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LOW-ENERGY PARTICLE PRODUCTION AND RESIDUAL NUCLEI PRODUCTION FROM HIGH-ENERGY HADRON-NUCLEUS COLLISIONS[*]

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ABSTRACT

The high-energy hadron-nucleus collision model, EVENTQ, developed by J. Ranft et al., has been modified to include a calculation of the excitation and kinetic energy of the residual compound nucleus. The specific purpose of the modification is to make it possible to use the model in the high-energy radiation transport code, HETC, which, in conjunction with MORSE, is used to transport the low energy particles. It is assumed that the nucleons in the nucleus move in a one-dimensional potential well and have the momentum distribution of a degenerate Fermi gas. The low energy particles produced by the deexcitation of the residual compound nucleus, and the final residual nucleus, are determined from an evaporation model. Comparisons of multiplicities and residual nuclei distributions with experimental data are given. The "grey" particles, i.e., charged particles with $0.25 < \beta < 0.7$, are in good agreement with experimental data but the residual nuclei distributions are not.

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I. INTRODUCTION

Particle production spectra from high-energy (hundreds and thousands of GeV) hadron-nucleus collisions are of considerable interest in particle physics as well as in accelerator shielding.[1,2,3] Because of the physics interest, a large amount of theoretical and experimental work has been conducted in the past several years. In particular, a multi-chain fragmentation model using quark physics has been implemented into a Monte Carlo cross section code, EVENTQ, by J. Ranft et al. (see Ref. 2 and references included). This model is based on work of A. Capella et al. (see Ref. 3 and included references). An intranuclear cascade secondary nucleon component was also included by J. Ranft et al. to account for lower energy secondary collisions. Comparisons with experimental data obtained by both J. Ranft et al. and A. Capella et al. showed good agreement, in general, for shower (charged particles with $\beta > 0.7$) particle multiplicities, rapidity distributions, etc. The version of the model that is used here is that available in the transport code FLUKA82 by P. A. Aarnio, J. Ranft, and G. R. Stevenson.[4]

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For some accelerator shielding studies, e.g., dose calculations and residual nuclei production, the production of low energy particles, especially "evaporation" neutrons, are of particular interest. For hadron calorimeter design calculations, the energy deposition by soft (<20 MeV) neutrons through proton recoil and neutron-nucleus collisions leading to γ-emission has been shown to be crucial in determining the energy resolution of the hadronic signal in some designs.[5,6,7] The model EVENTQ does not include an evaporation step explicitly, but instead sets aside a certain amount of energy, TV, initially, to account for the excitation and kinetic energies of the excited compound nucleus.

To calculate directly the low energy emitted particles, EVENTQ has been modified to set TV = 0 and to make baryons and antibaryons move in a nuclear potential (one-region nuclear well). Fermi momenta of target nucleons were already taken into account in EVENTQ. Particles with kinetic energies less than their well depths plus a Coulomb barrier for positively charged particles are now not permitted to escape the nucleus, but add their total energy to the energy of the resulting compound nucleus. The kinetic energies of outgoing baryons and antibaryons are decreased by their well depths. The excitation and kinetic recoil energies of the residual compound nuclei are calculated using relativistic kinematics. The calculation of the deexcitation of the compound nucleus was carried out using a previously developed evaporation model.[8]

To test the validity of the revised model, calculated results following evaporation for shower and grey particle multiplicities have been obtained and compared with the experimental data of A. Faessler.[1] Comparisons of calculated residual nuclei distributions with the experimental data of Katcof et al.,[9] are also presented. The modified EVENTQ was developed specifically for incorporation into the high-energy radiation transport code HETC and comparisons with experiment have also been obtained with this code.[10]

II. THEORY

In EVENTQ the intranuclear cascade nucleons are chosen first, from a distribution, rather than following from collisions. The remaining energy is expended in free-space hadron-nucleon collisions, using a quark model giving exclusive distributions of secondary particles. Momentum conservation for the cascade nucleons is obtained, at best, on the average, because the momentum entering the fragmentation collision stage is obtained from this remaining energy, without involving momentum conservation.

Energy conservation is possible in principle in EVENTQ, but failures in the four-momentum conservation occurred in 20-33 percent of the hadron-hadron collisions, due to approximations introduced when the mass of one or both of two jets in the center-of-mass system was specified as a stable particle, or resonance, which did not fragment. The error, E_{err}, in energy conservation inside the well for any given history was reduced to be within ±20 MeV for a 29 GeV proton collision with silver. This is important here because E_{err} varied between 0.0 and 1.0 GeV in individual histories and could be the leading term in the sum of the excitation energy, U_R, and the kinetic energy, KE_R, of the compound nucleus. Conservation of longitudinal and transverse momenta components in the hadron-nucleon collisions was improved to the same degree. The remaining errors in momentum conservation are absorbed in the kinetic and excitation energies. The initial excitation energy, TV, used in the original EVENTQ was set equal to zero, since the low energy particles are calculated explicitly here.

For a projectile with total energy E_o and momentum P_o, the energy E_R and momentum P_R of the residual compound nucleus are given by

$$E_R = E_o + M_T - \sum_{s=1}^{N_{sec}} E_s \; ; \; \vec{P}_R = \vec{P}_o - \sum_{s=1}^{N_{sec}} \vec{P}_s \; ; \tag{1}$$

$$M_R^* = \left[E_R^2 - P_R^2\right]^{1/2} \; ; \; KE_R = E_R - M_R^* \; ; \; U_R = M_R^* - M_R \; , \tag{2}$$

where the masses M_T and M_R are rest masses of the target and compound nucleus and N_{sec} is the number of escaping secondaries. The energies, E_s of the secondary particles escaping the well are decreased by an amount V_s equal to the appropriate well depth calculated from a degenerate Fermi gas. That is,

$$\begin{aligned} V_s &= 0 && ;\ \text{mesons} \\ &= KEF_{max,p} + BE && ;\ \text{charged baryons and antibaryons} \\ &= KEF_{max,n} + BE && ;\ \text{neutral baryons and antibaryons} \end{aligned} \tag{3}$$

where $KEF_{max,p}$ and $KEF_{max,n}$ are the maximum Fermi kinetic energies for protons and neutrons, respectively, and BE is an average binding energy which is taken to be 7 MeV. The antibaryons are assumed to be created in the well, but members of a baryon-antibaryon pair are given an increment of kinetic energy equal to their V_s value in order to conserve overall energy. The nuclear radius, r, in the Fermi gas calculations was taken to be

$$r = r_o A_T^{1/3} \; , \tag{4}$$

where r_o is a constant, and A_T is the atomic mass number of the target.

It is possible to define an average binding energy in a history, Beav, using an analysis of energy conservation in the modified EVENTQ. (In the following, for simplicity, incident antibaryons and baryon pair production are not considered.) Let N_{bary} be the number of emitted baryons; then if a baryon is incident,

$$N_{bary} = N_{coll} + N_C - N_R + 1 \; , \tag{5}$$

$$N_{bary}.\mathrm{Beav} = M_R + \sum_{c=1}^{N_C} m_c + \sum_{k=1}^{N_{coll}} m_k - \sum_{r=1}^{N_R} m_r - M_T \; . \tag{6}$$

where N_C is the number of cascade nucleons inside the well; N_{coll} is the number of hadron-hadron collisions and hence, of target nucleons; N_R is the number of particles retained inside the well because of insufficient energy to escape, and m denotes baryon mass.

The average (over many histories) value of the binding energy was generally ≈ 7 MeV, but the value of Beav defined by Eqs. (5) and (6) shows wide variations.

Using energy conservation inside the well in conjunction with Eqs. (1), (2), (5), and (6) gives

$$U_R + KE_R = TV + E_{err} + \sum_{s=1}^{N_{sec}} V_s - \Delta E_{o,well} - N_{bary}.\mathrm{Beav}$$
$$- \sum_{k=1}^{N_{coll}} KE_{F,k} - \sum_{c=1}^{N_C} KE_{F,c} + \sum_{r=1}^{N_R} KE_r \tag{7}$$

where $\Delta E_{o,well} = V_o$ is an increment to the kinetic energy of a baryon or antibaryon entering the well; and in the Fermi energy terms, $KE_{F,k}$ is the Fermi kinetic energy selected from the collision well (not necessarily the same as the cutoff well, V_s) for the target nucleon k; $KE_{F,c}$ is the same thing for cascade nucleons generated inside the well. The last term in Eq. (7) is the sum of the kinetic energies, KE_r, inside the well of any secondary particles (including mesons) that are retained inside the nucleus, i.e., they do not have enough energy to escape from the well.

The original EVENTQ does not include Fermi kinetic energies for the cascade nucleons, and they were not used in the results given in this paper. However, their inclusion would serve the obvious purpose of decreasing U_R + KE_R thus leading to fewer emitted particles from the compound nucleus and higher values of A in the final residual nuclei. In this case, care must be taken to keep U_R + KE_R greater than zero if the cutoff wells in V_s and the collision wells in Fermi KE are not the same. The relatively deep collision well in the original EVENTQ causes the $KE_{F,k}$ terms to be large, thus augmenting the shower multiplicities, but use of the deep well for cutoff reduces the grey particle multiplicity significantly. Finally, it should be noted that the final residual nucleus A after evaporation is given by

$$A = A_T - N_C - N_{coll} + N_R - N_{evap} \tag{8}$$

where N_{evap} is the number of nucleons in the evaporated particles (which include deuterons, tritons, etc.) and N_{evap} clearly increases with U_R in Eq. (7).

III. RESULTS AND DISCUSSION

In Fig. 1 the calculated and measured[1] multiplicities of shower and grey particles are shown as functions of atomic mass for 150- and 50-GeV incident protons. In Fig. 2, similar results are shown for 150- and 50-GeV incident π^+. The solid lines in these figures are drawn through the experimental points to aid in interpreting the results. The error bars on the measured data in Figs. 1 and 2 are of the order of the size of the plotted points and the statistical errors on the calculated values are of the order of the size of the plotted points.

The calculated results in Figs. 1 and 2 were obtained using the model described here. In this model the collision well in the original EVENTQ with r_o = .95 fm was retained, but for the cutoff well and Coulomb barrier an r_o value of 1.3 fm was used. The cascade nucleons originate in the potential well but no Fermi kinetic energy for the cascade nucleons is assumed.

In Fig. 1 the calculated and experimental multiplicities of shower particles are in substantial agreement and in Fig. 2 the agreement is moderately good. These comparisons are very similar to those obtained previously by J. Ranft and S. Ritter[11] using EVENTQ and thus have not been changed by the changes in EVENTQ described above. It has been well established for some time that the experimentally determined multiplicity of grey particles from hadron-nucleus collisions is independent of incident energy at the higher incident energies.[1] This fact is shown by the experimental data in Figs. 1 and 2 and is also reproduced very well by the calculational model over the entire range of atomic mass numbers considered in Figs. 1 and 2.

In Fig. 3 the measured partial cross section for producing various residual nuclei is shown for the case of 29 GeV proton-silver collisions. Also shown in Fig. 3 is the calculated partial cross section as a function of atomic mass described above. The total cross section of 1172 mb used in the calculation is approximately equal to the value obtained experimentally by summing the partial cross sections for the production of all nuclei. The calculated results in Figs. 3 do not agree with the experimental data. The calculated partial cross sections are approximately Gaussian about an average A of approximately 70 to 75 while the measured data generally decreases as one proceeds from high A to low A. From the comparison it seems that the present model gives too many excitation energies that are too large and this causes the emission of too many low energy particles. From the discussion in Sec. II, it is clear that there are many assumptions in the model, mostly those dealing with the intranuclear cascade component in EVENTQ, that can be changed to lower the excitation energies and perhaps improve the calculated distribution of residual nuclei. It is clear from Eq. (8) that A values near A_T can only be obtained if $N_C + N_{coll}$ is held to a minimum and U_R is simultaneously very small. The comparison with experiment shows not enough such cases occur in the present model. The experimental values at low (≈20) A are generally considered to arise from a fragmentation process not included in the present model. In considering the results it should be remembered that the authors of EVENTQ did not intend the intranuclear cascade component to be used as it is

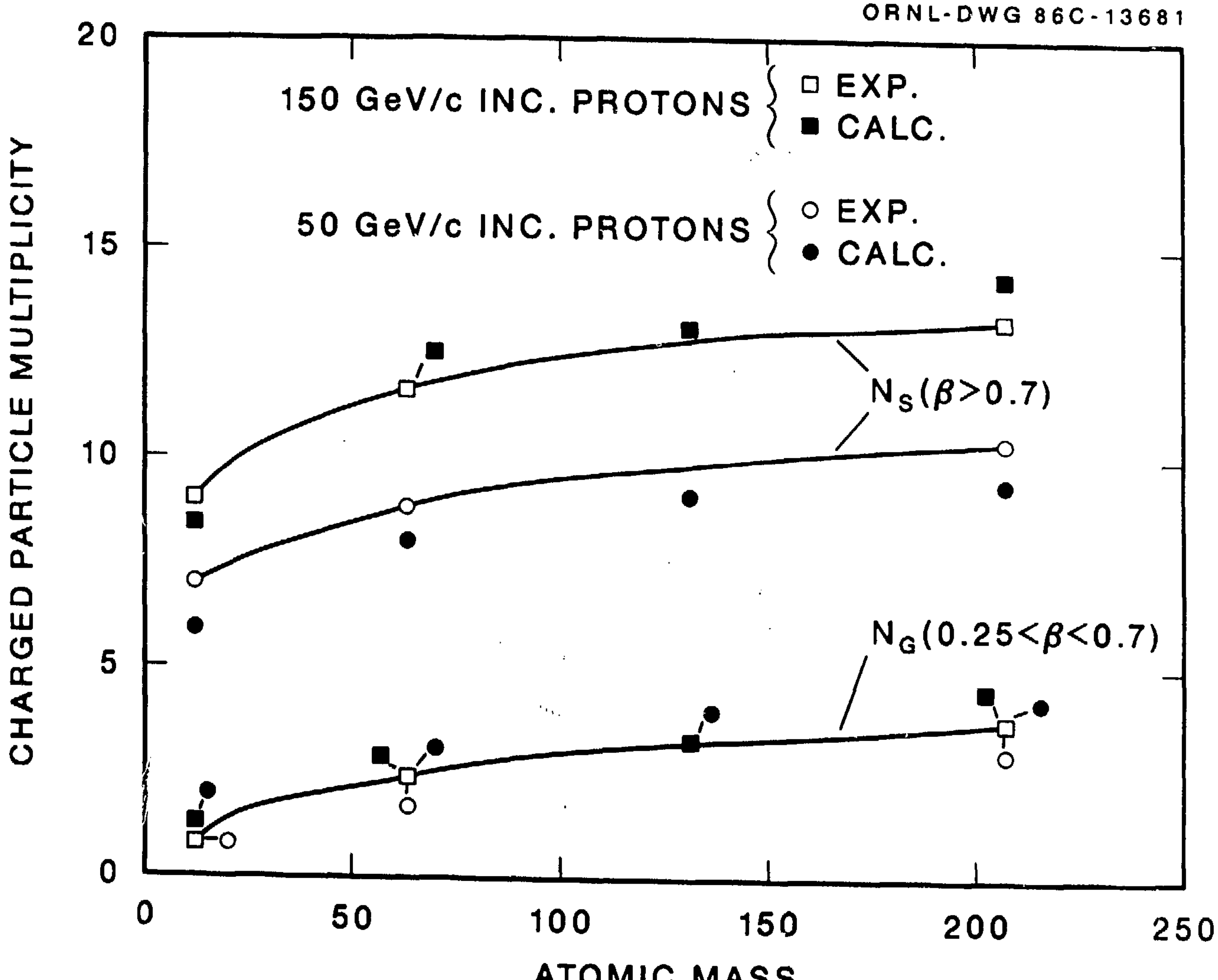

Fig. 1. Charged particle multiplicity vs. atomic mass for 29 GeV proton-silver collisions.

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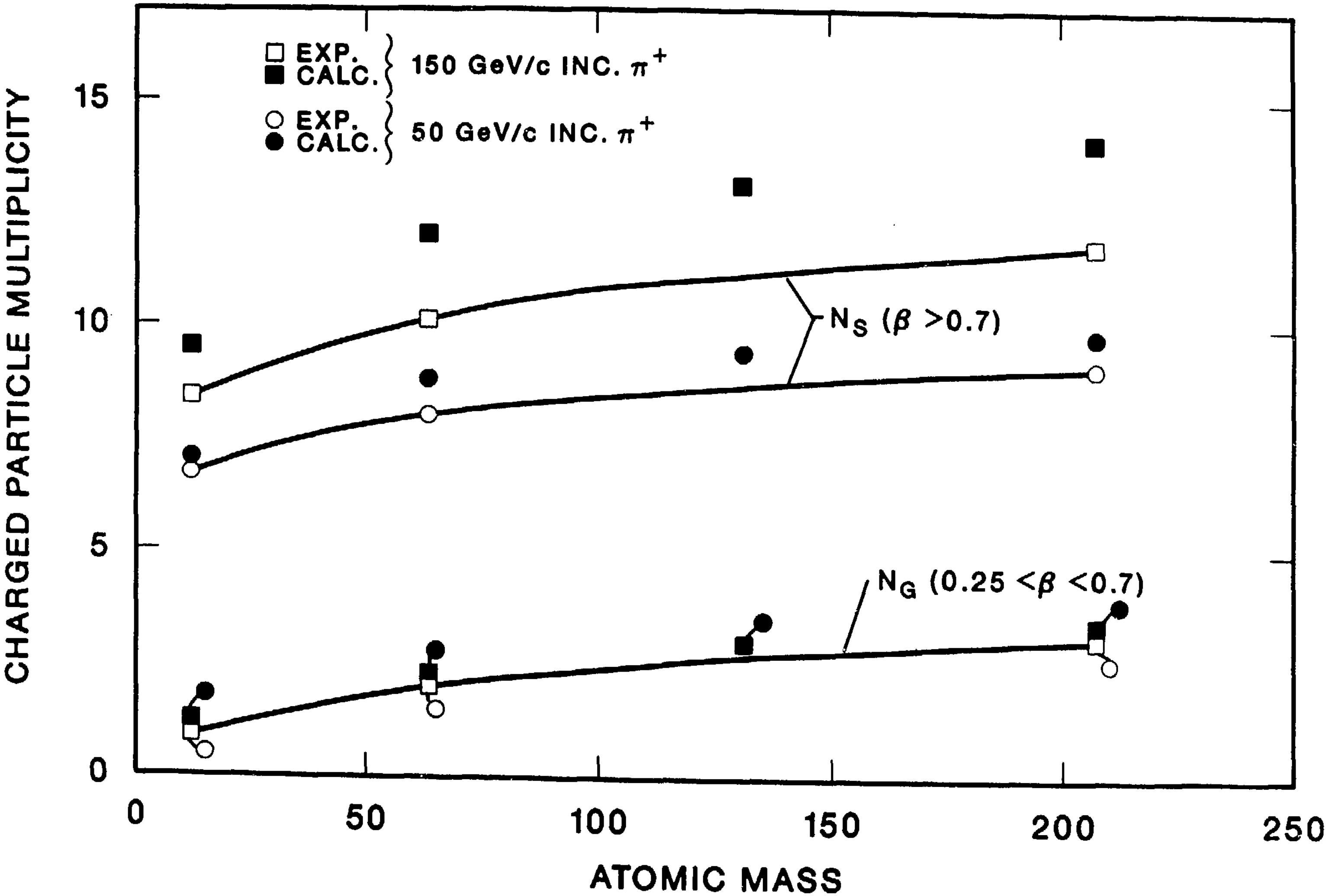

Fig. 2. Charged particle multiplicity vs. atomic mass for 29 GeV proton-silver collisions.

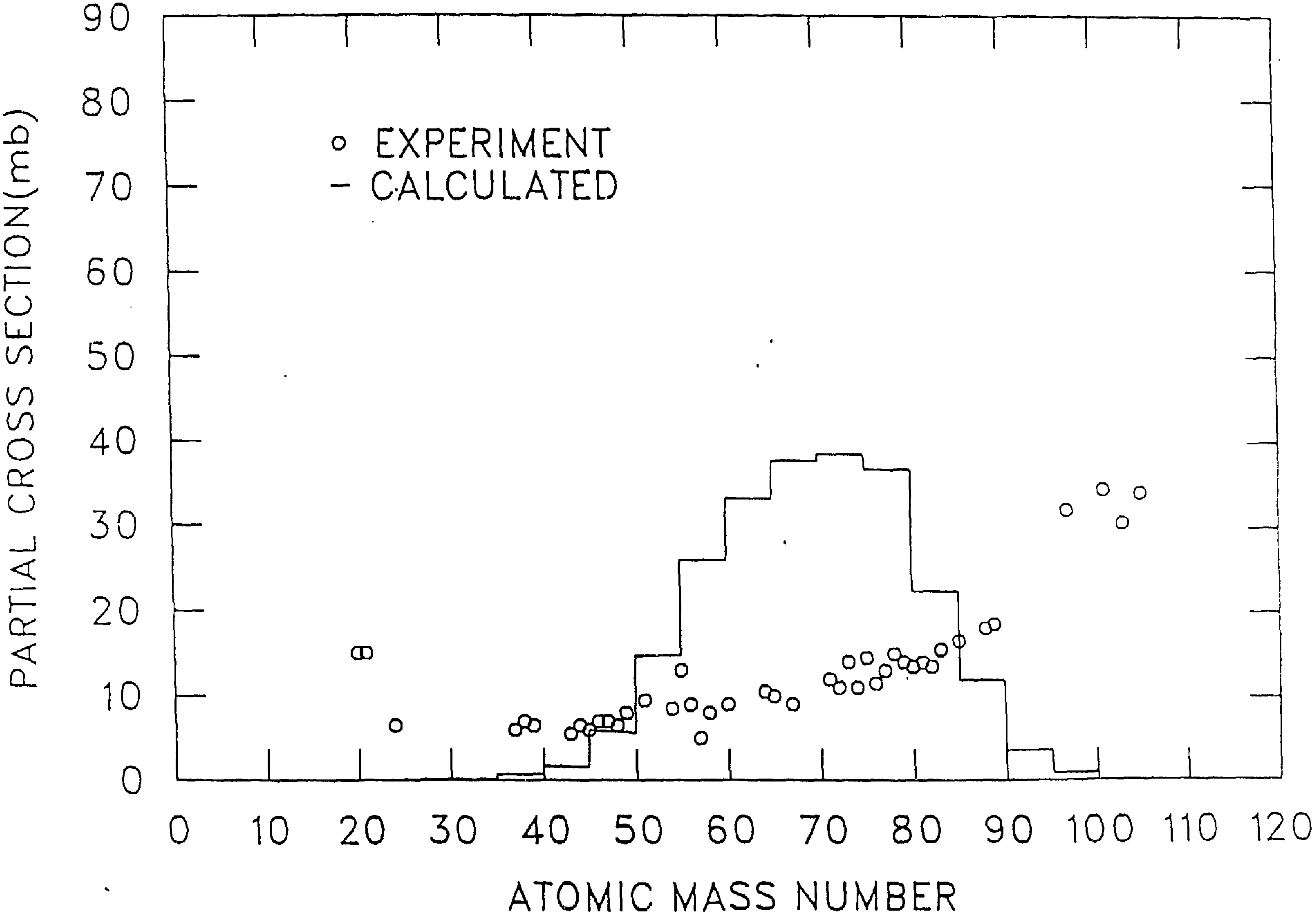

Fig. 3. Partial cross section for the production of residual nuclei vs. atomic mass for 29 GeV proton-silver collisions.

used here. Also, there is an updated version of EVENTQ in FLUKA86[13] and this version has not been used in the studies reported here.

IV. CONCLUSIONS

The modifications to EVENTQ described in this paper gave very good results for the average "grey" particle multiplicities over a range of energies and target nuclei and did not significantly alter the "shower" multiplicities given previously by Ranft and Ritter.[12] The residual nuclei mass yield distributions are not as yet satisfactory.

REFERENCES

1. M. A. Faessler, "New Experimental Results for Particle Production from Nuclei," Annals of Physics 137, 44 (1981).

2. J. Ranft and S. Ritter, "Rapidity Ratios, Feynman-X Distributions and Forward-Backward Correlations in Hadron-Nucleus Collisions in a Dual Monte Carlo Multi-Chain Fragmentation Model," Z. Phys. C - Particles and Fields, 27, 569 (1985).

3. A. Capella and J. Tran Thanh Van, "Hadron-Nucleus Interactions and the Leading Particle Effect in a Dual-Parton Model," Z. Phys. C - Particles and Fields 10, 249 (1981).

4. P. A. Aarnio, J. Ranft, G. R. Stevenson, "A Long Writeup of the FLUKA82 Program," European Organization of Nuclear Research, TIS-RP/1-6-Rev (1984).

5. R. Wigmans, "On the Energy Resolution of Uranium and Other Hadron Calorimeters," European Organization for Nuclear Research, CERN/EF 86-18 (CERN/EP 86-141), (1986)

6. T. A. Gabriel, Nucl. Instrum. Methods 150, 145 (1978).

7. T. A. Gabriel, "The Physics of HETC," Proc. Workshop on Compensated Calorimetry, Pasadena, CA, CALT-68-1305 (1985).

8. F. S. Alsmiller, R. G. Alsmiller, Jr., T. A. Gabriel, R. A. Lillie, and J. Barish, "A Phenomenological Model for Particle Production from the Collisions of Nucleons and Pions with Fissile Elements at Medium Energies," Nucl. Sci. Eng. 79, 147 (1981).

9. S. Katcoff, H. R. Fickel, and A. Wyttenbach, "Distribution of Radionuclides from the Interaction of 3- and 29-GeV Protons with Silver," Phys. Rev. 166, 4 (1968).

10. R. G. Alsmiller, Jr., F. S. Alsmiller, T. A. Gabriel, and O. W. Hermann, "Modifications of the High-Energy Transport Code (HETC) and Comparisons with Experimental Results," to be presented at the ANS Topical Conference on the Theory and Practices in Radiation Protection and Shielding, April 22-24, 1987, Knoxville, TN

11. J. Ranft and S. Ritter, "Particle Production in Hadron-Nucleus Collisions in a Multi-Chain Fragmentation Model," Z. Phys. C - Particles and Fields 20, 347 (1983).

12. P. A. Aarnio et al., "FLUKA86 User's Guide, Europeans Organization of Nuclear Research, TIS-RP/168 (1986).