# Updated Semiempirical Cross Sections for Cosmic Rays Propagation

**C.H. Tsao, R. Silberberg, and A.F. Barghouty**[1]
*Physics Department, Roanoke College, Salem, VA 24153, USA*

### Abstract

High precision cross sections estimates are crucial to help infer the source abundance of elements and isotopes that have large secondary components in the arriving cosmic-ray abundances, e.g., N, Na, Al and P. We propose here correction factors to further refine our recent semiempirical cross sections estimates. Factors for elements that are nearly purely secondary, e.g, B and F, are also proposed for improved propagation calculations. We also point to some inconsistencies in the measured cross sections. The nucleus-nucleus component, including scaling factors, as well as a non-nuclear contribution to the inelastic cross section therein are also discussed.

## 1 Introduction:

The cross sections estimates (Tsao et al. 1998 and Silberberg et al. 1998) we recently updated can still be further improved by replacing certain cross sections by the actual measured values, while retaining our equations for energy dependence, when used for energies at which there are no measurements yet (see Sec. 2). To inspire future measurements, there are some inconsistencies in the experimental data that we point out in Sec. 3. Future publications, e.g., spallation of $^{32}$S on protons, by the Transport Collaboration may prove significant to our recent semiempirical estimates.

We have explored various procedures for calculating the charge-changing cross sections of nucleus-nucleus reactions (see Sec. 4). About equally good estimates are obtained with our procedures with Sihver et al. (1993) as with Tsao et al. (1998). [The new code for the nucleus-nucleus cross-section calculation will soon be deposited at the web-site: //spdsch.phys.lsu.edu.] In addition to partial cross sections, semiempirical expressions for the total inelastic cross sections are also discussed in Tsao et al. (1998, 1999) and Silberberg et al. (1998). In particular, the contribution of electromagnetic dissociation can be significant, as we briefly allude to its role here.

## 2 Correction Factors for Some Reactions:

The semiempirical cross sections of nuclei with $Z \leq 30$ have a precision of about 20%. In cosmic-ray propagation calculations a higher degree of precision is required. The source abundances of $^{14}$N, $^{23}$Na, $^{27}$Al and $^{31}$P are difficult to determine unless their large secondary component and the pertinent production cross sections are well known. The mean-path-length traversed by cosmic rays enters into much of cosmic rays data analysis. The pertinent cross sections $^{12}$C and $^{16}$O into $^{10}$B and $^{11}$B and $^{20}$Ne into $^{19}$F, for example, ought to be known as precisely as possible.

The partial cross sections of reactions $(ij)$ at energy/nucleon are calculated from $\sigma_{ij}$(E) = $a_{ij}\sigma_{ij}^{se}$(E). Here $\sigma_{ij}^{se}$(E) is the semiempirically calculated cross section at an energy/nucleon E. The correction factors $a_{ij}$ for the calculation of the abundances, including those alluded to above, are given for the following reactions: $^{40}$Ca$\rightarrow^{31}$S, 0.7; $^{40}$Ca$\rightarrow^{31}$P, 1.3; $^{40}$Ar$\rightarrow^{31}$P, 1.2; $^{36}$Ar$\rightarrow^{31}$S, 1.2; $^{28}$Si$\rightarrow^{26}$Mg, 1.3; $^{24}$Mg$\rightarrow^{23}$Mg, 1.4; $^{20}$Ne$\rightarrow^{19}$Ne, 1.3; $^{20}$Ne$\rightarrow^{19}$F, 1.2; $^{16}$O $\rightarrow^{14}$N, 0.8; $^{16}$O $\rightarrow^{14}$C, 1.2; $^{12}$C $\rightarrow^{11}$B, 0.8; $^{12}$C $\rightarrow^{10}$B, 0.7; $^{12}$C $\rightarrow^{10}$Be, 1.5. These correction factors are based on the measurements from Chen et al. (1997) for Ca, Knott et al. (1977) for Ar, and Webber et al. (1990, 1998) for the remainder of the reactions.

With these factors the mean-path-length $X$(g/cm$^2$) estimate from measured B/C ratio is larger. Due to $a_{ij}$ and the increased path length, the secondaries are generally increased. For N, though, the secondary component is reduced while the primary is increased. But for Na and P, the secondary component is increased while the primary one is decreased.

[1]Present address: California Institute of Technology, MC 220-47, Pasadena, CA 91125, USA.

# 3 Some Inconsistencies in Cross Sections Measurements:

One of the most important nuclides for evaluating the galactic confinement time is $^{10}$Be (e.g., Tsao et al. 1999). The cross section of $^{11}$B into $^{10}$Be is relatively large, $\sim$ 10 mb, which is about 4 times larger than that of $^{12}$C into $^{10}$Be. The abundance of $^{12}$C considerably exceeds $^{11}$B. Yet, the yield of $^{10}$Be from $^{11}$B is important for propagation calculations. Fig. 1 shows the isotopic yields of Be from $^{11}$B at energies near 0.6 GeV/nucleon. The solid line connects our calculated values. The measured values are those of Webber et al. (1990), Raisbeck and Yiou (1971), Yiou and Raisbeck (1972), and Webber et al. (1998). The latter gives 7.7 mb for $^{10}$Be at 0.365 GeV/nucleon. Using the energy dependence of (p,2p) reactions (Silberberg & Tsao 1973), the yield of $^{10}$Be at 600 MeV/nucleon is about 10 mb. The yields of $^{7}$Be of Webber et al. (1990) and Webber et al. (1998) differ by nearly a factor of 10.

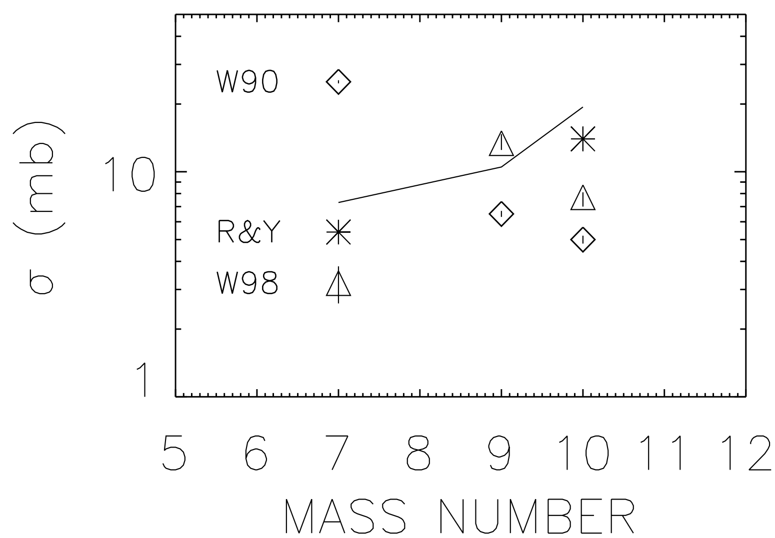


Figure 1: Isotopic yield of Be from $^{11}$B at energies near 600 MeV/nucleon.

There are also inconsistencies in the cross section measurements of nucleus-nucleus reactions, hence also in the scaling factors relative to proton-nucleus cross sections. These inconsistencies affect significantly the semiempirical estimates. For example, from the measurements of Geer et al. (1995), Kaufman et al. (1980), and Morrisey et al. (1981), the measured values for Au differ by a factor of 2. Also, from the measurements of Cumming et al. (1978), Olson et al. (1983), and Porile et al. (1979), the values of Cu and Fe should be quite similar, but differ by a factor of 3.

# 4 Nucleus-Nucleus Charge-Changing Cross Sections:

Scaling the proton-nucleus partial cross sections to estimate the corresponding nucleus-nucleus ones generally appears to be applicable for estimating many relevant nucleus-nucleus reactions' cross sections (e.g., Tsao et al. 1993). Yet, there are several systematic deviations, some of which are discussed by Tsao et al. (1998, 1999): (1) At lower energies, instead of scaling at a given energy per nucleon, the scaling is more a function of energy per nucleus. (2) For $\Delta A > A/2$, where $\Delta A$ is the target-product (or projectile-product) mass number difference, the ratio of nucleus-nucleus to proton-nucleus cross section increases with increasing $\Delta A$. (3) The electromagnetic dissociation cross sections, due to virtual photon exchange via the dipole resonance, is large in interactions between heavy nuclei, especially for single and double nucleon removal.

Hill et al. (1988), for example, measured the electromagnetic dissociation $\sigma(^{138}\mathrm{La} + {}^{197}\mathrm{Au} \rightarrow {}^{196}\mathrm{Au})$ to be 2000 mb at an energy of 1.26 GeV/nucleon. At ultra-high beam energies, $\sim 100$ GeV/nucleon, the virtual pion is sufficiently energetic for photo-pion reactions, giving rise to spallation-like reactions with multiple emission of nucleons. Brechtmann and Heinrich (1988) measured $\sigma(^{32}\mathrm{S} + \mathrm{Pb})$ to be 4600 mb for the dissociation of $^{32}$S, using a $^{32}$S beam at 200 GeV/nucleon incident on Pb. As such, electromagnetic dissociation must be included as a non-nuclear contribution to the inelastic cross section.

As an illustrative sample calculation, Fig. 2 compares the calculated cross sections of Tsao et al. (1998) with the measured values of Webber et al. (1990) for the isotopic production of elements Sc, V, and Mn from collisions of Fe on C at 0.6 GeV/nucleon. Solid lines connect the calculated fragmentation cross sections.

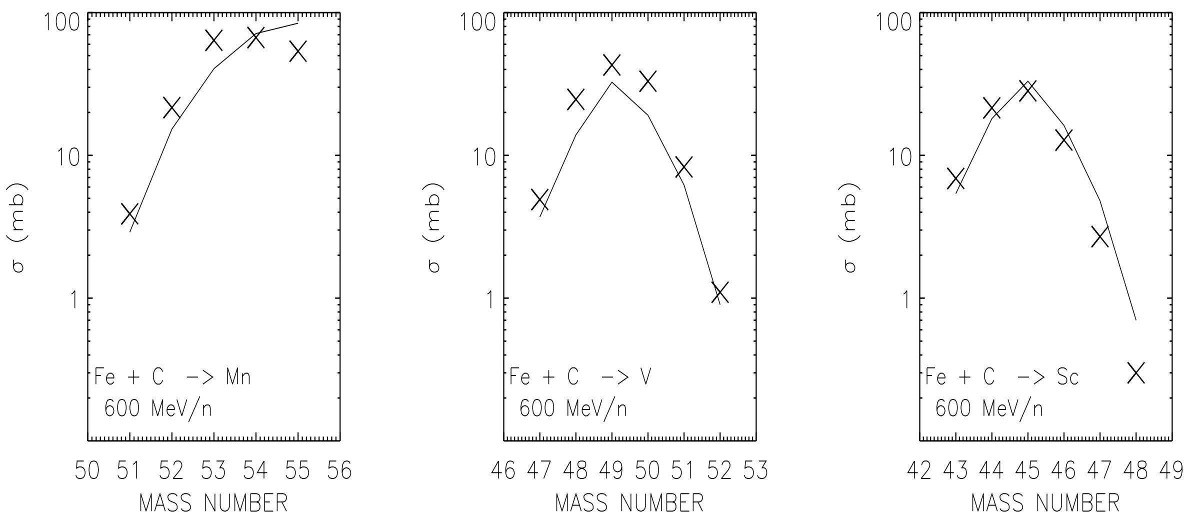


Figure 2: Yields of Sc, V, and Mn from Fe on C collisions at 600 MeV/nucleon.

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