CALCULATION OF IMPROVED SPALLATION CROSS SECTIONS

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Several research groups have recently carried out highly precise measurements (to about 10 percent) of high-energy nuclear spallation cross sections. These measurements, above 5 GeV, cover a broad range of elements: V, Fe, Cu, Ag, Ta and Au. Even the small cross sections far off the peak of the isotopic distribution curves have been measured. The semiempirical calculations are compared with the measured values. Preliminary comparisons indicate that the parameters of our spallation relations (Silberberg and Tsao, 1973) for atomic numbers 20 to 83 need modifications, e.g. a reduced slope of the mass yield distribution, broader isotopic distributions, and a shift of the isotopic distribution toward the neutron-deficient side. The required modifications are negligible near Fe and Cu, but increase with increasing target mass.

1. Introduction. Recent highly precise measurements of partial cross sections permit us to explore systematic deviations in our semiempirical partial cross section calculations (Silberberg and Tsao, 1973). In the present paper we confine our investigation to high-energy interactions, E > 5 GeV/u, to target nuclei with atomic numbers $Z_t > 20$, and to proton-nucleus reactions. The experimental data are discussed in Section 2. Comparisons with semiempirical calculations are presented in Section 3, as a function of the exponential expressions of the semiempirical equation, in order to explore systematic deviations. Procedures to modify the semiempirical equations are outlined in Section 4.

2. The New Experimental Data. While earlier experimental data were derived from radioactivity measurements after chemical separation of product elements, most of the measurements selected for the present investigation are based on gamma ray line intensity measurements as a function of time. Any systematics introduced by chemical separation are thus avoided.

Table 1 shows the sources of experimental data used in our current analysis. Some of the spallation cross sections are cumulative, i.e. contain the contributions of shorter lived progenitor isotopes. Reactions are omitted in which several isomers are produced, but only one is measured.

Table 1. Sources of Recent High-Energy Experimental Data, 20<Z<80

Author	Target	Energy (GeV)
Husain and Katcoff (1973)	V	3, 30
Asano et al. (1983)	Ti, Fe, Co, Ni, Cu	12
Cumming et al. (1976)	Cu	25
Hudis et al. (1970)	Cu, Ag, Au	3, 29
Porile et al. (1979)	Ag	300
Chu et al. (1974)	Ta	28
Kaufman et al. (1976)	Au	12, 300

3. Comparison of Data and Calculations. The semiempirical equation for calculating non-peripheral spallation cross sections is of the form

$$\sigma = \sigma_o \exp(-P\Delta A) \exp(-R|Z-SA+TA^2|^{3/2}) \, \Omega\eta\xi$$

The factors in this equation are defined by Silberberg and Tsao (1973). Systematic deviations from this equation can be explored by comparing the measured and calculated cross sections as a function of $Z-SA+TA^2$ and of ΔA. The former comparison permits a test of systematic deviations as a function of the neutron richness of product isotopes and of the width of the isotopic spread of the products. The latter permits a test of systematic deviations as a function of the target-product mass difference. After these systematics are corrected for we can explore the smaller systematic difference, as a function of the nuclear pairing factor η, which represents the enhancement of even-even product nuclei and the suppression of the odd-odd products.

Fig. 1 shows the ratios of calculated to experimental cross sections of Cu as a function of $Z-SA+TA^2$. A large value of this function implies a small value of A, i.e. a neutron-deficient product. We note a positive slope as a function of $Z-SA+TA^2$. This means that the calculated cross sections of neutron-deficient products, e.g. ^{52}Fe are overestimated, and neutron-rich ones, e.g. ^{47}Ca are underestimated.

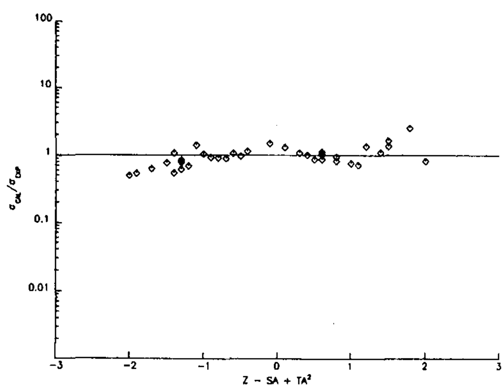

Fig. 1. The ratio of calculated to experimental cross sections of Ta, as a function of $Z-SA+TA^2$, for E > 3 GeV.

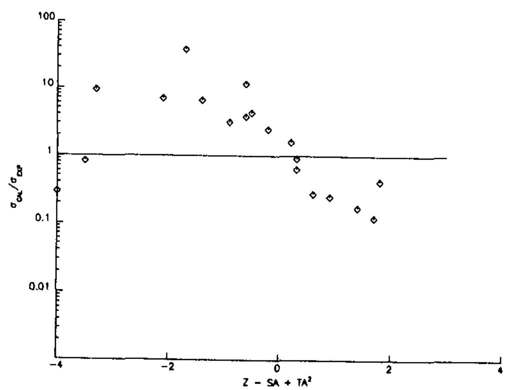

Fig. 2. The ratio of calculated to experimental cross sections of Cu, as a function of $Z-SA+TA^2$, for E > 6 GeV.

Fig. 2 shows the corresponding data for tantalum. The large negative slope shows that a significant systematic deviation occurs in the calculated cross sections, however, opposite to that for lighter target nuclei like Cu of Fig. 1. For Ta, the neutron-rich products are overestimated, instead.

Fig. 3 compares the calculated and experimental spallation cross sections of Cu as a function of ΔA. We note that for Cu, the systematic deviations are rather small. The largest and smallest values are those near the extreme values of $Z-SA+TA^2$. After the latter are corrected for, the spread of the ratios about 1 will be very small.

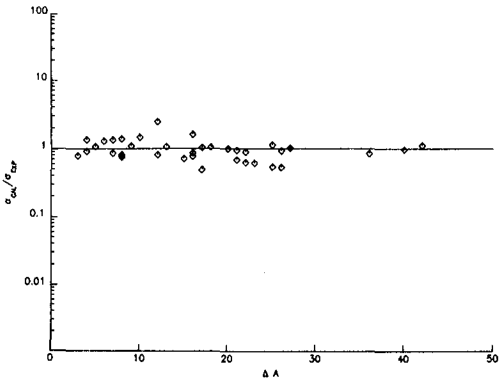

Fig. 3. The ratio of calculated to experimental cross sections of Cu, as a function of ΔA, for E > 3 GeV.

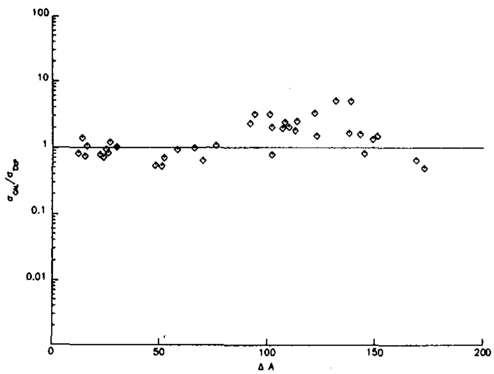

Fig. 4. The ratio of calculated to experimental cross sections of Au, as a function of ΔA, for E > 6 GeV. The temporary adjustment factors of Tsao et al. 1983 were applied to the calculations.

Fig. 4 compares the calculated and measured cross sections of Au as a function of ΔA. The agreement of the spallation cross sections (i.e. those with ΔA less than approximately 60) is good. However, this agreement was achieved by special corrections for nuclei with $76 \leq Z_t \leq 83$ we proposed (Tsao et al., 1983). Our aim will be to eliminate such special corrections, and adjust the parameters P, R, S, and T so that the whole region $20 \leq Z_t \leq 83$ can be adequately fitted. We note from Fig. 2, that for Ta (with $Z_t = 73$), the fit to the data is rather poor. A simultaneous fit to Ta and Au is necessary.

4. Procedures to Modify the Semi-Empirical Equations. We noted from Figs. 1 and 2 that one should increase the calculated cross sections of the n-rich products for targets near $Z_t = 30$, while increasing those of the neutron-deficient products near $Z_t = 70$ and 80. This can be accomplished by decreasing S or increasing T in the former case, and by increasing S or decreasing T in the latter case. Since S is associated with A and T with A^2, S is more sensitive for lighter nuclei and T is more sensitive to heavier nuclei. Thus the correction can be accomplished by reducing both S and T, replacing the values 0.486 and 0.00038 given in Table 1D of Silberberg and Tsao by 0.48 and 0.0003 and reducing R to 0.9R. Fig. 5 shows how Fig. 2 is transformed when the above parameters are used and Fig. 6 how Fig. 1 is transformed. A correction for $Z-SA+TA^2 < -2$ is still required.

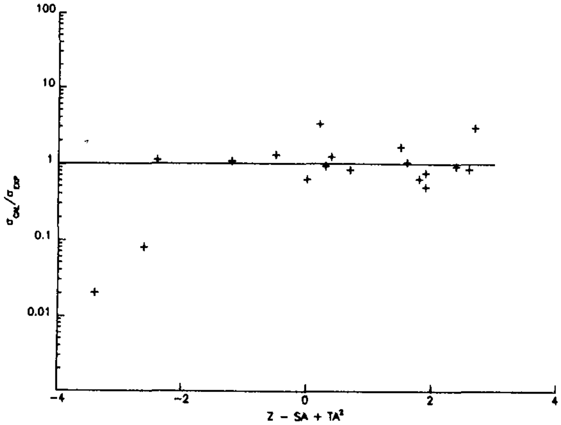

Fig. 5. The ratio of calculated to experimental cross sections of Ta as a function of Z-SA+TA^2, with the new values of S and T, for E > 6 GeV.

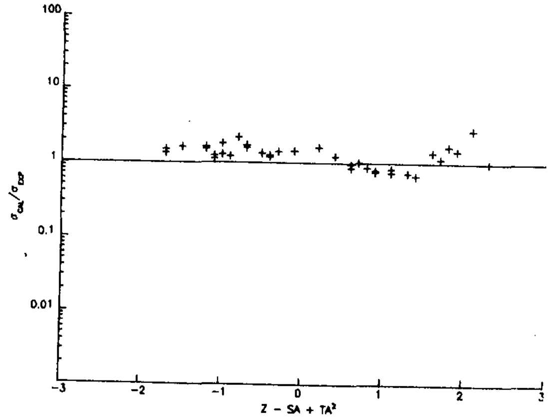

Fig. 6. The ratio of calculated to experimental cross sections of Cu, as a function of Z-SA+TA^2, with the values of S and T, for E > 3 GeV.

The modifications we plan to introduce involve special complications, because of multiple feed-back loops. An adjustment of P affects the overall normalization factor σ_o, and the energy dependence of the calculations. Adjustments in S and T affect the calculations of fission and fragmentation cross section, and the parameters f(A) and f(E) of Silberberg and Tsao (1973) must be re-formulated.

5. Conclusions. The recent highly precise experimental data have permitted us to find systematic deviations in the calculated cross sections, and significantly more accurate calculations are possible after optimizing the parameters P, R, S, and T over the range of targets $20 \leq Z_t \leq 83$.

References

Asano, T. et al. 1983, Phys. Rev. C28, 1718.
Chu, Y.Y. et al. 1974, Phys. Rev. C10, 156.
Cumming, J.B. et al. 1976, Phys. Rev. C14, 1554.
Hudis et al. 1970, Phys. Rev. C1, 2019.
Husain, L. and Katcoff, S. 1973, Phys. Rev. C7, 2452.
Kaufman, S.B. 1976, Phys. Rev. C14, 1121.
Porile, N.T. 1979, Phys. Rev. C19, 2288.
Silberberg, R. and Tsao, C.H. 1973, Ap. J. Suppl. 25, 315.
Tsao, C.H. et al. 1981, 18th ICRC (Bangalore) 2, 194.