Proton production cross sections in proton-nucleus collisions

John R. Letaw
Severn Communications Corporation, Severna Park, Maryland 21146
(Received 6 April 1983)

The partial cross sections for production of protons in high-energy proton-nucleus collisions are estimated using the conservation of baryon number constraint on semiempirical cross-section formulas.

[NUCLEAR REACTIONS Deduce σ for protons in high-energy proton-nucleus ($6 \leq A \leq 60$) collisions.]

The partial cross sections for mass changing, high-energy nuclear reactions, are of importance in several areas of physics and astrophysics because they are an essential factor in charged particle propagation calculations. In particular, they are used to determine changes in cosmic ray composition in propagation through the galaxy, excitation of materials (e.g., the lunar surface), and radiation effects and damage due to charged particles. At energies greater than 100 MeV/nucleon, the principal source of such cross sections has been the semiempirical formulas of Silberberg and Tsao.[1] These formulas predict partial cross sections for proton-nucleus collisions when the fragment mass is greater than 5 amu. In this Brief Report we propose an extension of the semiempirical formulas to light product nuclei. On the basis of baryon conservation one may calculate the total number of nucleons making up light products. The distribution of these nucleons among neutrons and the isotopes of hydrogen and helium are estimated using Monte Carlo results[2] and emulsion data.[3] These data allow the partial cross sections for protons to be calculated with an accuracy of 20%–30%.

The change, due to fragmentation, on the number of particles of type j in a beam of nuclei is governed by

$$\frac{dN_j}{dt} = -\sigma_j n v N_j + \sum_i \sigma_{ji} n v N_i \quad . \tag{1}$$

Here n is the number density of scattering centers and v is the beam velocity. This equation effectively defines the total inelastic collision cross section σ_j, and partial cross sections σ_{ji}. For our purposes an inelastic collision is defined as changing the mass A_j, or charge of the nucleus. At high energies other inelastic modes are rare. The total number of nucleons in the beam is conserved, thus

$$\sum_j \frac{d}{dt}(A_j N_j) = 0 \quad . \tag{2}$$

Substituting Eq. (1) into Eq. (2) yields the restriction

$$\sigma_j A_j = \sum_k \sigma_{kj} A_k \quad . \tag{3}$$

The partial cross sections for light particle production may be derived from this expression using known quantities by rewriting it as

$$\sigma_j A_j - \sum_{k \ni A_k \geq 6} \sigma_{kj} A_k = \sigma(n) + \sigma(^1\mathrm{H}) + 2\sigma(^2\mathrm{H}) + 3\sigma(^3\mathrm{H}) + 3\sigma(^3\mathrm{He}) + 4\sigma(^4\mathrm{He}) \quad . \tag{4}$$

The unknown cross sections are proportional to the number of each of the particles created in a nuclear collision. If the ratio of neutrons to protons is denoted $f(n)$, and others likewise,

$$\sigma(^1\mathrm{H}) = \frac{\sigma_j A_j - \sum_{k \ni A_k \geq 6} \sigma_{kj} A_k}{1 + f(n) + f(^2\mathrm{H}) + f(^3\mathrm{H}) + f(^3\mathrm{He}) + f(^4\mathrm{He})} \quad . \tag{5}$$

It appears possible from this result that a large cancellation error occurs in the numerator; however, the error is small if a substantial fraction of the target is fragmented into light products. The primary sources of error in Eq. (5) are the partial cross sections and the fractions $f(n)$, etc., in the denominator. If the fractional errors in the cross sections and the denominator are taken to be ϵ and δ, and assumed to be small and random, then the fractional error in the proton production cross section is

$$\left[\frac{\epsilon^2 \left(\sum_{j \ni A_j \geq 6} \sigma_{ji}^2 A_j^2 \right)}{\left(\sigma_i A_i - \sum_{k \ni A_k \geq 6} \sigma_{ki} A_k \right)} + \delta^2 \right]^{1/2} \quad . \tag{6}$$

We use the method described above to estimate the proton production cross section in proton-nucleus collisions at high energies. These cross sections are essentially independent of energy between 2 and 100 GeV for target nuclei with mass < 60. The total inelastic cross sections are given by the empirical formula[4]

$$\sigma_j = 44.9 A_j^{0.7} \text{ mb} \quad . \tag{7}$$

Error in this formula is a few percent and negligible for our purposes. For partial cross sections we use the semiempirical formulas of Silberberg and Tsao[1] at 2.3 GeV. These cross sections have an estimated error of 35% or less for all nuclei through Ni.

Light fragment multiplicities have been measured at 24 GeV in an emulsion experiment.[3] In collisions with Ag and Br they found protons, deuterons, and tritons in the ratio 9:3:1, respectively. Roughly 6% doubly charged particles were found. Monte Carlo calculations[2] have predicted the number of light particles evaporated from Cu, Ag, and Ta targets as a function of excitation energy. In order of decreasing abundance the light particles are n, ^{1}H, ^{2}H, ^{4}He, ^{3}H, ^{3}He. The ratios among singly charged particles are again roughly 9:3:1. The ^{3}He/^{1}H ratio is about 0.05, while ^{4}He/^{1}H is about 15%. It is consistent with these results to take the n/^{1}H ratio as $(A/Z)-1$. On the basis of this work we esti-

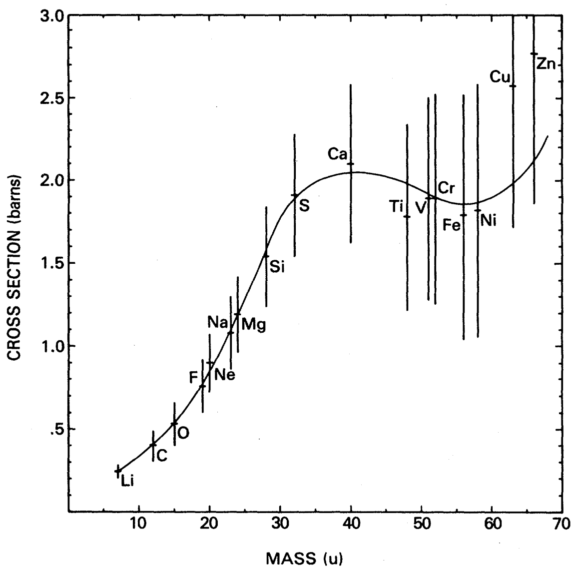

FIG. 1. The partial cross section for proton production in collisions of protons with nuclei of various masses for energies between 2 and 100 GeV.

mate

$$f(\mathrm{n}) = A/Z - 1, \quad f(^2\mathrm{H}) = 0.35, \quad f(^3\mathrm{H}) = 0.12 \ ,$$
$$f(^3\mathrm{He}) = 0.05, \quad f(^4\mathrm{He}) = 0.15 \ .$$

We estimate an overall error of 15% in the sum of these fractions occurring in the denominator of Eq. (5).

With semiempirical partial and total cross sections discussed above, the proton production cross sections for collisions of protons with various target nuclei were calculated. The results and associated errors are displayed in Fig. 1. An interesting feature of these results is the apparent shoulder in the cross sections in the mass range $40 < A < 60$. To our knowledge no exact measurements of the cross sections discussed in this report have been made.[6] Measurements of cross sections for heavier particles are routinely made for cosmic ray compositional studies (e.g., Ref. 5), and some limits on light particle production might be drawn from this data. Experimental tests of our results would provide information on systematic errors in the semiempirical cross sections. These errors are of special interest in the propagation of ultraheavy cosmic rays.[7]

The author appreciates conversations on this subject with Rein Silberberg and C. H. Tsao. This work was supported in part by Naval Research Laboratory Contract No. N00014-83-C-2042.

[1]R. Silberberg and C. H. Tsao, Astrophys. J. Suppl. Ser. 25, 315 (1973).
[2]I. Dostrovsky, P. Rabinowitz, and R. Bivins, Phys. Rev. 111, 1659 (1958).
[3]A. R. Khan, M. Irfan, M. Zafar, I. Ahmad, Z. Ahmad, and M. Shafi, Can. J. Phys. 56, 226 (1978).
[4]J. R. Letaw, R. Silberberg, and C. H. Tsao, Astrophys. J. Suppl. Ser. 51, 271 (1983).
[5]W. R. Webber and D. A. Brautigam, Astrophys. J. 260, 894 (1982).
[6]Extrapolations of large angle scattering data [S. Nagamiya *et al.*, Phys. Rev. C 24, 971 (1981)] are consistent with our results.
[7]For example, see comments concerning cross sections in N. R. Brewter, P. S. Freier, and C. J. Waddington, Astrophys. J. 264, 324 (1983).