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# SOME EFFECTS OF A MODIFIED EVAPORATION PROGRAM ON CALCULATIONS OF RADIOCHEMICAL CROSS SECTIONS AND PARTICLE MULTIPLICITIES FOR PROTONS ON CARBON AND ALUMINUM TARGETS

Hugo W. Bertini



ABSTRACT

Earlier calculations of radiochemical cross sections by the usual cascade-evaporation approach for 25- to 400-MeV protons incident on aluminum and carbon have been repeated to determine the effects of some of the modifications made by Peelle and Aebersold in the evaporation program originally coded by Dresner. For aluminum the effect is to improve the agreement of the calculated dross section with experiment for the two reactions calculated, but for carbon the modifications resulted in no change in one case and decreased the agreement in another case. The most significant change in the particle multiplicities is that the average number of neutrons evaporated in the higher energy reactions with aluminum is about 25% higher when the modified program is used.

Author

NOTE:

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## INTRODUCTION

The Dresner evaporation program[1] that was used in earlier intranuclear cascade calculations of reaction cross sections[2,3] has since been modified by Peelle and Aebersold.[4] The modified version has been used in recent calculations of radiochemical cross sections* and particle multiplicities for approximately 200-MeV protons incident on various targets. The results of these later calculations will be compared with experimental data in a forthcoming report.[5] Since in some cases there are significant differences in the results obtained with the two programs, this paper presents comparisons for a few typical reactions involving 25- to 400-MeV protons incident on carbon and aluminum.

All the cross sections were calculated by the usual two-step cascade-evaporation procedure in which the initial reactions are assumed to be fast particle-particle reactions that occur inside the nucleus. These reactions generate the cascade. When the energies of all the particles in the cascade fall below a certain arbitrary energy, the cascade phase is terminated, and it is then assumed that the nucleus (which is usually in a highly excited state at this point) loses energy by the "boiloff" or evaporation of particles. The modifications that are referred to above are in the program that handles the evaporation -- the cascade calculation remains unchanged.

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*The reactions under discussion are those usually measured by means of chemical separation followed by radioactive analysis of the exposed target, and the term "radiochemical cross sections" or "excitation functions" has been used to describe the cross sections.


1. L. Dresner, EVAP - A FORTRAN Program for Calculating the Evaporation of Various Particles from Excited Compound Nuclei, ORNL CF-61-12-30 (Dec. 19, 1961).
2. Hugo W. Bertini, Phys. Rev. 131, 1801 (1963) with erratum Phys. Rev. 138, AB2 (1965).
3. Hugo W. Bertini, Results from Low-Energy Intranuclear Cascade Calculation, ORNL TM-1225 (Sept. 10, 1965).
4. R. W. Peelle and P. M. Aebersold, Energy Parameters for Light Nuclides in Monte Carlo Nuclear Evaporation Programs Based on EVAP, ORNL TM-1538 (Oct. 17, 1966).
5. Hugo W. Bertini, Calculated Radiochemical Cross Sections and the Effects of a Few Nuclear Parameters for Incident Protons and $\pi^-$ Mesons in the 200-MeV Energy Region, ORNL TM-1562 (to be published).

## MODIFICATIONS

All changes reflected by the Peelle-Aebersold evaporation program were not applicable to the work reported here; only those changes which strongly affect the results for residual nuclei whose neutron or proton numbers are 10 or less were used. These were the estimated masses, the shell-plus-pairing-energy terms, and the pairing terms of Tables 1 (col. 4), 2 (cols. 3 and 6), and 4 (cols. 3 and 6), respectively, of ref. 4. Generally speaking, these modifications supply input parameters that are more consistent with the evaporation model.

The unmodified evaporation program that was used here and in the earlier calculations is the same as that described by Dresner, which incorporates the results of Dostrovsky et al.,[6] except that it involves only six particles -- neutrons, protons, deuterons, tritons, $^{3}He$, and alpha particles -- of the 19 particles used by Dresner.

## COMPARISONS

The effect of the modifications on a few reaction cross sections involving protons on carbon and aluminum targets is illustrated in Figs. 1-4. The cross section for the $^{12}C(p,pn)^{11}C$ reaction as a function of incident proton energy remains relatively unchanged (see Fig. 1). The effect on the $^{12}C(p,3p3n)^{7}Be$ reaction (Fig. 2) is to decrease the agreement with experiment. The effect on both reactions with aluminum (Figs. 3 and 4) is to improve the agreement with experiment.

The evaporation neutron and proton multiplicities, i.e., the average number of protons and neutrons produced in the evaporation process, are illustrated in Table 1. The results obtained with the modified and unmodified program are similar at the lowest energies, but there is a noticeable divergence in most of the results beyond about 100 MeV, particularly for the aluminum targets. For aluminum the average number of protons evaporated is about 10% higher when the unmodified evaporation program is used, but the neutron multiplicity is about 25% lower. For carbon, however, the average number of protons evaporated based on the

6. D. Dostrovsky, Z. Fraenkel, and G. Friedlander, Phys. Rev. 116, 683 (1959).

unmodified program is about 10% lower than the number from the modified program, but the neutron multiplicities are about the same.

These comparisons do not reflect the ability of the modified evaporation program to predict experimental results, because such results are affected by the rather complicated cascade calculation, which preceded the evaporation calculations. If such a test is desired, one should compare the predictions from this program with experiments for reactions in which the evaporation process is the sole or dominant process. The comparisons presented here are given so that the users of the data that have already been generated and distributed[3] can see some of the effects that modifications of this type will produce.

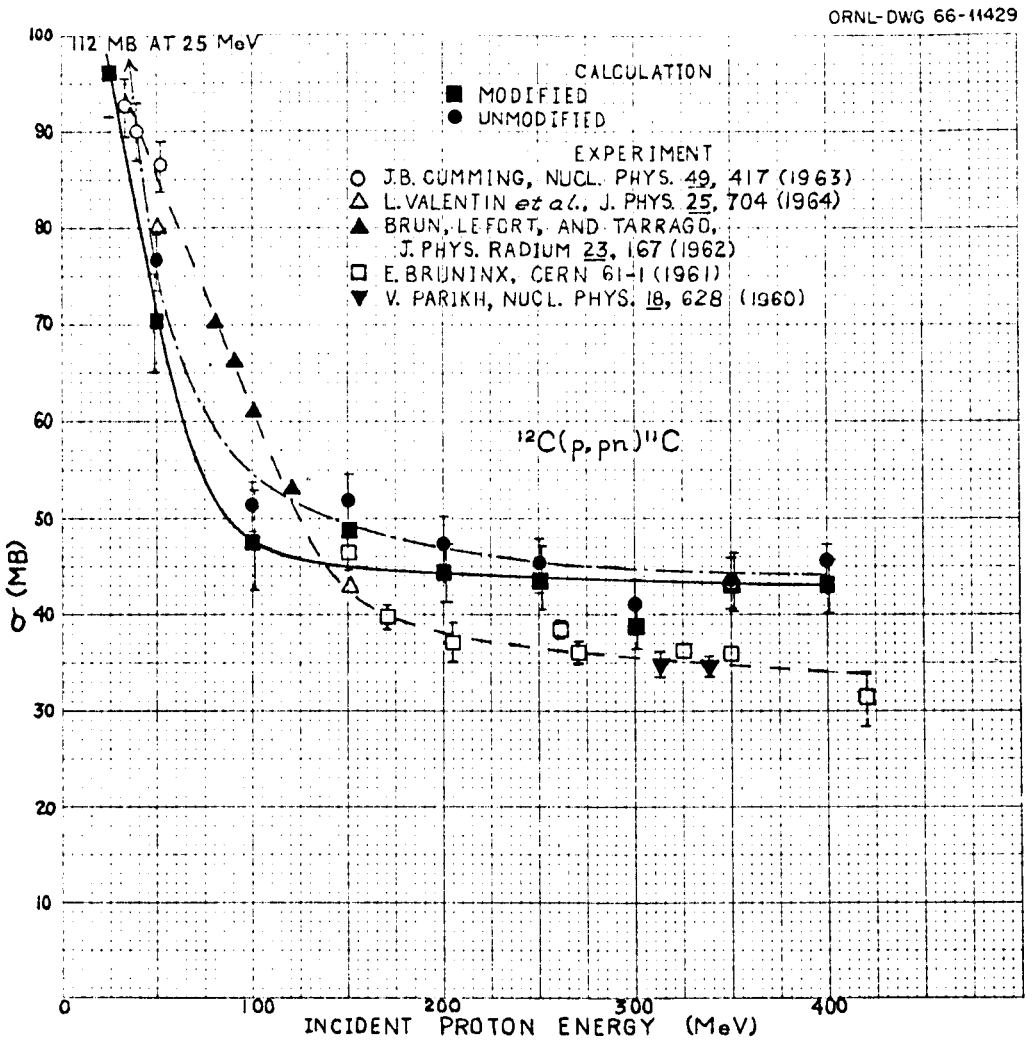


Fig. 1. Cross Section for the $^{12}C(p,pn)^{11}C$ Reaction vs Incident Proton Energy. The dashed curve is drawn through the experimental data; the dash-dotted curve is drawn through the calculated results for which the unmodified evaporation program was used; the solid curve is drawn through the calculated results for which the modified evaporation program was used.

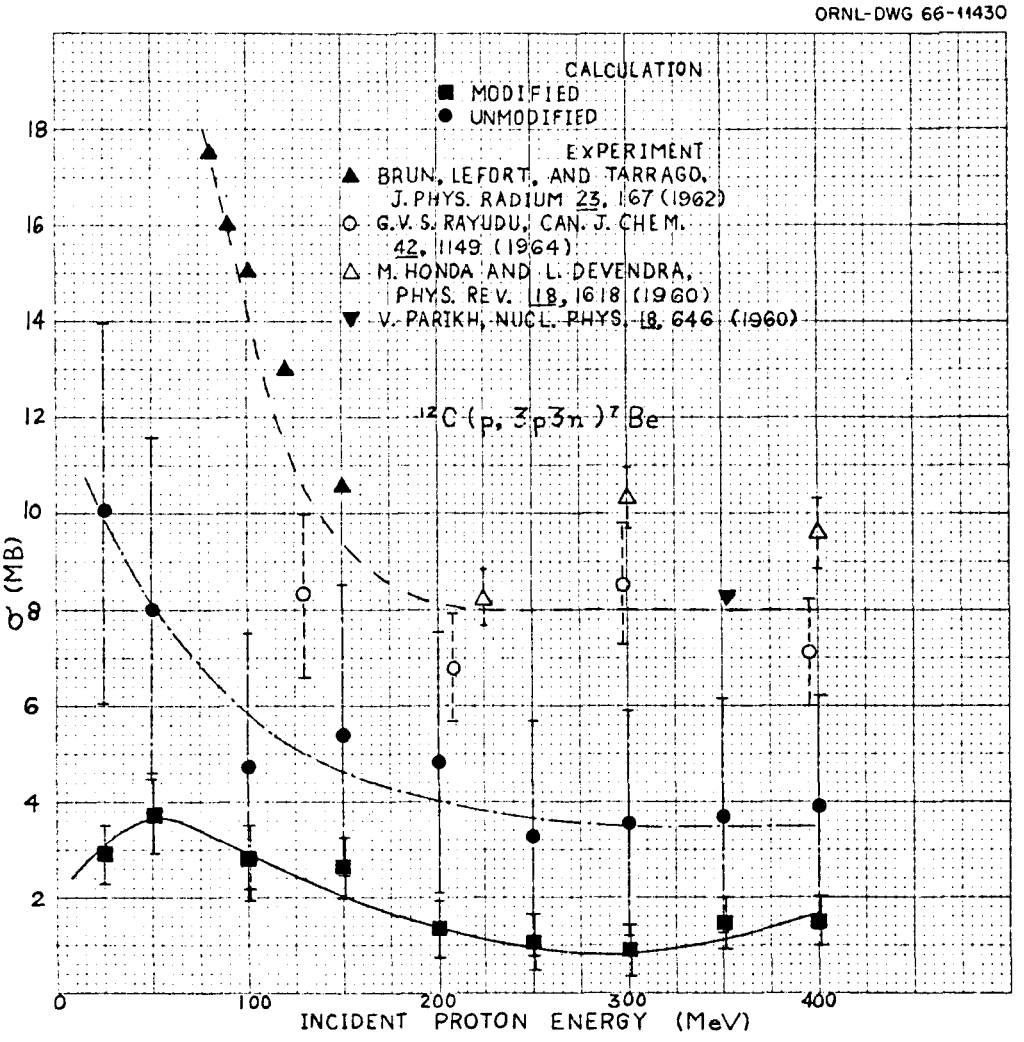


Fig. 2. Cross Section for the $^{12}C(p,3p3n)^{7}Be$ Reaction vs Incident Proton Energy. The dashed curve is drawn through the experimental data; the dash-dotted curve is drawn through the calculated results for which the unmodified evaporation program was used; the solid curve is drawn through the calculated results for which the modified evaporation program was used.

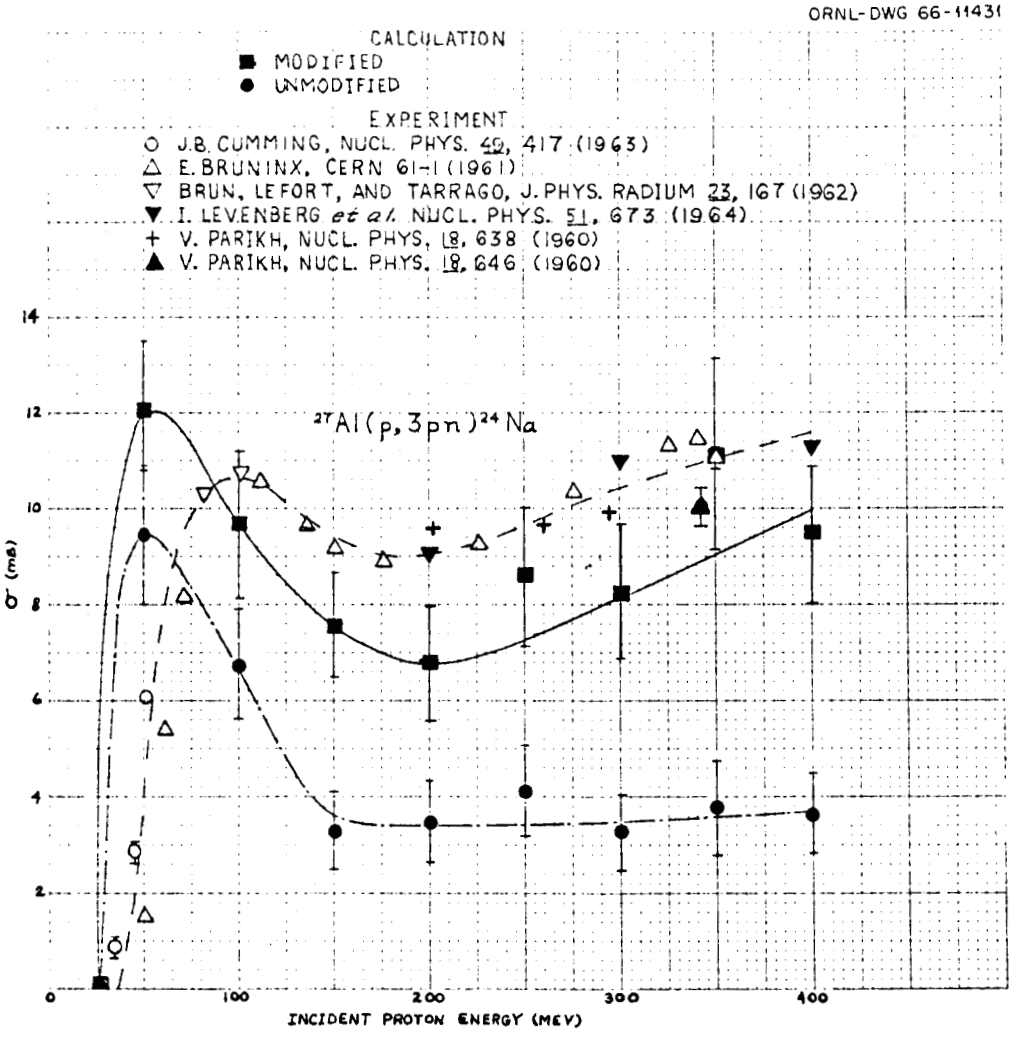


Fig. 3. Cross Section for the $^{27}Al(p,3pn)^{24}Na$ Reaction vs Incident Proton Energy. The dashed curve is drawn through the experimental data; the dash-dotted curve is drawn through the calculated results for which the unmodified evaporation program was used; the solid curve is drawn through the calculated results for which the modified evaporation program was used.

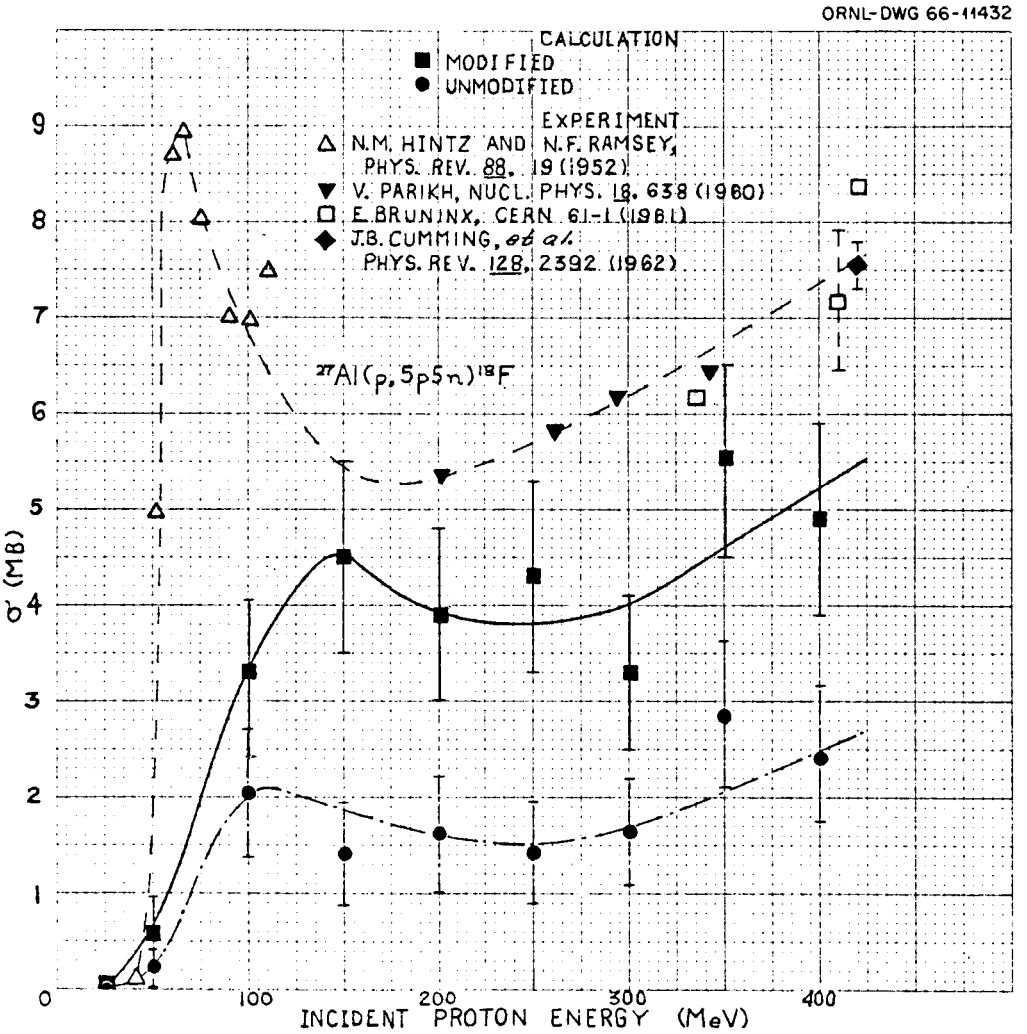


Fig. 4. Cross Section for the $^{27}Al(p,5p5n)^{18}F$ Reaction vs Incident Proton Energy. The dashed curve is drawn through the experimental data; the dash-dotted curve is drawn through the calculated results for which the unmodified evaporation program was used; the solid curve is drawn through the calculated results for which the modified evaporation program was used.

Table 1. Calculated Average Number of Protons and Neutrons Evaporated Per Nonelastic Reaction Involving Incident Protons at Various Energies on Carbon and Aluminum Targets

| Proton Energy (MeV) | Average Number of Protons Evaporated | | | | Average Number of Neutrons Evaporated | | | |
|---|---|---|---|---|---|---|---|---|
| | Carbon | | Aluminum | | Carbon | | Aluminum | |
| | Modified Evaporation Calculation | Unmodified Evaporation Calculation | Modified Evaporation Calculation | Unmodified Evaporation Calculation | Modified Evaporation Calculation | Unmodified Evaporation Calculation | Modified Evaporation Calculation | Unmodified Evaporation Calculation |
| 25 | 0.59 | 0.53 | 0.57 | 0.56 | 0.02 | 0.03 | 0.35 | 0.36 |
| 50 | 0.70 | 0.55 | 0.83 | 0.83 | 0.16 | 0.17 | 0.49 | 0.49 |
| 100 | 0.76 | 0.62 | 0.92 | 0.98 | 0.29 | 0.28 | 0.69 | 0.58 |
| 150 | 0.69 | 0.59 | 0.95 | 1.03 | 0.29 | 0.28 | 0.72 | 0.57 |
| 200 | 0.64 | 0.54 | 0.91 | 1.00 | 0.33 | 0.33 | 0.74 | 0.56 |
| 250 | 0.64 | 0.55 | 0.92 | 1.04 | 0.35 | 0.36 | 0.81 | 0.55 |
| 300 | 0.60 | 0.53 | 0.93 | 1.06 | 0.33 | 0.32 | 0.83 | 0.62 |
| 350 | 0.60 | 0.51 | 0.88 | 1.00 | 0.35 | 0.35 | 0.81 | 0.57 |
| 400 | 0.57 | 0.49 | 0.93 | 1.03 | 0.35 | 0.35 | 0.82 | 0.58 |

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