \frac{1}{2} \xi^2 \beta^2 (K_1^2 - K_0^2)] \tag{3a}$$

$$N_{E2}(E) = \frac{1}{E}\frac{2}{\pi} Z^2 \alpha \frac{1}{\beta^4} [2(1 - \beta^2) K_1^2 + \xi (2 - \beta^2)^2 K_0 K_1 - \frac{1}{2} \xi^2 \beta^4 (K_1^2 - K_0^2)] \tag{3b}$$

with

$$\xi = \frac{E b_{min}}{\gamma\beta(\hbar c)} \tag{4}$$

where all of the Bessel functions K are functions of ξ. In the above equation E is the virtual photon energy, Z is the nuclear charge, α is the EM fine structure content, and b_{min} is the minimum impact parameter, below which the collision occurs via the Strong interaction. Also $\beta = \frac{v}{c}$ and $\gamma = \frac{1}{\sqrt{1 - \beta^2}}$ where c is the speed of light and v is the speed of the cosmic ray.

The minimum impact parameter is given by

$$b_{min} = R_{0\cdot 1}(T) + R_{0\cdot 1}(P) - d \tag{5a}$$

where $R_{0\cdot 1}$ are the 10 per cent charge density radii of the projectile and target and d is an adjustable overlap parameter. An excellent approximation to $R_{0\cdot 1}$ is (Norbury, Cucinotta, Townsend and Badavi 1988).

$$R_{0\cdot 1} = (1.18\, A^{1/3} + 0.75)\ \text{fm} \tag{5b}$$

where A is the nuclear mass number.

Jackson has provided high and low virtual photon energy approximations as

$$N_{WW}(E) \approx \frac{1}{E}\frac{2}{\pi} Z^2 \alpha \frac{1}{\beta^2} [\ln(\frac{1.123}{\xi}) - \frac{1}{2}\beta^2] \tag{6a}$$

for small ξ, and

$$N_{WW}(E) \approx \frac{1}{E} Z^2 \alpha \frac{1}{\beta^2} (1 - \frac{1}{2}\beta^2) \exp(-2\xi) \tag{6b}$$

for large ξ.

In equation (1) the E1 photonuclear cross section can be written in terms of the electric giant dipole resonance (GDR) cross section as

$$\sigma_{E1}(E) = \frac{\sigma_m}{1 + [(E^2 - E_{GDR}^2)^2 / E^2 \Gamma_{GDR}^2]} \tag{7}$$

where E_{GDR} is the energy of the peak in the GDR cross section, Γ_{GDR} is the width of GDR, and

$$\sigma_m = \frac{\sigma_{TRK}}{\pi \Gamma_{GDR}/2} \tag{8}$$

with the Thomas-Reiche-Kuhn cross section (Levinger 1960) given by

$$\sigma_{TRK} = \frac{60NZ}{A}\ \text{MeV mb} \tag{9}$$

where N and A are the neutron and mass numbers. The GDR energy is given by (Westfall, Wilson, Lindstrom, Crawford, Greiner and Heckman 1979)

$$E_{GDR} = \hbar c \left[\frac{m^* c^2 R_0^2}{8J} (1 + u - \frac{1 + \varepsilon + 3u}{1 + \varepsilon + u}\varepsilon)\right]^{-1/2} \tag{10}$$

with

$$u = \frac{3J}{Q'} A^{-1/3} \tag{11}$$

and

$$R_0 = r_0 A^{1/3} \tag{12}$$

where $\varepsilon = 0.0768$, $Q' = 17$ MeV, $J = 36.8$ MeV, $r_0 = 1.18$ fm, and m^* is 7/10 of the nucleon mass. Note that other expressions for E_{GDR} such as $80A^{-1/3}$ (Bertulani and Baur 1988) provide very inaccurate results for light nuclei. Equation (10) is accurate for all mass regions.

The E2 cross section is dominated by the giant quadrupole resonance (GQR). The main contribution to single nucleon emission (Bertulani and Baur 1988) comes from the isoscalar component given by (Bertrand 1976)

$$\sigma_{E2}(E) = \frac{\sigma_{EWSR} E^2}{1 + (E^2 - E_{GQR}^2)^2 / E^2 \Gamma^2_{GQR}} \tag{13a}$$

with the energy-weighted sum rule (EWSR) cross section

$$\sigma_{EWSR} = f \frac{0.22\, Z A^{2/3}\ \mu b\ \text{MeV}^{-1}}{\pi \Gamma_{GQR}/2} \tag{13b}$$

where f is the fractional exhaustion of the EWSR (Bertrand 1976) and

$$E_{GQR} = \frac{63}{A^{1/3}} \tag{14}$$

Finally, all of the above cross sections refer to total absorption cross sections. To obtain the reaction for proton or neutron emission they must be multiplied by the proton or neutron branching ratios. The proton branching ratio has been parameterized by Westfall et al (Westfall, Wilson, Lindstrom, Crawford, Greiner and Heckman 1979) as

$$g_p = \text{Min}\,[Z/A,\ 1.95 \exp(-0.075\, Z)] \tag{15a}$$

where Z is the number of protons and the minimum value of the two quantities in square brackets is to be taken. Assuming that only single nucleon emission occurs, the neutron branching ratio is

$$g_n = 1 - g_p \tag{15b}$$

Comparison Between Theory and Experiment

In the above paragraphs I have provided the basic equations to be used in the present work. However in analyzing the validity of the basic EM theory one uses only equations (3) - (5) and instead of equations (7) - (15) one uses actual experimental data for the photonuclear cross sections. A detailed study of the validity of this EM theory has been made (Norbury 1989a, b, c, d) and the results from this work are presented in Table 1, both for the WW theory and the separate E1 and E2 multipole theory calculations, and are compared to experimental data. A detailed discussion is to be found in Norbury 1989a, b, c, d, but the following features are to be noticed. Both WW and multipole theory give reasonably good results although multipole theory is somewhat better. It is found that electric quadrupole (E2) effects are not significant for proton and neutron emission from ^{12}C, ^{16}O or ^{18}O. However, E2 contributions are substantial for neutron emission from ^{59}Co, ^{89}Y and ^{197}Au, generally leading to improved agreement between theory and experiment. Notable disagreements occur for ^{139}La projectiles (1.26 GeV/N) where the theoretical $\sigma_{E1} + \sigma_{E2}$ are too big. Quadrupole effects improve the theoretical results for ^{16}O projectiles at 60 and 200 GeV/N, although the theoretical cross sections are still too small. In general it has been found (Norbury 1989a, d) that electric quadrupole effects are an important component in nucleus-nucleus collisions and that these effects can be calculated accurately.

Parameterizations

As mentioned above in testing the basic WW and multipole EM theory one uses experimental data for the photonuclear cross sections. However this is not a practical procedure for use in cosmic ray transport codes and instead my approach will be to use expressions (7) - (15).

In the present work I shall discuss three separate parameterizations of the above EM theory for use in cosmic ray transport codes. These will be presented in decreasing order of accuracy, but the aim is to provide parameterizations that will be useful in different contexts.

Parameterization #1 of Multipole Theory

This is the most accurate parameterization and uses the following equations:

1) Equation (1) is used for the total nucleus-nucleus EM cross section. The integration is done numerically using the Trapezoidal Rule.

2) Equations (3) are used for the virtual photon spectra N_{E1} (E) and N_{E2} (E).

3) Equations (5) are used for the minimum impact parameter with the overlap parameter adjusted to give the best fit to data at d = -1.5 fm.

4) Equations (7) - (14) are used for the photonuclear cross sections.

5) The width Γ_{GDR} in equations (7) and (8) is set at

$$\begin{aligned} \Gamma_{GDR} &= 10 \text{ MeV} \text{ for } A < 50 \\ &= 4.5 \text{ MeV} \text{ for } A \geq 50 \end{aligned} \qquad (16)$$

and Γ_{GQR} in equations (13) is set at

$$\begin{aligned} \Gamma_{GQR} &= 2.5 \text{ MeV} \text{ for } A > 180 \\ &= 4.5 \text{ MeV} \text{ for } 70 < A \leq 180 \\ &= 5.5 \text{ MeV} \text{ for } 19 < A \leq 70 \\ &= 3.0 \text{ MeV} \text{ for } A \leq 19 \end{aligned} \qquad (17)$$

These values for Γ_{GRD} are discussed in Norbury, Cucinotta, Townsend and Badavi (1988) and for Γ_{GQR} in Bertrand (1976).

6) The fractional exhaustion of the Energy-Weighted Sum Rule in equation (13b) is given by (Bertrand 1976)

$$\begin{aligned} f &= 0.9 \text{ for } A > 100 \\ &= 0.6 \text{ for } 40 < A \leq 100 \\ &= 0.3 \text{ for } 40 \leq A \end{aligned} \qquad (18)$$

7) The proton and neutron branching ratios are given by equations (15).

The results of the above parameterizations are given in Table 1. It can be seen that it agrees extremely well with the multipole theory. Thus I regard this parameterization #1 of the multipole theory as describing very accurately the most advanced state-of-the-art EM theory. Agreement between this parameterization and experiment is, of course, of the same quality as between the multipole theory and experiment.

Parameterization #1 of WW Theory

WW theory gives a simpler treatment of the virtual photon field and is included here for the sake of completeness. The only difference between parameterization #1 of WW theory and parameterization #1 of multipole theory is that equation (2) is used for the total cross section instead of equation (1). Results are listed in Table 1 and are fairly comparable to the parameterization #1 of the multipole theory.

Parameterization #2 of Multipole Theory

A difficulty that might occur in some cosmic ray transport theories is the necessity of having to do a numerical integration in equation (1) every time σ is to be evaluated. To get around this, parameterization #2 is based on the technique of Bertulani and Baur (1988). This involves taking N_{Ei} (E) outside of the integral in equation (1) and evaluating N_{E1} (E) at E_{GDR} (see equation 10) and N_{E2} (E) at E_{GQR} (equation 14). The remaining integral is evaluated from sum rules. That is (Bertulani and Baur 1988), equation (1) becomes

$$\sigma \approx N_{E1}(E_{GDR}) \int \sigma_{E1}(E)\, dE + N_{E2}(E_{GQR})\, E_{GQR}^2 \int \frac{\sigma_{E2}(E)}{E^2}\, dE \tag{19}$$

with the sum rules

$$\int \sigma_{E1}(E)\, dE \approx \frac{60\, NZ}{A} \text{ mb MeV} \tag{20a}$$

and

$$\int \frac{\sigma_{E2}(E)}{E^2}\, dE \approx f\, \frac{0.22\, ZA^{2/3}}{1000} \text{ mb MeV}^{-1} \tag{20b}$$

Bertulani and Baur (1988) claim that this is an accurate procedure. However, I found it necessary to change d to d = -2.4 fm (see equation 5a) in order to give good comparison to experiment.

In the present parameterization #2 of multipole theory items 1) - 3) of parameterization #1 were changed to those discussed in the preceding paragraph. Note especially that a numerical integration is no longer necessary. Items 4) - 5) are no longer relevant. Items 6) - 7) remained the same. Results are again listed in Table 1. With the new value of d = -2.4 fm parameterization #2 agrees well with parameterization #1 (which used d = -1.5 fm).

Parameterization #2 of WW Theory

WW theory is again included for completeness. In this case equation (2) was replaced with

$$\sigma_{WW} \approx N_{WW}(E_{GDR}) \int \sigma_{E1}(E)\, dE + N_{WW}(E_{GQR})\, E_{GQR}^2 \int \frac{\sigma_{E2}(E)}{E^2}\, dE \qquad (21)$$

with the same sum rules in equations (20). Results are listed in Table 1.

Parameterization #3

Parameterizations #1 and #2 require the evaluation of Bessel functions as indicated in equations (3) for the virtual photon spectra. In the interest of providing an even simpler parameterization that could be used on a pocket calculator for rough estimates of the cross section, a third parameterization is presented. The E2 cross section was ignored and equations (1) or (2) were replaced with

$$\sigma \approx N_{WW}(E_{GDR}) \int \sigma_{E1}(E)\, dE \qquad (22)$$

Note that this is identical to neglecting the GQR in equation (1). The sum rule in equation (20a) was used for the integral. $N_{WW}(E_{GDR})$ was evaluated using equations (6), with (6a) used for $\xi \leq 0.5$ and (6b) for $\xi > 0.5$. This prescription avoids the evaluation of Bessel functions and almost allows one to calculate σ in one's head. In this case the value of d was d = +1.0 fm. Items 4) - 6) are not relevant and item 7) was again used. The results are presented in Table 1 and are seen to give surprisingly similar results to the other parameterizations.

Conclusion and Recommendations

As discussed in previous work (Norbury 1989a, d) the multipole theory is generally more accurate than WW theory. This is also true for the above parametrizations as can be seen from Table 1.

However, WW theory and multipole theory do not describe ^{18}O very well, and the parameterizations are even worse. I trace this to the fact that the branching ratio equations (15) do not work well for nuclei off the stability curve.

Both WW theory and multipole theory do not describe ^{197}Au very well either, but the parameterizations do a somewhat better job due to the choice of the overlap parameter d. There seems to be a problem also for very high energies especially 200 GeV/N.

Apart from these problems the multipole theory and multipole parameterizations (#1, #2 and #3) seem to describe the data quite accurately.

As regards which parameterization to use, they all seem to do an equivalent job in describing the data. This of course is because a different value for d was chosen for each. Even the parameterization #3 does quite well, although it is a little high for nucleon emission from the lighter nuclei.

Given the above problems with ^{18}O, ^{197}Au and 200 GeV/N I recommend that the above parameterizations be used $^{i)}$ only with nuclei on the stability curve, $^{ii)}$ for nuclei lighter than ^{197}Au and $^{iii)}$ for energies less than 10 GeV/N. These requirements should not be too restrictive in Cosmic Ray work because most nuclei have energies of around 1 GeV/N and the most abundant nuclei are not much heavier that ^{56}Fe (Simpson 1983). Having to deal only with nuclei on the stability curve is probably the most severe restriction.

Parameterizations #1, #2, #3 decrease in order of accuracy, but, as discussed above, not by very much. I would recommend using the most accurate parameterization (#1), but if one's computer codes are such that it would save CPU time by using either #2 or #3, then I would recommend their use. However, one should perhaps be careful about using parameterization #3 for light nuclei. I recommend the multipole parameterizations, but I do not recommend the use of the WW parameterizations.

Finally, by combining the above EM parameterizations with the Strong Interaction parameterization of Wilson, Townsend and Badavi (1987), which is not subject to the same restrictions as above, transport of cosmic rays through matter can be described very accurately. Future work will involve parameterization of both multiple nucleon emission (a much smaller effect) and also neutron branching ratios for nuclei off the stability curve.

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Table 1 Theoretical (Norbury 1989 a, c, d), Parameterized (this work) and Experimental (Heckman and Lindstrom 1976, Olson et al. 1981, Mercier et al. 1986, Smith et al. 1988, Hill et al. 1988, 1989) EM Cross Sections, all in units of mili-barn (mb).

Projectile	Target	Energy (GeV/N)	Final State	σ_{expt}	σ_{WW} (theory)	σ_{E1} (theory)	σ_{E2} (theory)	$\sigma_{E1} + \sigma_{E2}$ (theory)	Parameterization #1 d = - 1.5 fm		Parameterization #2 d = - 2.4 fm		Parameterization #3 d = +1.0 fm
									σ_{WW}	$\sigma_{E1} + \sigma_{E2}$	σ_{WW}	$\sigma_{E1} + \sigma_{E2}$	σ
^{12}C	Pb	2.1	^{11}C	51±18	47	46	2	48	59	59	56	57	62
"	"	"	^{11}B	50±25	68	68	2	70	59	59	56	57	62
"	"	1.05	^{11}C	39±24	28	28	1	29	35	36	29	30	33
"	"	"	^{11}B	50±25	42	42	1	43	35	36	29	30	33
^{16}O	"	2.1	^{15}O	50±24	59	58	2	60	87	88	84	85	93
"	"	"	^{15}N	96±26	111	110	4	114	87	88	84	85	93
^{12}C	Ag	"	^{11}C	21±10	18	18	0	18	22	22	21	22	26
"	"	"	^{11}B	18±13	26	26	1	27	22	22	21	22	26
"	"	1.05	^{11}C	21±10	12	11	1	12	14	14	12	12	13
"	"	"	^{11}B	25±19	17	17	1	18	14	14	12	12	13
^{16}O	"	2.1	^{15}O	26±13	23	22	1	23	32	32	32	32	39
"	"	"	^{15}N	30±16	42	42	1	43	32	32	32	32	39

Table 1 (cont.)

Projectile	Target	Energy (GeV/N)	Final State	σ_{expt}	σ_{WW} (theory)	σ_{E1} (theory)	σ_{E2} (theory)	$\sigma_{E1} + \sigma_{E2}$ (theory)	Parameterization #1 d = - 1.5 fm		Parameterization #2 d = - 2.4 fm		Parameterization #3 d = +1.0 fm
									σ_{WW}	$\sigma_{E1} + \sigma_{E2}$	σ_{WW}	$\sigma_{E1} + \sigma_{E2}$	σ
^{12}C	Cu	2.1	^{11}C	10±7	8	8	0	8	9	9	9	9	12
"	"	"	^{11}B	4±8	11	11	0	11	9	9	9	9	12
"	"	1.05	^{11}C	9±8	5	5	0	5	6	6	5	5	6
"	"	"	^{11}B	5±8	8	8	0	8	6	6	5	5	6
^{16}O	"	2.1	^{15}O	9±8	10	10	0	10	13	14	13	13	17
"	"	"	^{15}N	15±8	18	17	1	18	13	14	13	13	17
^{12}C	Al	"	^{11}C	0±5	2	2	0	2	2	2	2	2	3
"	"	"	^{11}B	0±5	3	3	0	3	2	2	2	2	3
"	"	1.05	^{11}C	1±6	1	1	0	1	1	1	1	1	2
"	"	"	^{11}B	1±7	2	2	0	2	1	1	1	1	2
^{16}O	"	2.1	^{15}O	0±5	2	2	0	2	3	3	3	3	4
"	"	"	^{15}N	-1±9	4	4	0	4	3	3	3	3	4
^{12}C	C	"	^{11}C	-2±5	0.4	0.4	0	0.4	0.5	0.5	0.5	0.5	0.7
"	"	"	^{11}B	-1±4	0.6	0.6	0	0.6	0.5	0.5	0.5	0.5	0.7
"	"	1.05	^{11}C	-2±5	0.3	0.3	0	0.3	0.3	0.4	0.3	0.3	0.5
"	"	"	^{11}B	-2±5	0.5	0.5	0	0.5	0.3	0.4	0.3	0.3	0.5

Table 1 (cont.)

Projectile	Target	Energy (GeV/N)	Final State	σ_{expt}	σ_{WW} (theory)	σ_{E1} (theory)	σ_{E2} (theory)	$\sigma_{E1} + \sigma_{E2}$ (theory)	Parameterization #1 d = - 1.5 fm		Parameterization #2 d = - 2.4 fm		Parameterization #3 d = +1.0 fm
									σ_{WW}	$\sigma_{E1} + \sigma_{E2}$	σ_{WW}	$\sigma_{E1} + \sigma_{E2}$	σ
^{16}O	C	2.1	^{15}O	-1±4	0.5	0.5	0	0.5	0.7	0.7	0.7	0.7	1
"	"	"	^{15}N	-1±4	1	1	0	1	0.7	0.7	0.7	0.7	1
^{18}O	Ti	1.7	^{17}O	8.7±2.7	15	15	0	15	9	9	9	9	11
"	"	"	^{17}N	-0.5±1.0	3	3	0	3	7	7	7	7	9
"	Pb	"	^{17}O	136±2.9	155	154	4	158	96	98	91	92	93
"	"	"	^{17}N	20.2±1.8	28	27	2	29	77	78	73	74	74
"	U	"	^{17}O	140.8±4.1	191	189	5	194	117	119	110	112	108
"	"	"	^{17}N	25.1±1.6	34	33	3	36	94	95	88	89	87

Table 1 (cont.)

Projectile	Target	Energy (GeV/N)	Final State	σ_{expt}	σ_{WW} (theory)	σ_{E1} (theory)	σ_{E2} (theory)	$\sigma_{E1}+\sigma_{E2}$ (theory)	Parameterization #1 d = - 1.5 fm		Parameterization #2 d = - 2.4 fm		Parameterization #3 d = +1.0 fm
									σ_{WW}	$\sigma_{E1}+\sigma_{E2}$	σ_{WW}	$\sigma_{E1}+\sigma_{E2}$	σ
^{12}C	^{197}Au	2.1	^{196}Au	75±14	38	37	6	43	36	41	37	41	43
^{20}Ne	"	"	"	153±18	100	97	16	113	98	108	99	110	116
^{40}Ar	"	1.8	"	348±34	289	278	48	326	279	310	281	311	321
^{56}Fe	"	1.7	"	601±54	565	545	93	638	547	609	549	609	617
^{139}La	"	1.26	"	1970±130	2076	2001	367	2368	2018	2272	1966	2213	1979
^{16}O	"	60	"	280±30	215	207	15	222	223	229	241	247	252
"	"	200	"	440±40	278	268	17	285	291	297	316	322	325

Table 1 (cont.)

Projectile	Target	Energy (GeV/N)	Final State	σ_{expt} (mb)	σ_{WW} (theory)	σ_{E1} (theory)	σ_{E2} (theory)	$\sigma_{E1} + \sigma_{E2}$ (theory)	Parameterization #1 d = - 1.5 fm		Parameterization #2 d = - 2.4 fm		Parameterization #3 d = +1.0 fm
									σ_{WW}	$\sigma_{E1} + \sigma_{E2}$	σ_{WW}	$\sigma_{E1} + \sigma_{E2}$	σ
^{12}C	^{89}Y†	2.1	^{88}Y	9±12	12	12	1	13	12	13	12	13	15
^{20}Ne	"	"	"	43±12	32	31	3	34	32	34	32	34	39
^{40}Ar	"	1.8	"	132±17	90	88	9	97	90	95	89	94	106
^{56}Fe	"	1.7	"	217±20	175	171	16	187	175	186	172	182	202

Table 1 (cont.)

Projectile	Target	Energy (GeV/N)	Final State	σ_{expt} (mb)	σ_{WW} (theory)	σ_{E1} (theory)	σ_{E2} (theory)	$\sigma_{E1}+\sigma_{E2}$ (theory)	Parameterization #1 d = - 1.5 fm		Parameterization #2 d = - 2.4 fm		Parameterization #3 d = +1.0 fm
									σ_{WW}	$\sigma_{E1}+\sigma_{E2}$	σ_{WW}	$\sigma_{E1}+\sigma_{E2}$	σ
^{12}C	^{59}Co	2.1	^{58}Co	6±9	7	7	0	7	6	6	6	6	7
^{20}Ne	"	"	"	32±11	18	18	1	19	16	17	15	16	19
^{56}Fe	"	1.7	"	88±14	98	96	7	103	85	89	82	87	99
^{139}La	"	1.26	"	280±40	339	333	24	357	297	313	277	294	281