THE ASTROPHYSICAL JOURNAL, 501:911–919, 1998 July 10

UPDATED PARTIAL CROSS SECTIONS OF PROTON-NUCLEUS REACTIONS

R. SILBERBERG, C. H. TSAO, AND A. F. BARGHOUTY
Physics Department, Roanoke College, Salem, VA 24153
Received 1997 December 24; accepted 1998 February 17

ABSTRACT

We have updated our 1973–1990 cross section calculations by using the measured partial cross sections of the hydrogen target of the transport collaboration for beams of nuclei $10 \leq Z \leq 28$, of the hydrogen-carbon targets of Webber et al. for beams of $5 \leq Z \leq 28$, and of the University of Minnesota–Washington University–Caltech collaboration for beams of Fe, Kr, Ag, La, Ho, and Au nuclei. We have developed 18 modifications of equations of cross section parameters. Exact values of partial cross sections are important for evaluating the source composition of cosmic rays that have small relative abundances relative to the secondary spallation products, e.g., ^{13}C, ^{14}N, ^{18}O, ^{25}Mg, ^{26}Mg, and ^{31}P. The isotopic ratios ^{13}C/^{12}C, ^{18}O/^{16}O, ^{22}Ne/^{20}Ne, and (^{25}Mg + ^{26}Mg)/^{24}Mg are affected by the Wolf-Rayet star contributions to cosmic rays, while ^{14}N and particularly H and He are affected by the suppression of light nuclei in cosmic rays. The abundance of P is crucial in distinguishing between the two models: (1) stellar flare versus (2) enhanced nonvolatile grain-sputtering material contribution to cosmic rays. The earlier S and T cross sections of ^{20}Ne and ^{24}Mg into ^{14}N and ^{15}N are increased by a factor of 1.5, which reduces the calculated source component of N. The earlier calculated S and T cross sections of Au (and presumably of the Pt to Pb group), into elements with $\Delta Z < 23$ have to be reduced by about 15%, while the even-odd Rudstam parameters are eliminated for the heaviest nuclei. As a result, the calculated secondary components of $61 < Z < 74$ are reduced and the calculated primary components are enhanced. This reinforces the need for an enhancement of *r*-process elements with $Z > 60$ above the solar system abundances.

Subject headings: atomic processes — cosmic rays — nuclear reactions, nucleosynthesis, abundances

1. INTRODUCTION

About half of the cosmic-ray nuclides with atomic numbers $Z \geq 6$ are known to have suffered nuclear spallation in the interstellar gas between the source regions and arrival at Earth. Hence, the partial and total cross sections are essential for the analysis of cosmic-ray data.

The partial inelastic cross sections σ_{ij} (for the production of species j from spallation of species i) have systematic regularities that permit the formulation of semiempirical equations. Rudstam (1966) noted that these systematic regularities depend on the mass difference of the target and product nuclides and on the neutron-to-proton ratio of the product nuclides, upon which he formulated semiempirical equations. Silberberg & Tsao (1973a, 1973b) have constructed a semiempirical equation resembling that of Rudstam (1966), with additional parameters, and extended the regions of target and product mass intervals where these parameters apply. Of particular importance to cosmic-ray investigations was the extension to lighter targets like C, N, O, Ne, Na, Mg, and the light products Li, Be, and B, and to peripheral reactions with $\Delta Z < 3$, ΔZ being the charge change in the reaction. As experimental data from heavy ion beams became available, we improved the equations and parameters further, as described by Silberberg, Tsao, & Letaw (1985) and Silberberg & Tsao (1990). For nuclei with $Z \leq 28$, Webber, Kish, & Schrier (1990) carried out detailed measurements (with a hydrocarbon target) of the production of both stable and radioactive isotopes, and derived parametric semiempirical equations. Recently the transport collaboration of Chen et al. (1995, 1997a, 1997b), Knott et al. (1993, 1996, 1997), and Tull et al. (1993) carried out highly precise measurements with heavy ion beams incident on a hydrogen target. Spallation of ultraheavy nuclei like Kr, Ag, La, Ho, and Au has been explored by Binns et al. (1987), Cummings et al. (1990), Garrard et al. (1995), Geer et al. (1995), Nilsen et al. (1995), and Waddington et al. (1997) from the University of Minnesota, Washington University, and Caltech collaboration, with elemental (i.e., no isotopic) resolution. Using these new measurements, we have updated our semiempirical proton-nucleus cross sections as we describe them below while the updated nucleus-nucleus cross sections are described in the accompanying paper.

Formulae for the fragmentation cross sections of ^{4}He have been developed by Cucinotta (1993).

2. NEW IMPROVED SEMIEMPIRICAL CROSS SECTIONS

For completeness, this section details our latest (1996 and 1997) cross section revisions.[1]

1. The production of the highly stable semimagic nuclei ^{12}C and ^{16}O is enhanced by a factor of 2 from targets of Ne, Na, Mg, and Al. In the earlier calculated cross sections various (p, pα) reactions were enhanced, including $^{20}\mathrm{Ne} \rightarrow {}^{16}\mathrm{O}$. To avoid double enhancement, the earlier enhancement factor for the reaction $^{20}\mathrm{Ne} \rightarrow {}^{16}\mathrm{O}$ is eliminated. This modification is based on Knott et al. (1993), Webber et al. (1990), Chen et al. (1995), and Guzik (1997).

2. Production of F from nuclei Ne to S ($10 \leq Z_t \leq 16$) is suppressed by a factor of 0.8 based on Knott et al. (1993).

3. For targets with $Z_t = 9$–16, products of $Z \geq 8$ and $N_n - N_p = -1$ are reduced by a factor of 0.7, and for $Z_t =$ 6–11, products with $N_n - N_p = -2$ are suppressed by a factor of 0.4 based on Webber et al. (1990).

4. For $Z_t = 17$–20, products with $Z > 10$, the *p*-rich products ($N_p - N_n \geq 1$) and *n*-rich products ($N_n - N_p \geq 3$) are suppressed by a factor of 0.5 based on Chen et al. (1997a, 1997b).

[1] Implementation of which in readily usable and transportable routines is available from http://SPDSCH.PHYS.LSU.EDU.

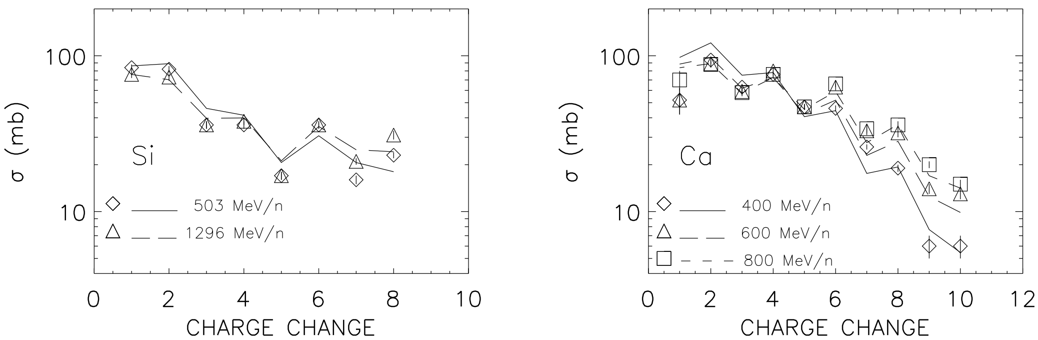

FIG. 1.—*Left:* Si charge-change cross sections. Lines are drawn connecting our calculated values to help visualize trends in the calculations. Data are from Knott et al. (1997). *Right:* Ca charge-change cross sections. Data are from Knott et al. (1997).

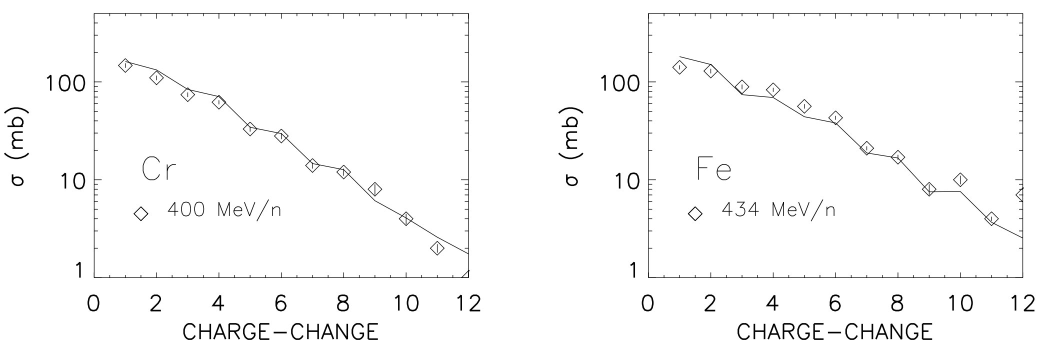

FIG. 2.—*Left:* Cr charge-change cross sections. Data are from Knott et al. (1997). Solid lines connect our calculated values. *Right:* Fe charge-change cross sections. Data are from Knott et al. (1997).

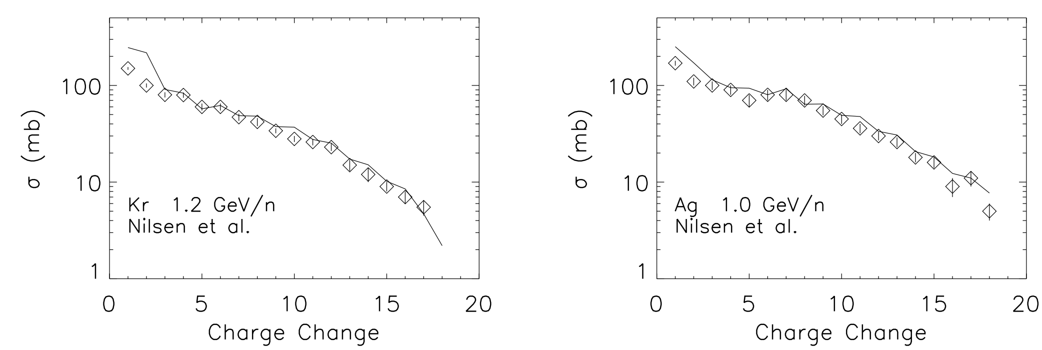

FIG. 3.—*Left:* Charge-change cross sections of Kr at 1.2 GeV nucleon^{-1}. Solid lines connect our calculated values. Measurements are those of Nilsen et al. (1995). *Right:* Charge-change cross sections of Ag at 1.0 GeV nucleon^{-1}. Measurements are those of Nilsen et al. (1995).

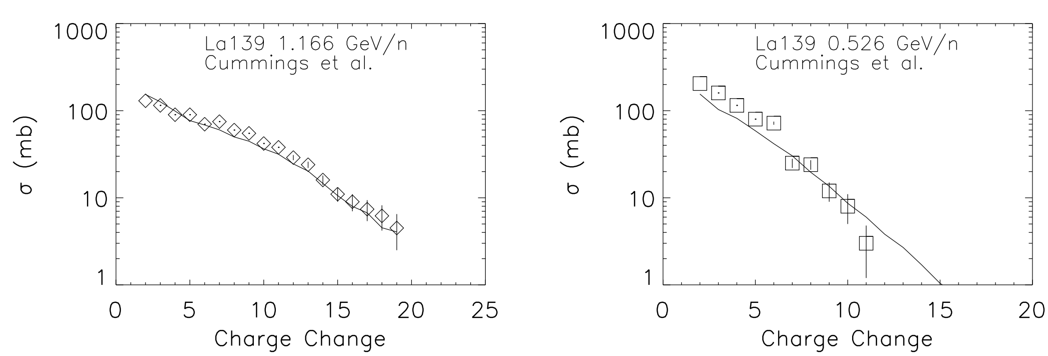

FIG. 4.—*Left:* Charge-change cross sections of ^{139}La at 1.166 GeV nucleon^{-1}. Solid lines connect our calculated values. Measurements are those of Cummings et al. (1990). *Right:* Charge-change cross sections of ^{139}La at 0.526 GeV nucleon^{-1}. Measurements are those of Cummings et al. (1990).

5. Products with $\Delta Z = 1$ or 3 are suppressed by a factor of 0.7 for the even-even nuclei with $N_p = N_n$ and $18 \leq Z \leq 20$ based on Knott et al. (1993).

6. The production of Mg and Si from ^{40}Ca is enhanced by a factor of 2.4 and of Ar and S from ^{40}Ca by 1.6 based on Knott et al. (1993).

7. The production of the even-elements Ca, Ar, and S, is enhanced by a factor of 1.3 from ^{52}Cr and ^{56}Fe based on Knott et al. (1993). Also, the products with $Z = 19$–22 from ^{58}Ni are enhanced by 1.4 based on Knott et al. (1993).

8. The production of ^{14}N and ^{15}N from ^{20}Ne and ^{24}Mg is enhanced by a factor 1.5 based on Webber et al. (1990).

9. For the targets ^{24}Mg, ^{28}Si, and ^{32}S, the reactions (p, $p\alpha$) and (p, $2p$) are enhanced by a factor of 1.6 and (p, pd) by 1.8 based on Webber et al. (1990). For target nuclei with $Z_t > 5$ and $A_t < 35$, the (p, $3p$) cross section is restricted to

$$\sigma(p, 3p) \leq 0.0022 A^2 \leq \sigma_s , \quad (1)$$

where σ_s is the corresponding spallation cross section.

10. For products between $A = 100$ and 180, the e-e, e-o, o-e, o-o (i.e., even-even, even-odd, etc.) factors are linearly phased out. The modification is based on Geer et al. (1995).

11. The spallation and peripheral cross sections for $A = 180$–200 are reduced by a factor of 0.84. This reduction is assumed to phase out (i.e., factor = 1.0) at $A = 100$. The modification is based on Geer et al. (1995). The assumed correction factor F is given by

$$F = 1 - 0.2(A_t - 100)/100 . \quad (2)$$

12. The enhancement by electromagnetic dissociation of (p, pn) cross sections at 10 GeV, for $Z = 80$ is about 1.15 based on Kaufman et al. (1976). The increase from 1.0 at $Z = 1$ is assumed to be proportional to Z^2, with a factor F given by

$$F = 1 + 0.15(Z_t/80)^2 . \quad (3)$$

13. The (p, $4pxn$) and (p, $5pxn$) reactions for $A > 100$ are to be calculated for the n-rich peripheral products from (p, $5pxn$)/(p, $4pxn$) = (p, $4pxn$)/(p, $3pxn$) = 0.1. For the neutron deficient portion from the spallation (Rudstam-like equation), including the peak calculated cross section, we assume a linear interpolation from this peak to the peripheral region.

14. The previous reduction (based on older data) of production cross sections of iodine is now eliminated.

15. Neutron-rich products of ^{16}O and ^{20}Ne with $N_n - N_p > 1$ and $Z > 4$ are reduced by a factor of 0.7.

16. For targets Cr to Ni ($Z_t = 24$–28), the n-rich products ($Z = 21$–23) with $N_n - N_p \geq 6$ are reduced by a factor of 0.5 based on Webber et al. (1990).

17. Near the energy $E = 1200$ MeV, the products with large $\Delta Z \geq 5$ from heavy targets ($Z_t > 30$) are corrected empirically to be close to the measured values based on data from Binns et al. (1987), Cummings et al. (1990), Geer et al. (1995), and Nilsen et al. (1995) according to the factor

$$F = 1 + 0.9 \exp[-(|E - 1230|/150)^2] \times \exp[-(|\Delta Z - 12|/5)^2] . \quad (4)$$

18. The asymptotic high-energy threshold for the spallation of heavy nuclei is shifted from 3 down to 2 GeV nucleon^{-1}.

3. COMPARISONS TO EXPERIMENTAL DATA

Comparisons of our calculations to experimental data from the transport collaboration (Knott et al. 1993) are shown in Figure 1 for Si at energies 500 and 1300 MeV n^{-1}, and for Ca from 400 to 800 MeV nucleon^{-1}. In Figure 2 similar comparisons near 400 MeV nucleon^{-1} are shown for spallation of Cr and Fe.

Next we explore the spallation of heavy, trans-iron nuclei. Comparisons of our calculations to the measured cross sections of Kr at 1.2 GeV nucleon^{-1} and of Ag at 1.0 GeV nucleon^{-1} are shown in Figure 3. The data are from Nilsen et al. (1995). Comparisons of our calculations to the measured cross sections of La at 1.166 GeV nucleon^{-1} and 0.526 GeV nucleon^{-1} are shown in Figure 4. The measured values are from Cummings et al. (1990). Comparisons between the measured and calculated cross sections of Au at 0.56, 0.92, and 10.6 GeV nucleon^{-1} are shown in Figure 5. The data are from Geer et al. (1995) and Garrard et al. (1995).

There are many measured partial cross sections for the production of isotopes, which we used to derive our semiempirical cross sections. Only a limited sample is displayed in the figures below. More such data are presented by Bardayan et al. (1997) for products of Mo and Te generated by protons at 1.8 GeV, and Te by protons at 5.0 GeV.

Figure 6 displays the breakup cross section of ^{16}O into isotopes of O, N, C, and B, respectively. The experimental values are from Olson et al. (1983). The energy of the beam of ^{16}O particles was 2.1 GeV nucleon^{-1}.

The products of neutron-rich nuclei also tend to be neutron-rich, and the degree of enhancement is essential for semiempirical formulations. In Figure 7 the breakup of the neutron-rich nuclide ^{22}Ne into F, O, and N is shown at 0.581 GeV nucleon^{-1}. The experimental values are from Chen et al. (1995). These isotopic distributions are to be compared to those from the breakup of ^{20}Ne discussed further below.

The calculated and measured cross sections of ^{32}S into isotopes of Si, Al, Mg, and Ne at 0.6 and 0.4 GeV nucleon^{-1} are displayed in Figure 8. The experimental values are from Tull et al. (1993).

Extensive cross section measurements ranging from ^{11}B to ^{58}Ni as beam particles were carried out by Webber et al.

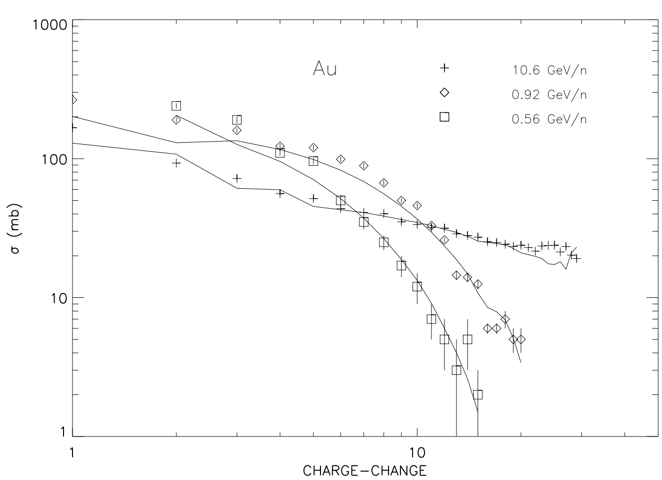

FIG. 5.—Au charge-change cross sections. Solid lines connect our calculated values. Data are from Geer et al. (1995) and Garrard et al. (1995).

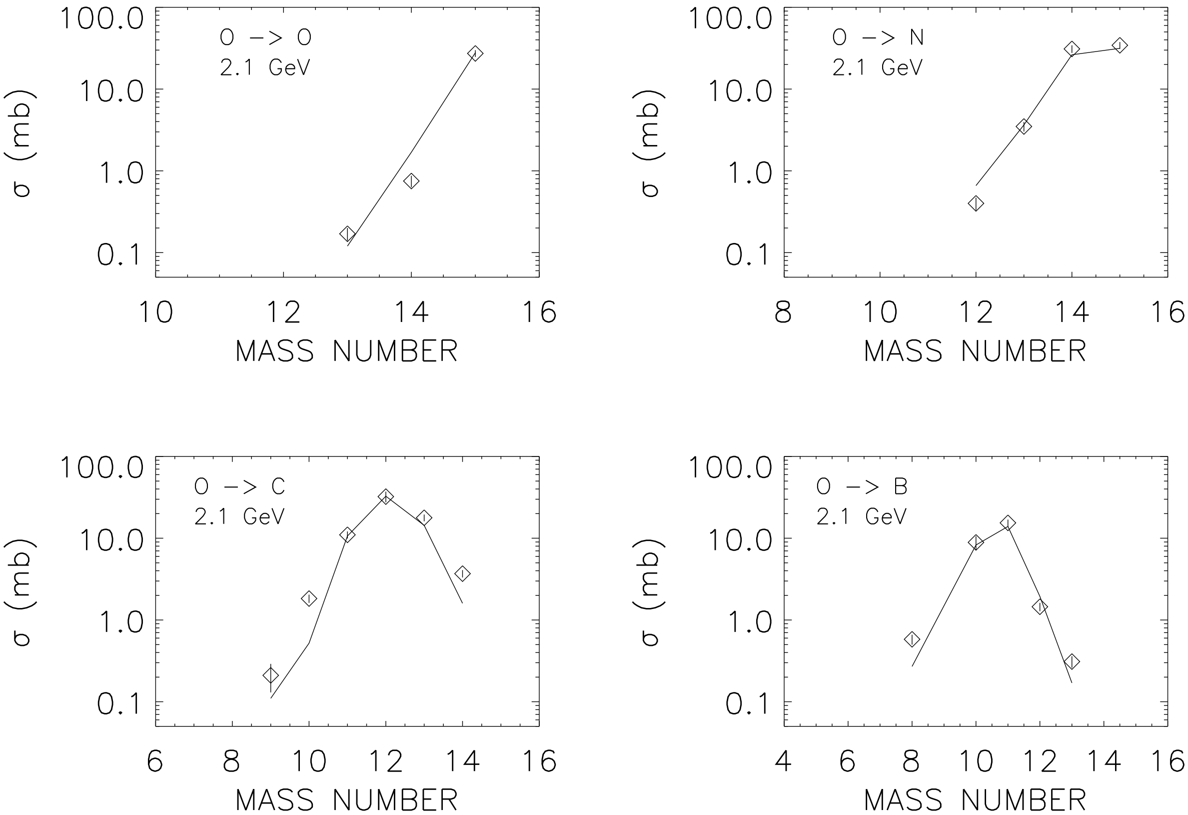

FIG. 6.—Isotopic yields of O, N, C, B from breakup of ^{16}O at 2.1 GeV nucleon^{-1}. Solid lines connect our calculated values. Measurements are those of Olson et al. (1983).

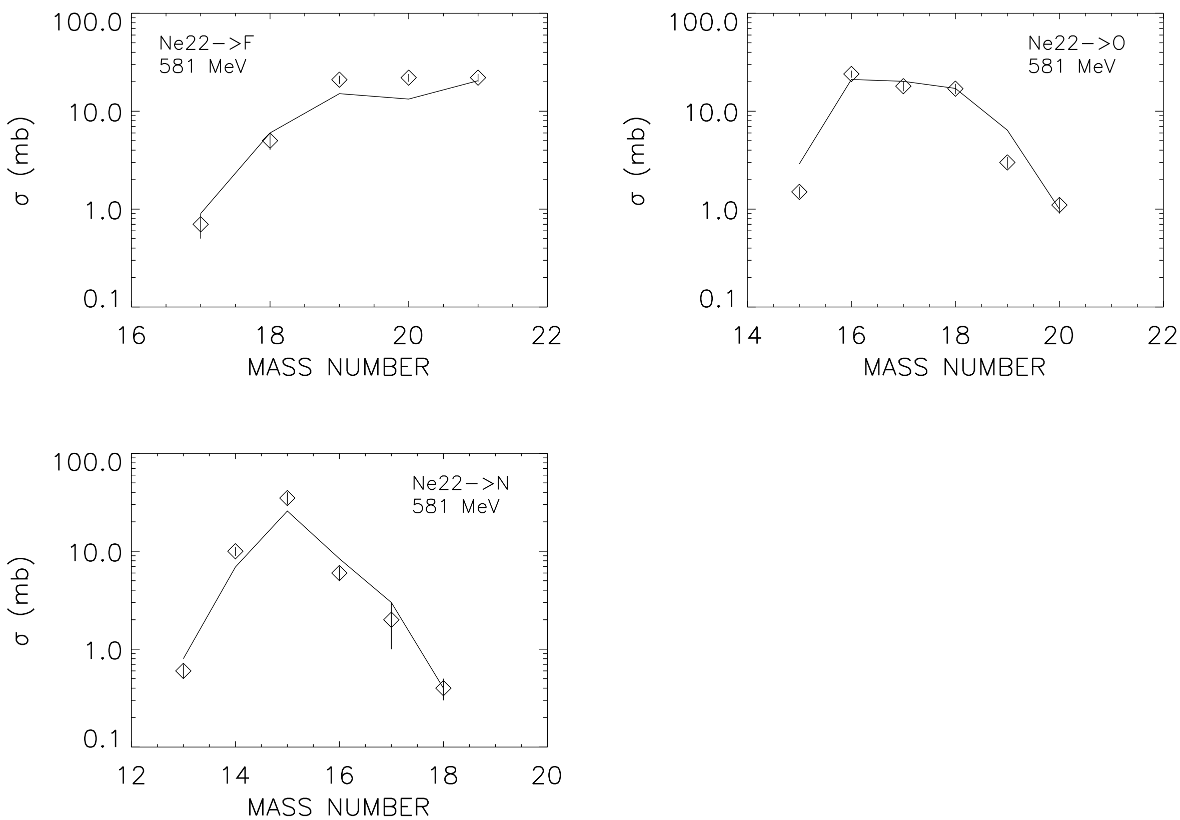

FIG. 7.—Isotopic yields of F, O, and N from breakup of ^{22}Ne at 0.581 GeV nucleon^{-1}. Solid lines connect our calculated values. Measurements are those of Chen et al. (1995).

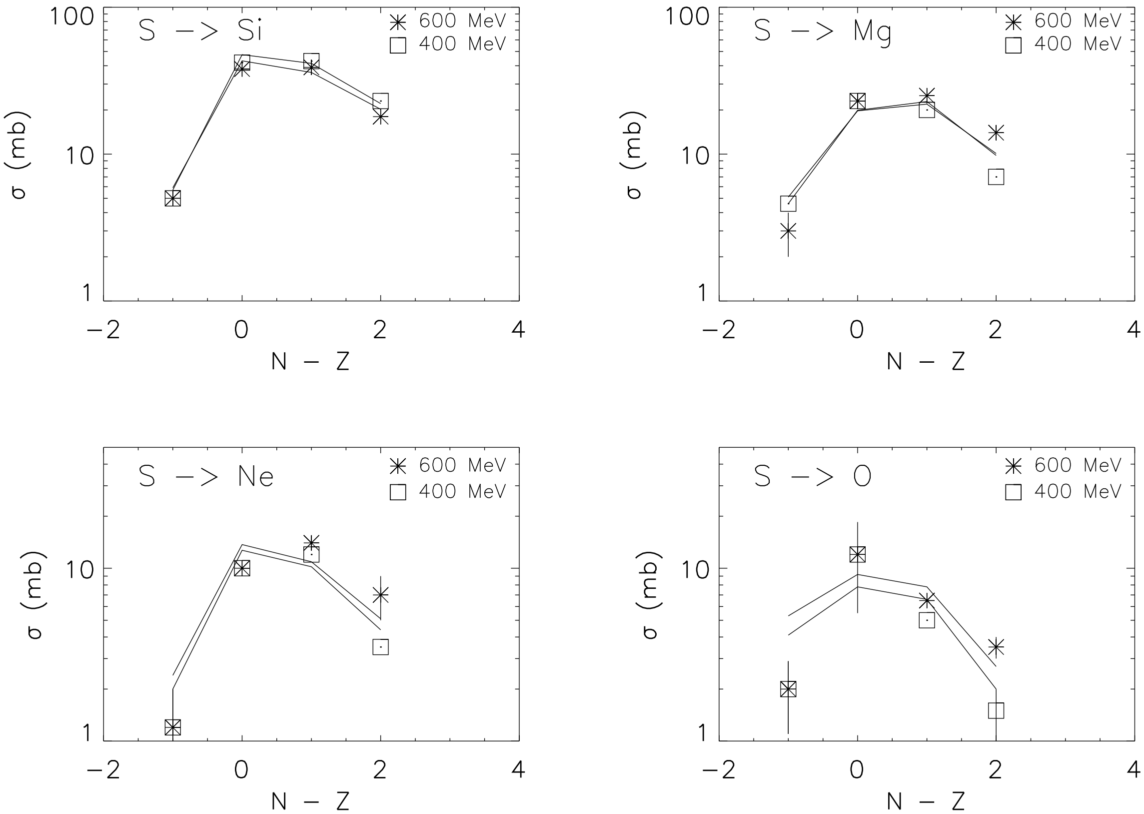

FIG. 8.—Isotopic yields of Si, Al, Mg, and Ne from breakup of ^{32}S at 0.6 and 0.4 GeV nucleon^{-1}. Solid lines connect our calculated values. Measurements are those of Tull et al. (1993).

(1990) at energies near 0.6 GeV nucleon^{-1}. They used a hydrocarbon target, and the cross sections with hydrogen were deduced by subtracting the contribution of carbon. These data are displayed in the figures referred to below.

Figure 9 shows the production of isotopes of Be from ^{11}B and ^{12}C. The values from ^{11}B should be remeasured since these values and those of Raisbeck & Yiou (1971) and Yiou & Raisbeck (1972), which are also shown in Figure 9 (*left*), are mutually inconsistent.

Figure 10 displays the breakup cross sections of ^{20}Ne into isotopes of F, O, N, and C; Figure 11 displays the breakup cross sections of ^{24}Mg into isotopes of F and O; and Figure 12 displays the breakup of ^{28}Si into isotopes of Mg, Na, and Ne.

Figure 13 displays the spallation cross sections of ^{56}Fe into isotopes of Cr, V, Ti, and Sc.

Figure 14 compares the measured cross sections of Bardayan et al. (1997) of ^{42}Mo into isotopes of Rb, Kr, and Br to our calculations.

Figure 15 shows experimental versus calculated cross sections plotted using the experimental values for elements of Webber et al. (1990). Figure 15 (*left*) is for the revised semiempirical equations reported in this work, while Figure 15 (*right*) shows a comparison to the parametric equations of

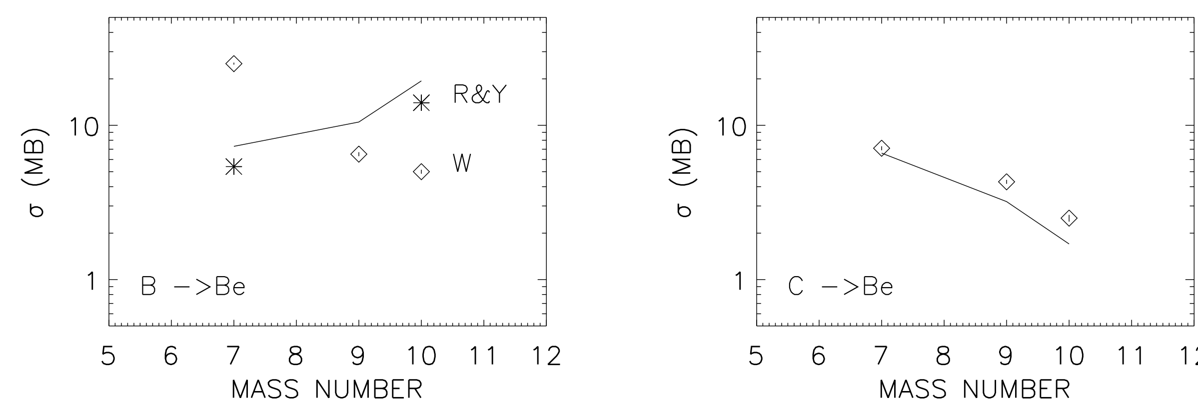

FIG. 9.—*Left:* Isotopic yields of Be from ^{11}B at energies near 0.6 GeV nucleon^{-1}. Solid lines connect our calculated values. The measured values of Webber et al. (1990), Raisbeck & Yiou (1971), and Yiou & Raisbeck (1972) are shown. *Right:* Isotopic yields of Be from ^{12}C at 0.6 GeV nucleon^{-1}. The measurements are those of Webber et al. (1990).

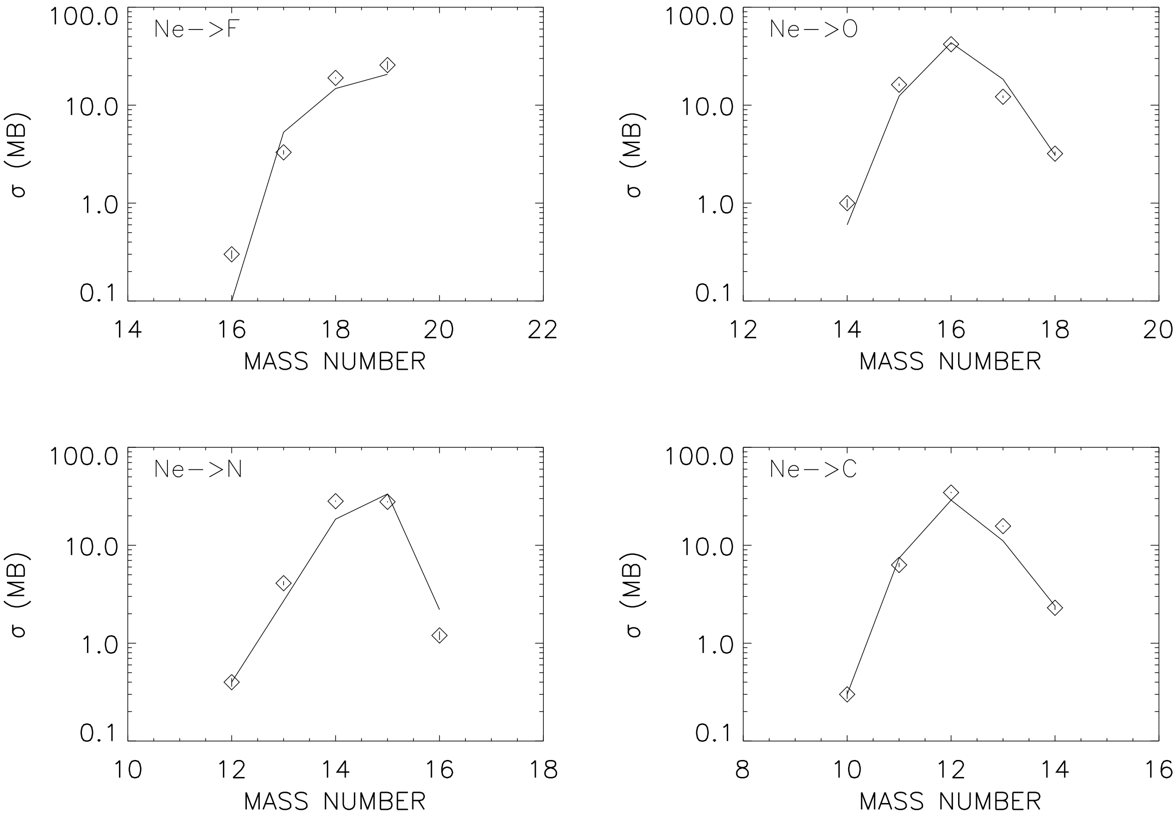

FIG. 10.—Isotopic yields of F, O, N, C from ^{20}Ne at 0.6 GeV nucleon^{-1}. Solid lines connect our calculated values. The measurements are those of Webber et al. (1990).

Webber et al. (1990). The former has a standard deviation of about 20%, while that of Webber et al. (1990) has about 10% for the set in which their measured data were used to derive the parametric equations. For values unmeasured by Webber et al. (1990), the parametric equations yield a considerably poorer fit; the cross section of ^{22}Ne to ^{18}O is underestimated by a factor of 4, while our equations (see Fig. 7, *top right*) yield a near perfect fit. According to Guzik (1997), the overall fit to the transport collaboration data of the calculations of Webber et al. (1990) and of the previous (i.e., preupdated) calculations of Silberberg & Tsao (1990) are quite similar.

The parametric equations of Webber et al. (1990) are not applicable to heavy nuclei with $Z > 28$. The equations developed for these nuclei by the University of Minnesota–Washington University–Caltech collaboration apply to the elements they measured and fitted, but are not designed for product isotopes. Relatively recent isotopic measurements, especially those of Cumming, Stoenner, & Haustein (1976) for Cu, of Porile, Cole, & Rudy (1979) for Ag, and of Kaufman et al. (1976) and of Kaufman & Steinberg (1980) for Au, were used by us to develop improved semiempirical equations, Silberberg & Tsao (1990). Our fit to the spallation products of Cu has a standard deviation of only 10%.

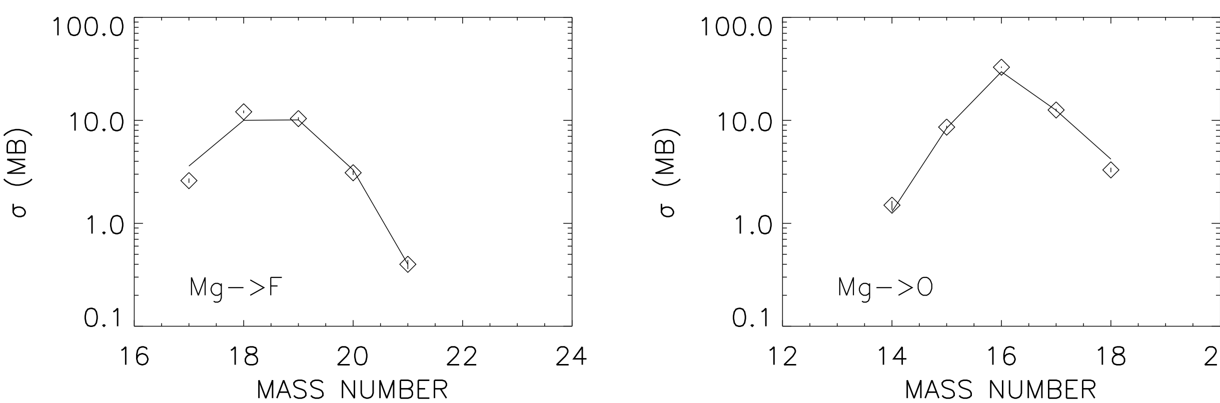

FIG. 11.—Isotopic yields of F and O from ^{24}Mg at 0.6 GeV nucleon^{-1}. Solid lines connect our calculated values. The measurements are those of Webber et al. (1990).

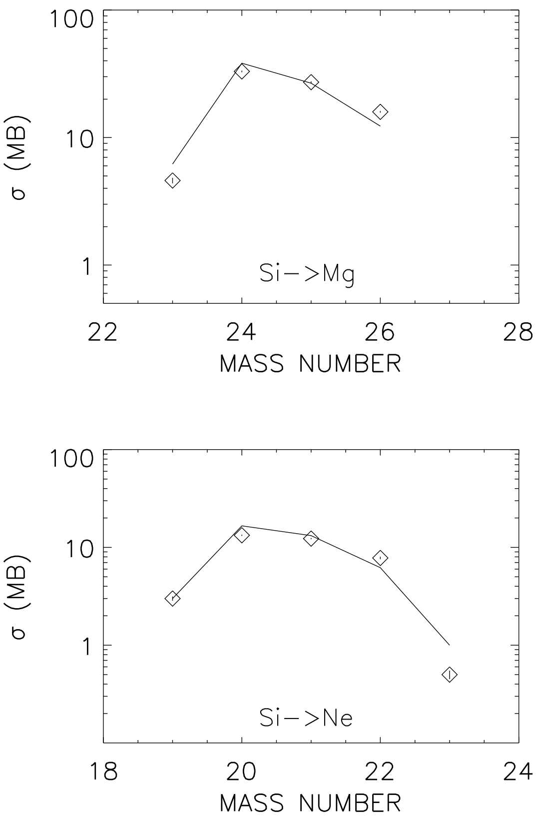

FIG. 12.—Isotopic yields of Mg, Na, Ne from ^{28}Si at 0.6 GeV nucleon^{-1}. Solid lines connect our calculated values. The measurements are those of Webber et al. (1990).

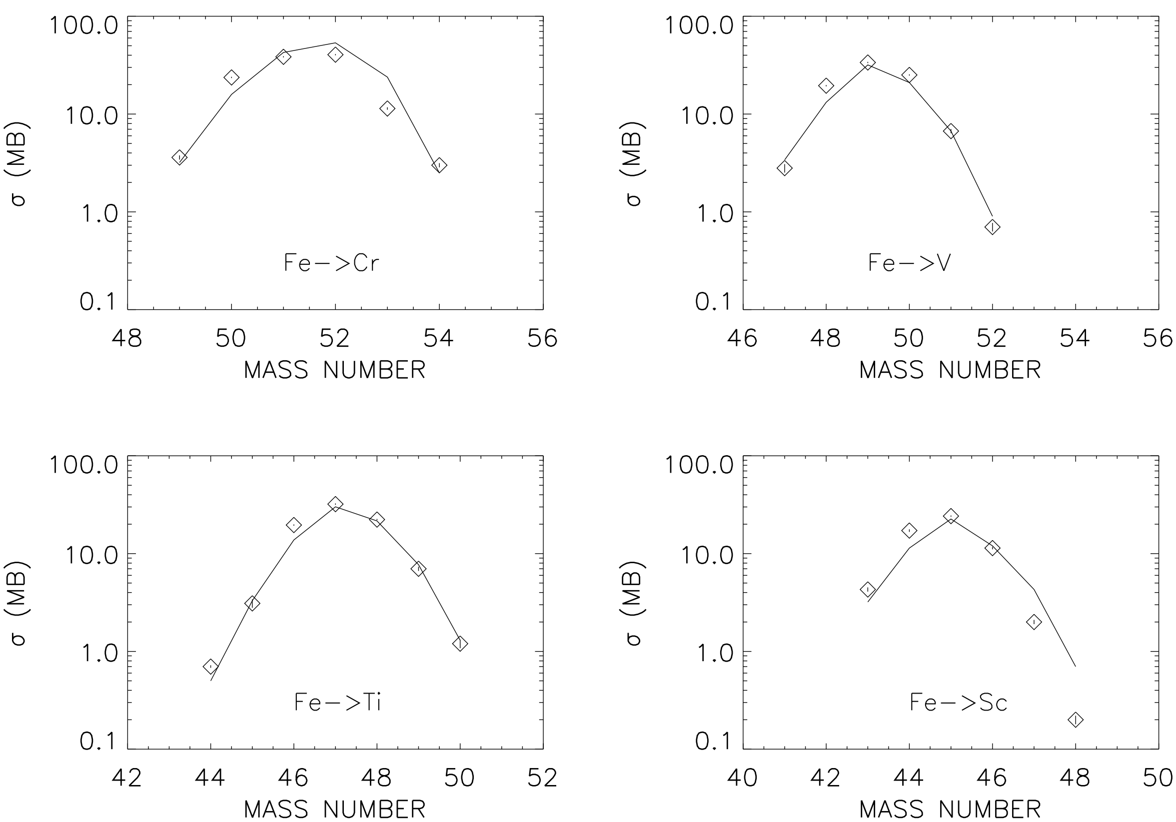

FIG. 13.—Isotopic yields of Cr, V, Ti, and Sc from Fe at 0.6 GeV nucleon^{-1}. Solid lines connect our calculated values. The measurements are those of Webber et al. (1990).

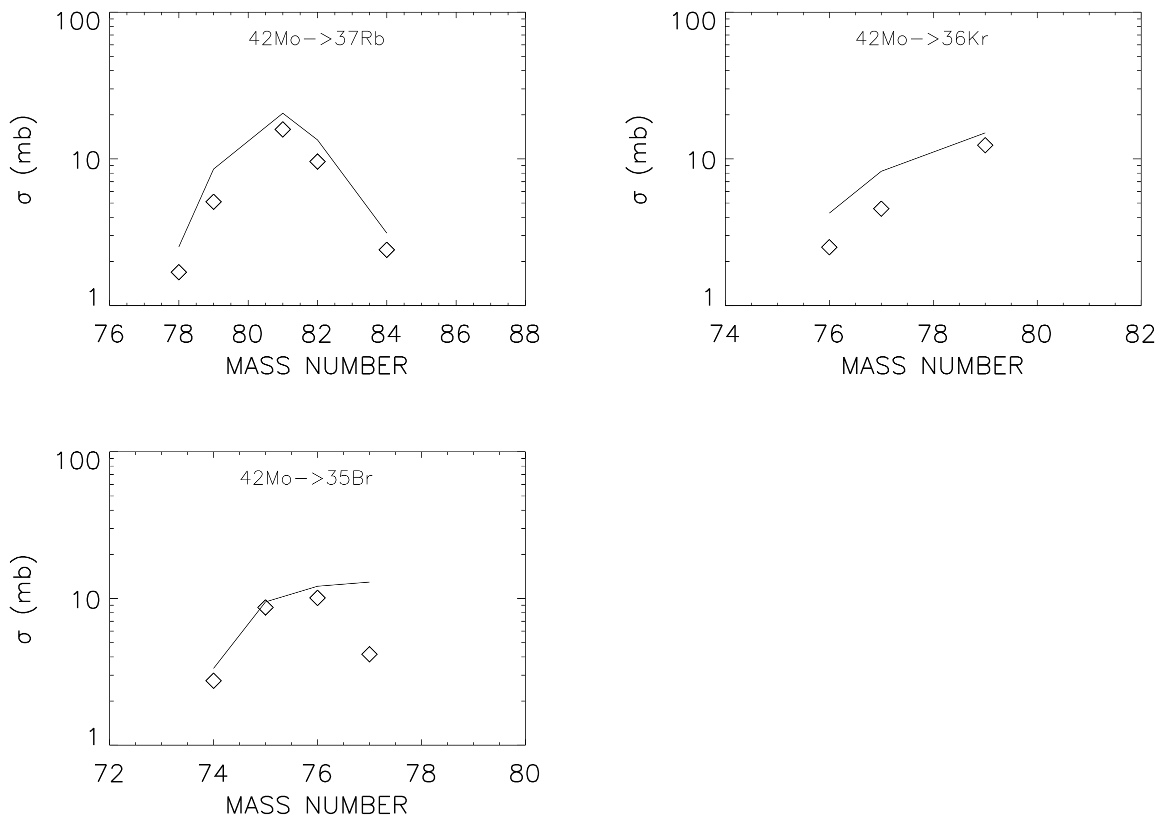

FIG. 14.—Isotopic yields of Rb, Kr, and Br from Mo at 1.85 GeV. Solid lines connect our calculated values. The measurements are those of Bardayan et al. (1997).

Our calculated experimental isotopic yields of Cu and Au are shown by Letaw, Silberberg, & Tsao (1987).

4. TOTAL INELASTIC CROSS SECTIONS

In addition to partial cross sections, cosmic-ray propagation calculations also require precise estimates of total inelastic cross sections. To illustrate, we have compared such estimates from Letaw, Silberberg, & Tsao (1983), Sihver et al. (1993), Wellish & Axen (1996), and Tripathi, Cucinotta, & Wilson (1997) as shown in Figure 16. The experimental points are sampled from those of Tripathi et al. (1997) which appear to fit their parametric calculations rather well.

The work is supported by NASA grant NAG5-5053 and by NASA-JOVE grant NAG8-1208 (AFB). The authors are also grateful for the use of computer facilities at the Naval Research Laboratory, Washington, D.C.

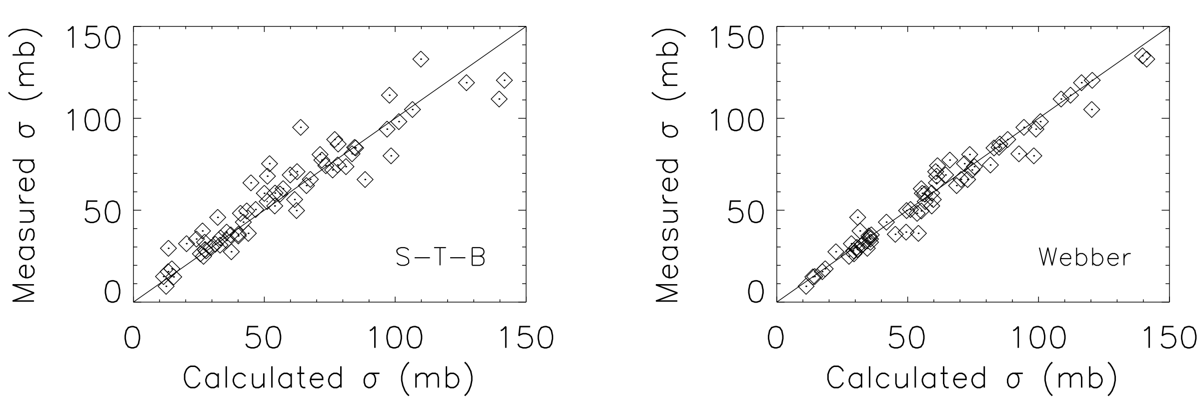

FIG. 15.—*Left:* Experimental vs. calculated cross sections, plotted using experimental values of Webber et al. (1990) for product elements and our semiempirical values. *Right:* Experimental vs. calculated cross sections, plotted using experimental values of Webber et al. (1990) for products elements, and the parametric calculations of Webber et al. (1990).

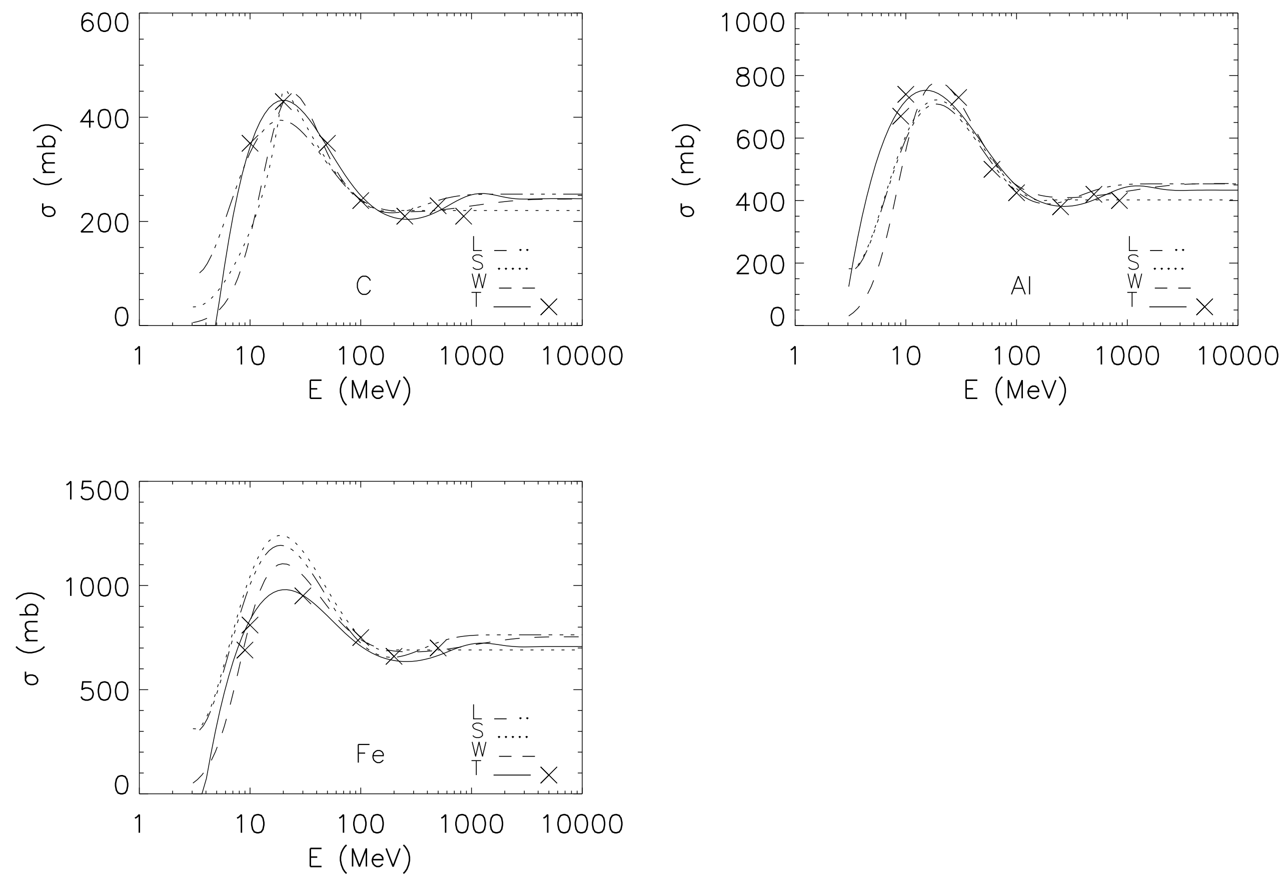

FIG. 16.—Energy dependence of the total inelastic proton-nucleus cross sections of C, Al, and Fe. The data points are sampled from those shown in Tripathi et al. (1997).

REFERENCES

Bardayan, D. W., et al. 1997, Phys. Rev. C, 55, 820
Binns, W. R., Garrard, T. L., Israel, M. H., Klarmann, J., Stone, E. D., & Waddington, C. J. 1987, Phys. Rev. C, 36, 1820
Chen, C. X., et al. 1995, in Proc. 24th Int. Cosmic Ray Conf. (Rome), 3, 184
———. 1997a, Phys. Rev. C, 56, 1536
———. 1997b, ApJ, 179, 504
Cucinotta, F. A. 1993, NASA Tech. Paper 3354
Cumming, J. B., Stoenner, R. W., & Haustein, P. E. 1976, Phys. Rev. C, 14, 1554
Cummings, J. R., Binns, W. R., Garrard, T. L., Israel, M. H., Klarmann, J., Stone, E. C., & Waddington, C. J. 1990, Phys. Rev. C, 42, 2530
Garrard, T. L., Cummings, J. R., Geer, L. Y., Klarmann, J., Nilsen, B. S., & Waddington, C. J. 1995, in Proc. 24th Int. Cosmic Ray Conf. (Rome), 3, 192
Geer, L. Y., Klarmann, J., Nilsen, B. S., Waddington, C. J., Binns, W. R., Cummings, J. R., & Garrard, T. L. 1995, Phys. Rev. C, 52, 334
Guzik, T. G. 1997, in Proc. 25th Int. Cosmic Ray Conf. (Durban), 2, 317
Kaufman, S. B., Weisfield, M. W., Steinberg, E. P., Wilkins, B. D., & Henderson, D. 1976, Phys. Rev. C, 14, 1121
Kaufman, S. B., & Steinberg, E. P. 1980, Phys. Rev. C, 22, 167
Knott, C. N., et al. 1993, in Proc. 23rd Int. Cosmic Ray Conf. (Calgary), 2, 187
———. 1996, Phys. Rev. C, 53, 347
———. 1997, Phys. Rev. C, 56, 398
Letaw, J. R., Silberberg, R., & Tsao, C. H. 1983, ApJS, 51, 271
———. 1987, in Proc. 20th Int. Cosmic Ray Conf. (Moscow), 2, 133
Nilsen, B. S., Waddington, D. J., Cummings, J. B., Garrard, T. L., & Klarmann, J. 1995, Phys. Rev. C, 52, 3277
Olson, D. L., Berman, B. L., Greiner, D. E., Heckman, H. H., Lindstrom, P. J., & Crawford, H. A. 1983, Phys. Rev. C, 28, 1602
Porile, N. T., Cole, G. D., & Rudy, C. R. 1979, Phys. Rev. C, 19, 2288
Raisbeck, G. M., & Yiou, F. 1971, Phys. Rev. Lett., 27, 875
Rudstam, G. 1966, Z. Naturforsch., A21, 1027
Sihver, L., Tsao, C. H., Silberberg, R., Kanai, T., & Barghouty, A. F. 1993, Phys. Rev. C, 47, 1225
Silberberg, R., & Tsao, C. H. 1973a, ApJS, 25, 315
———. 1973b, ApJS, 25, 335
———. 1990, Phys. Rep., 191, 351
Silberberg, R., Tsao, C. H., & Letaw, J. R. 1985, ApJS, 58, 873
Tripathi, R. K., Cucinotta, F. A., & Wilson, J. W. 1997, NASA Tech. Paper 3621
Tull, G. E., et al. 1993, in Proc. 23rd Int. Cosmic Ray Conf. (Calgary), 2, 163
Waddington, C. J., Cummings, J. R., Garrard, T., Hink, P., & Nilsen, B. S. 1997, in Proc. 25th Int. Cosmic Ray Conf. (Durban), 2, 345
Webber, W. R., Kish, J. C., & Schrier, D. A. 1990, Phys. Rev. C, 41, 547
Wellish, H. P., & Axen, D. 1996, Phys. Rev. C, 54, 1329
Yiou, F., & Raisbeck, G. M. 1972, Phys. Rev. Lett., 29, 372