MODEL CALCULATIONS OF THE NUCLEON REMOVAL BY 80-164 MeV PROTONS FROM MEDIUM-MASS NUCLEI

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The quantities extracted in the measurements[1] of nucleon removal by medium energy protons have been compared with the results obtained in terms of the cascade model[2] using the computer code VEGAS[3] and those in terms of the multi-pre-equilibrium emission hybrid model[4] using the code EVAHYB.

The cross sections predicted by EVAHYB and VEGAS, including the evaporation which was calculated with the codes ALICE [5] and DFFMH [3] in the two cases, respectively, are illustrated in Fig. 1 for the 164 MeV protons bombarding the ^{62}Ni target. The qualitative features of the cross section predicted by the two models are similar and are of the same kind as shown (see Fig. 2) by the observed cross sections.

However, there are noticeable differences. First, the EVAHYB predicts more cross section for Mn, Cr and V isotopes than either predicted by cascade model or actually observed. This discrepancy, along with the necessity to increase the MFP by a factor of two to get reasonable comparison with the observations is, hopefully, expected to get corrected when the geometry dependent effects arising from the diffuseness of the nuclear surface are incorporated. The cascade model on the whole not only gives a rather satisfactory account of the absolute magnitude of the observed cross sections, but also of trends among isotopes of various nuclear species over the entire mass range of the product nuclei. Some quantitative deviations are expected since in many cases the ob-

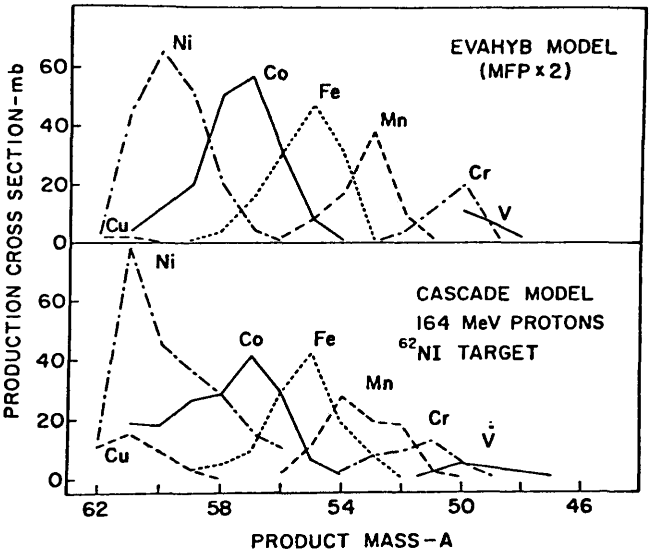

Figure 1.

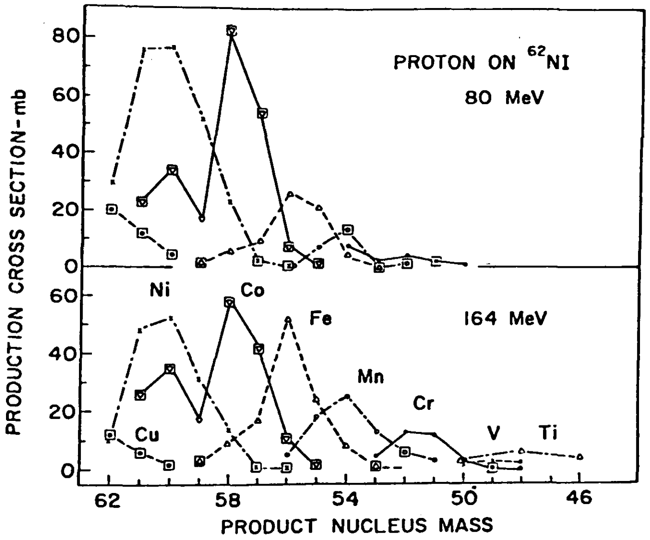

Figure 2.

served cross sections are only a part of the total production cross sections. The other deviations arise from the limitations inherent in the models. For example, consistently lower cross sections (by a factor of 2) observed for ^{61}Ni as compared to the calculations may be due to the first cause. Since odd-A nuclei are likely to decay through many transitions, resulting in smaller average cross section per transition, one is more likely to miss some as compared to an even-even nucleus where all of the decays tend to funnel through the first 2^+ excited state. On the other hand, lower predicted cross sections for some of the Co isotopes, the observed values for which were determined through activation measurements, must be due to inherent limitation of the model or improper choice of the values of the parameters used. It is felt that a quantitatively detailed comparison with the observed results would be asking a little too much from the model at this stage knowing that it does not embody some of the physical effects, such as the role of the collective excitations, interactions involving correlated cluster of nucleons and the like.

However, if one lumps some of the cross sections together, as is done in Figs. 3-5, the models, especially the cascade model, show even greater success in representing the observations. In Figs. 3 and 4, the production cross sections for nuclei of a given mass are plotted along with the predictions of various models for 80-164 MeV protons on ^{62}Ni target. It is worth noting that at 80 MeV, where single pre-equilibrium emission is adequate, including the geometric effects of the GDH model[4,5] is not able to give as good an account of the observed cross section as the EVAHYB with

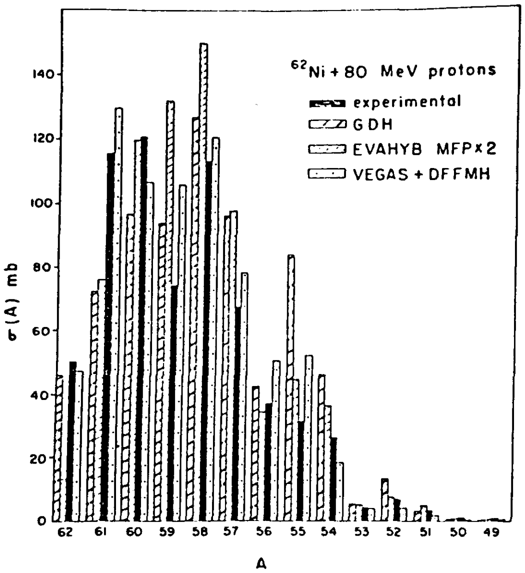

Figure 3.

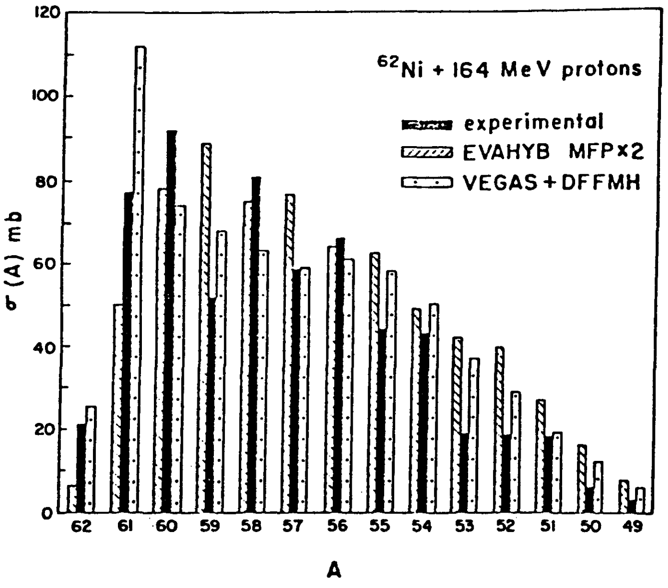

Figure 4.

doubled MFP. It is this trend which gives the hope that when this effect is included, the unphysical enhancement of MFP in the hybrid model for higher energies would not be necessary. Further, it may also correct for the systematically higher and lower cross sections it predicts for nuclei farther and nearer to the target mass, respectively. The cascade model, on the other hand, is consistently able to reproduce the observed cross sections within about 25% at all energies. In Fig. 5, the observed production cross section for each nuclear species is compared with the predictions of the two models for the 164 MeV case. Again the cascade model is able to give a noticeably better account of the measurements than the hybrid model.

In Fig. 6, the predictions of the two models regarding the behavior of $<\Delta A>$ with energy are compared with the trend of the experimental values. Whereas both models predict that $<\Delta A>$ increases with energy at the rate of about 0.02 nucleon per MeV which is a little larger than the observed value of 0.015, the cascade model is able to predict the correct absolute magnitude for $<\Delta A>$ for different targets as well as of variations of $<\Delta N> - <\Delta Z>$ with the N-Z of the target. Higher values of $<\Delta A>$ given by the hybrid model are due to the same pathology which makes it predict larger cross sections for nuclei farther from the targets as discussed before.

In terms of the cascade model one can investigate some interesting features of the nucleon-nucleus interaction. First, as shown in Fig. 7, of the total of about 5 nucleons that are emitted, on an average, from various nickel isotopes at 136 MeV, about two are emitted in the pre-equilibrium phase and the remaining three are emitted in the equilibrium phase; of the latter, two are either neutrons or protons and one is in the form of clusters such as d, t, ^{3}He, and ^{4}He. The number of nucleons predicted to be emitted in the pre-equilibrium phase is consistent with the conclusion derived from the pattern of the observed production cross section.[1]

Emission of three nucleons, on an average, in the equilibrium phase implies, assuming that it

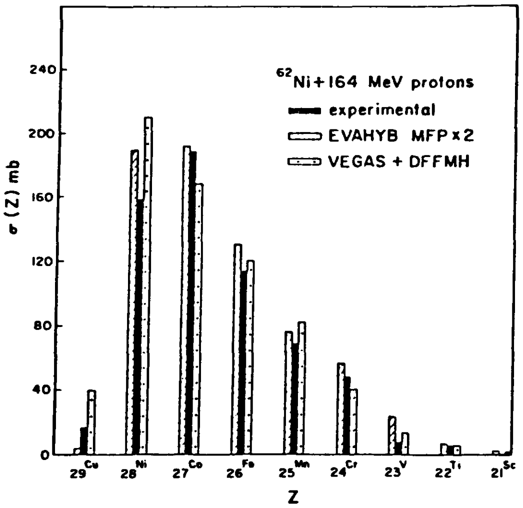

Figure 5.

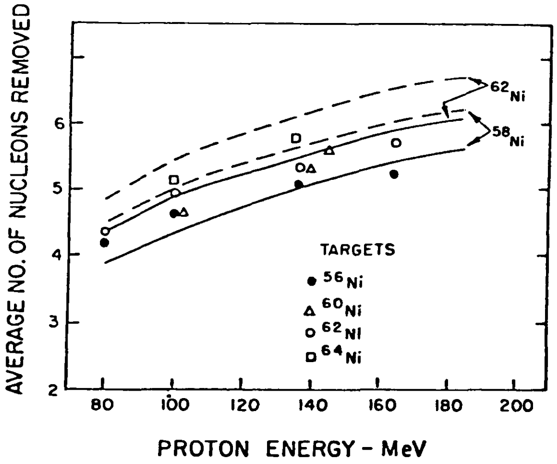

Figure 6.

takes about 10 MeV to evaporate a nucleon and that the final nucleus is generally left at about 10 MeV excitation, that the average excitation of the system at equilibrium is about 40 MeV. Thus, more than 2/3 of the incident energy on the average is taken away by the pre-equilibrium emissions. The corresponding fraction is closer to 1/2 at 80 MeV.

The nuclei which are produced in the pre-equilibrium phase and their relative cross sections, in terms of the cascade model, for 136 MeV protons on ^{59}Ni target, are plotted against the product mass in Fig. 8. Average excitation energy with which various of the nuclei are produced are also presented in Fig. 8. Typically nuclei closer to the target mass are produced with an average exciton of 60 MeV which tends to decrease at the rate of about 10 MeV for each additional nucleon removed; the latter is very close to average nucleon binding energy in this mass region.

The models, in particular the cascade model, are found to give a creditable account of the observed features of the experimental results. However, a more quantitative comparison with models must await incorporation in the models of such physical aspects as collective excitations and interactions involving formation of and scattering from clusters in nuclei.

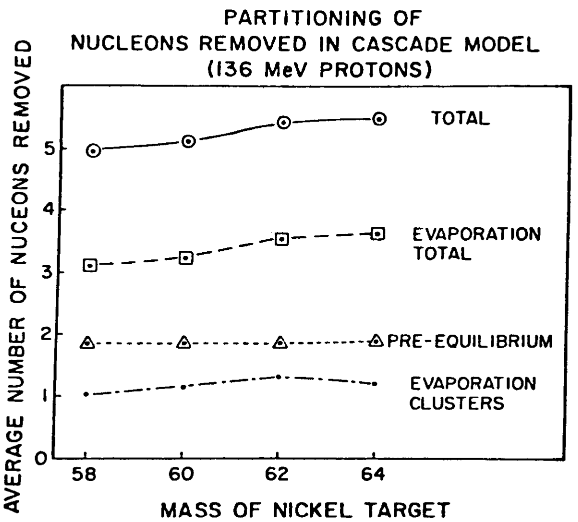

Figure 7.

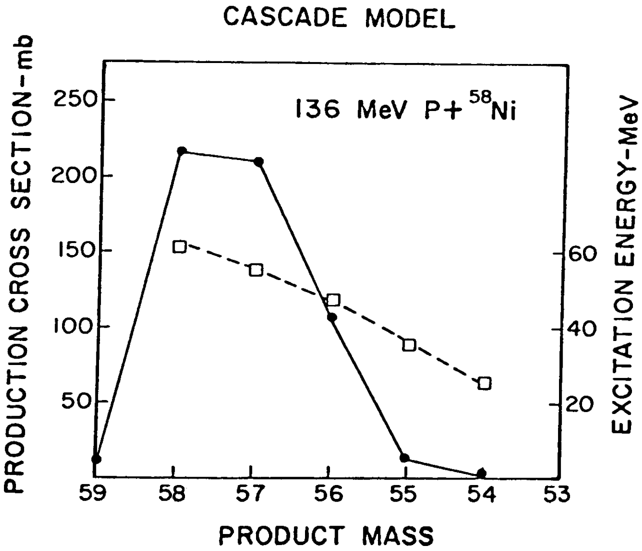

Figure 8.

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2) Chen et al., Phys. Rev. 166, 949 (1968); Phys. Rev. C4, 2234 (1977).

3) The Codes VEGAS and DFFMH were obtained from Dr. J. Ginocchio of Los Alamos Scientific Laboratory.

4) M. Blann, Annual Review of Nuclear Science 25, 123 (1975).

5) The Codes EVAHYB, ALICE and GDH were obtained from Dr. M. Blann of the University of Rochester.