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Theoretical Calculation of Medium-Energy Proton-Induced Reactions on $A\ell$, Zr, and Pb

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The intranuclear cascade model of nuclear reactions was used to calculate double differential cross sections for the (p, xn) reaction. The calculations were performed with a generalized version of the code VEGAS, CLUST. Model predictions are compared with recent experimental data. Calculated fast-particle spectral shapes at low angles are reproduced reasonably well for the experimental data. As one possible improvement to the model, the proton reaction cross sections were estimated independently using the prescriptions of Karol, and DeVries and Peng. The systematic trends that emerge from this analysis are discussed.

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When considering nuclear reactions at medium to high incident energies it is convenient to treat the reaction as taking place in two successive stages viz: the intranuclear cascade and the evaporation process. From a computational point of view, the T–matrix approach becomes impractical and a semi–classical treatment is more suitable. The Monte Carlo simulation of the two reaction processes has been formulated and the model parameter dependence extensively investigated in Refs. 1 and 2.

We have undertaken a comprehensive investigation of the model validity for reactions induced by nucleons, deuterons and α–particles on a variety of target nuclei over a wide range of incident energies. The intranuclear cascade calculations were performed using the code CLUST discussed in Ref. 3. It generalizes the intranuclear cascade code VEGAS of Ref. 1 to include deuteron and α particle collisions as discussed in the contributed paper to this conference.[4] The evaporation spectra of outgoing nucleons and light charged particles are calculated using the code DFF discussed in Ref. 2. As part of this program, we have calculated double differential cross sections, angle integrated and energy integrated spectra for outgoing particles in reactions produced by protons from about 80 to 300 MeV on targets ranging from ^{27}Aℓ to ^{208}Pb. Apart from comparing theory with experiment whenever possible, the objective was to provide benchmark calculations for comparison with other models frequently used to interpret nucleon induced reactions at medium energy. Existing "gaps" in data may be filled provided a better understanding of the reaction mechanism is realized at incident energies covered in these benchmark calculations.

In the present work, an analysis of proton induced reaction data[5,6] on ^{27}Aℓ, ^{90}Zr and ^{208}Pb at 90 and 318 NeV incident energy is carried out. The calculations are performed using the optimum model parameters as given in Ref. 1. As an example, the resulting double differential neutron spectra for 90 MeV protons on ^{27}Aℓ are shown in Fig. 1. Qualitative agreement between theory and the experimental data was obtained. In Ref. 5, the double differential neutron spectra have been analyzed in terms of PWIA, intranuclear cascade,[7] geometry dependent hybrid,[8] and exciton models.[9] Overall, consistent agreement with data was not achieved in any of the model calculations. In particular, the intranuclear cascade model results of Ref. 5 were obtained from calculations done for 100 MeV incident energy[7] by approximate scaling of the emitted nucleon energies and renormalizing the total cross section. Unlike the order of magnitude discrepancy between theory and experiment reported for example at $\theta = 45°$ in Ref. 5, the present calculations (Fig. 1) done for the exact incident energy and using a slightly different intranuclear cascade model are in better quantitative agreement with experiment.

In the case of the ^{90}Zr target, the qualitative features of the data are well reproduced by the model. In quantitative terms, theory underestimates the cross section (Fig. 2). At the higher incident energy of 318 MeV, in the case of ^{27}Aℓ as well as ^{208}Pb, the predicted cross sections qualitatively reproduce the observed energy dependence but are lower than the experimental values. While no other model calculations are available for the ^{90}Zr + proton case, in Ref. 6, the data for ^{208}Pb + p reaction have been compared with the calculations performed using the HETC code.[11] They report that theory underestimates the cross section by about a factor of 3. This result is very similar to the discrepancy obsreved here (Fig. 3).

It has been noted in Refs. 1 and 3 that the discrepancy noted above could be partly due to the fact that the model underestimates the reaction cross section [σ(R)]. In an attempt to establish if this was a possible source of the discrepancy, we estimated σ(R) in terms of a realistic model,[11] of a nucleon–nucleus interactions which have successfully interpreted σ(R) data over a wide range of target masses and incident energies. For the reactions of interest here, σ(R) was calculated using the code based on the formalism of Ref. 1 and compared with CLUST predictions. It turned out that except for 90 MeV protons incident on ^{27}Aℓ, in all other cases σ(R) values were within 3% to 8% of those predicted by CLUST. In the case of ^{27}Aℓ, the code CLUST underestimates σ_R by about 20%. Test calculations for Aℓ also indicated that the soft sphere model of Ref. 1 gives very similar results for σ(R).

The "normalized" double differential neutron spectra for ^{27}Aℓ(p, xn) reaction at 90 MeV incident energy are shown in Fig. 4. The quantitative agreement at θ below 45° is improved as a result of such normalization. At this incident energy, data on the outgoing neutron and proton angle integrated spectra are also available. The data is compared with model calculations in Figs.

5a and 5b. While exciton model calculations[5] underestimate the continuum high energy yields, the present model is in good quantitative agreement with experiment.

From this analysis, indications are that the evaporation and fast particle emission is predicted satisfactorily by the theory. However, the yield of "intermediate" energy particles is underestimated. As far as the improvements to the model are concerned, these analyses point to the need to invoke a mechanism that would account for the energy deposition in a more realistic manner. This possibility is now being explored. The authors acknowledge many useful discussions with Drs. J. C. Peng and L-W. Wu.

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Figure Captions

1. Double differential neutron spectra for the reaction $^{27}A\ell(p, xn)$, $E = 90$ MeV. Data are from Ref. 5 (see text).
2. Model predictions for $d^2\sigma/d\theta_n dE_n$ for the reaction $^{90}Zr(p, xn)$, $E = 90$ MeV compared with data.[5]
3. a. Comparison of predicted $d^2\sigma/d\theta_n dE_n$ with experiment (Ref. 6) for the reactions $^{27}A\ell + p$ and $^{200}Pb + p$ at $E = 318$ MeV.
4. 90 MeV data for the reaction $^{27}A\ell(p, xn)$ compared with theory after normalizing $\sigma(R)$ (see text).
5. Angle integrated neutron and proton spectra for 90 MeV protons incident on $^{27}A\ell$ compared with experiment. Data are from Ref. 5.

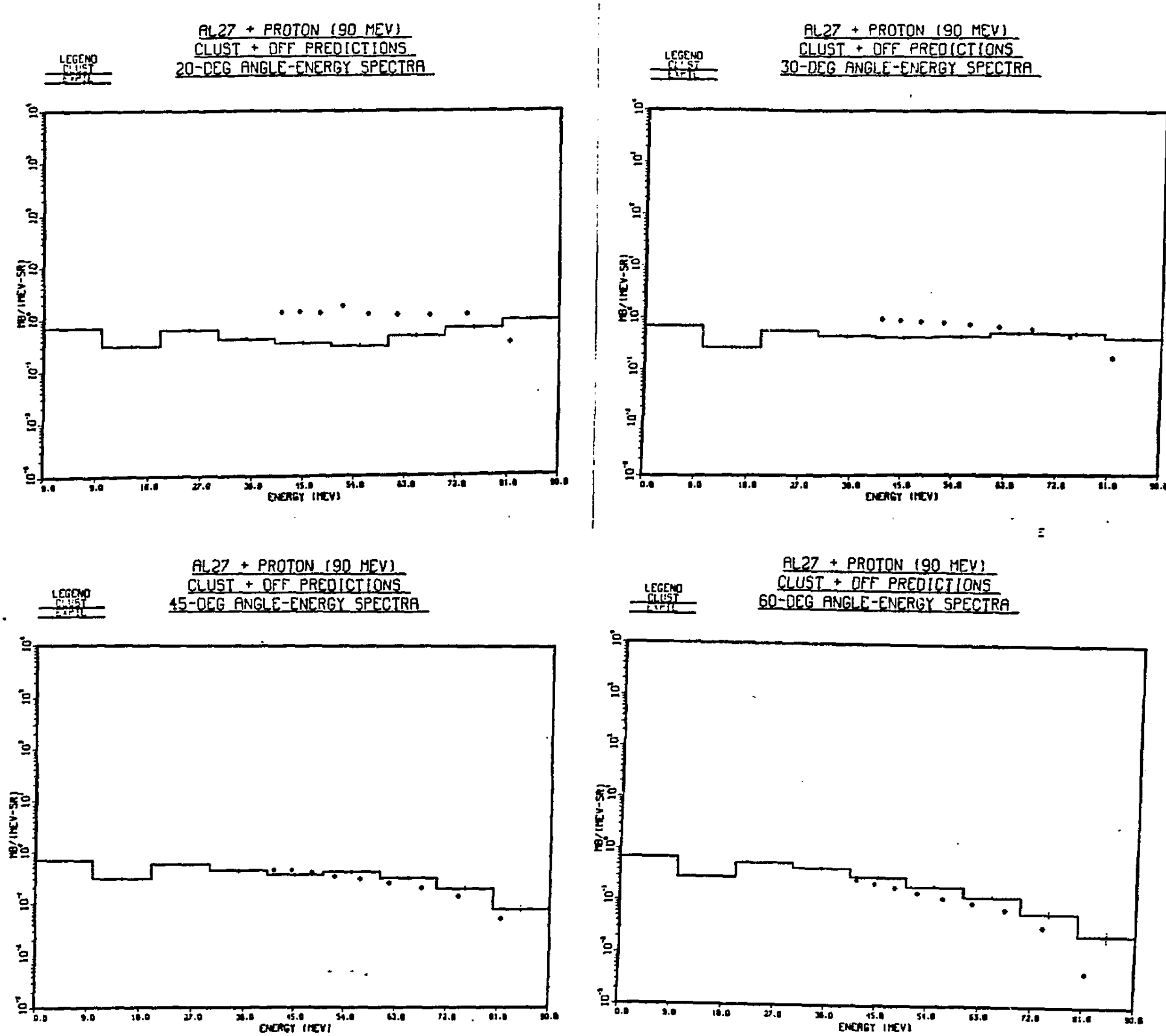
AL27 + PROTON (90 MEV)
CLUST + DFF PREDICTIONS
20-DEG ANGLE-ENERGY SPECTRA
LEGEND
CLUST
EXPTL
MB/(MEV-SR)
ENERGY (MEV)
0.0
9.0
18.0
27.0
36.0
45.0
54.0
63.0
72.0
81.0
90.0
AL27 + PROTON (90 MEV)
CLUST + DFF PREDICTIONS
30-DEG ANGLE-ENERGY SPECTRA
LEGEND
CLUST
EXPTL
MB/(MEV-SR)
ENERGY (MEV)
AL27 + PROTON (90 MEV)
CLUST + DFF PREDICTIONS
45-DEG ANGLE-ENERGY SPECTRA
LEGEND
CLUST
EXPTL
MB/(MEV-SR)
ENERGY (MEV)
AL27 + PROTON (90 MEV)
CLUST + DFF PREDICTIONS
60-DEG ANGLE-ENERGY SPECTRA
LEGEND
CLUST
EXPTL
MB/(MEV-SR)
ENERGY (MEV)

Figure 1

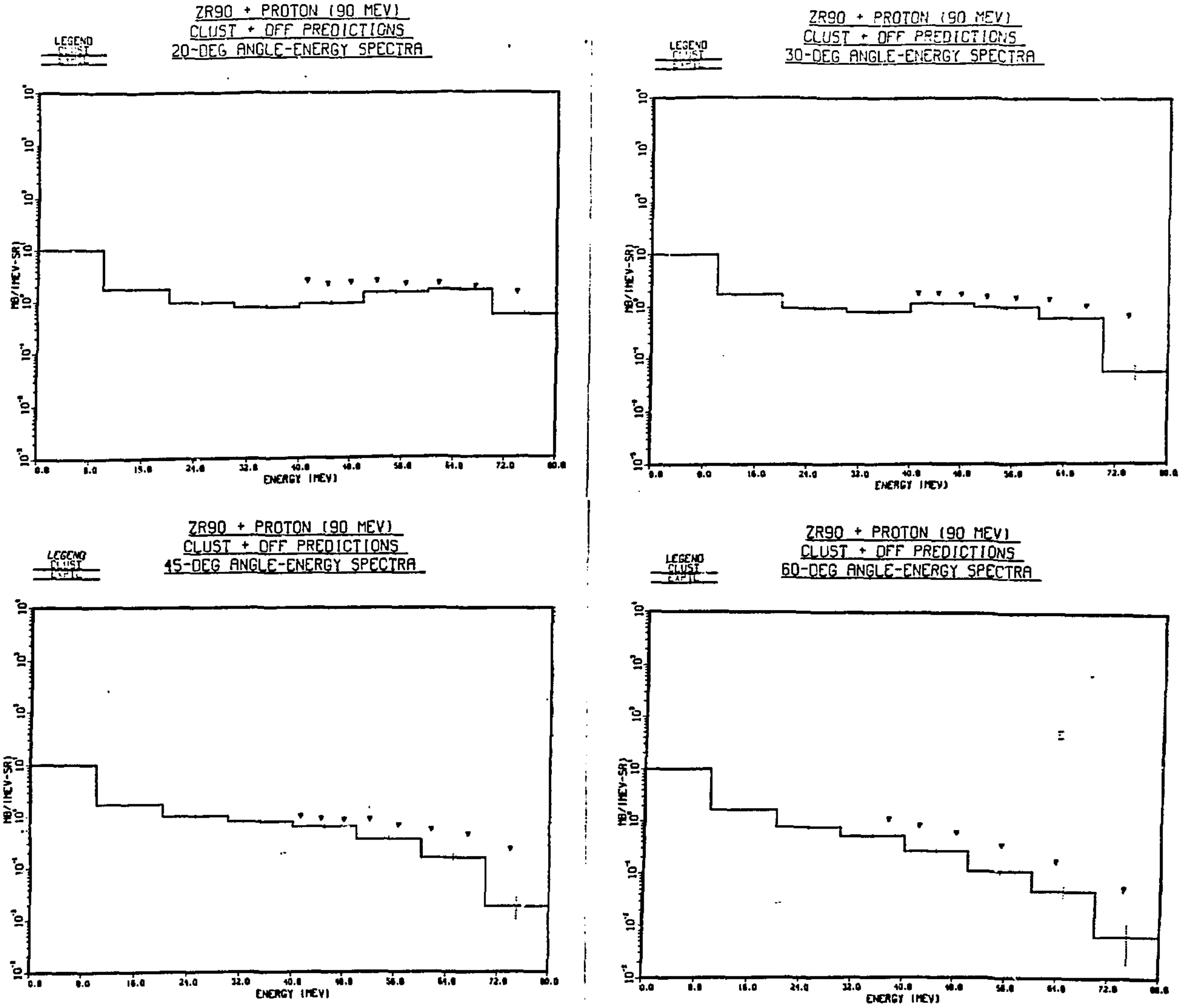
ZR90 + PROTON (90 MEV)
CLUST + OFF PREDICTIONS
20-DEG ANGLE-ENERGY SPECTRA
LEGEND
CLUST
EXPTL
MB/(MEV-SR)
ENERGY (MEV)
ZR90 + PROTON (90 MEV)
CLUST + OFF PREDICTIONS
30-DEG ANGLE-ENERGY SPECTRA
LEGEND
CLUST
EXPTL
MB/(MEV-SR)
ENERGY (MEV)
ZR90 + PROTON (90 MEV)
CLUST + OFF PREDICTIONS
45-DEG ANGLE-ENERGY SPECTRA
LEGEND
CLUST
EXPTL
MB/(MEV-SR)
ENERGY (MEV)
ZR90 + PROTON (90 MEV)
CLUST + OFF PREDICTIONS
60-DEG ANGLE-ENERGY SPECTRA
LEGEND
CLUST
EXPTL
MB/(MEV-SR)
ENERGY (MEV)
0.0
8.0
16.0
24.0
32.0
40.0
48.0
56.0
64.0
72.0
80.0

Figure 2

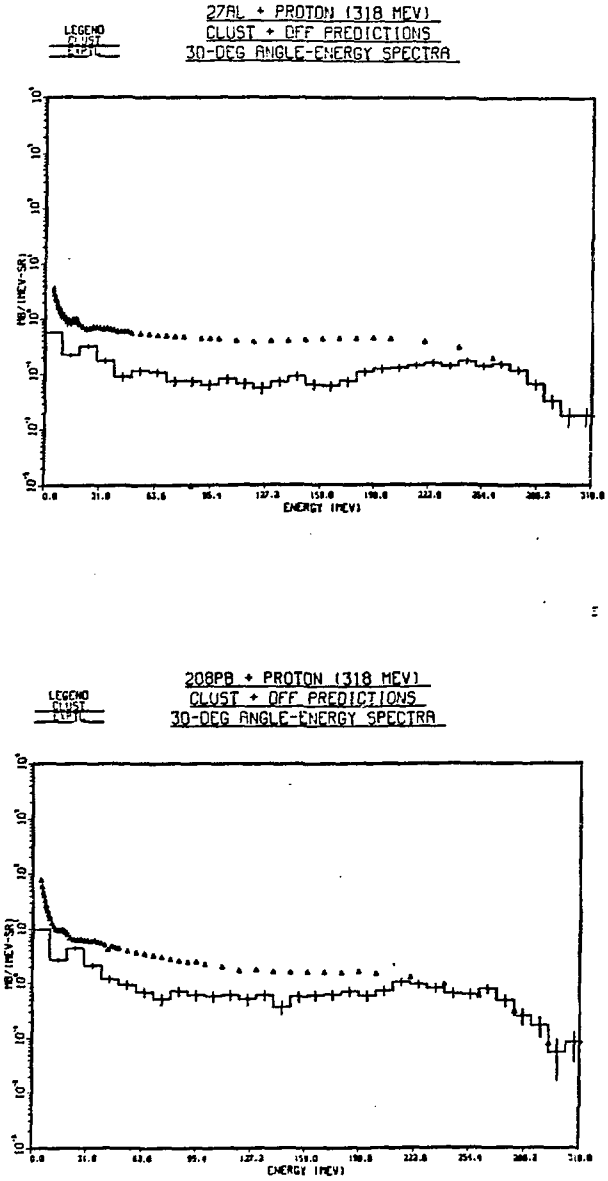
27AL + PROTON (318 MEV)
CLUST + DFF PREDICTIONS
30-DEG ANGLE-ENERGY SPECTRA
LEGEND
CLUST
EXPTL
MB/(MEV-SR)
10^{4}
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
0.0
31.8
63.6
95.4
127.2
159.0
190.8
222.6
254.4
286.2
318.0
ENERGY (MEV)
208PB + PROTON (318 MEV)
CLUST + DFF PREDICTIONS
30-DEG ANGLE-ENERGY SPECTRA
LEGEND
CLUST
EXPTL
MB/(MEV-SR)
ENERGY (MEV)

Figure 3

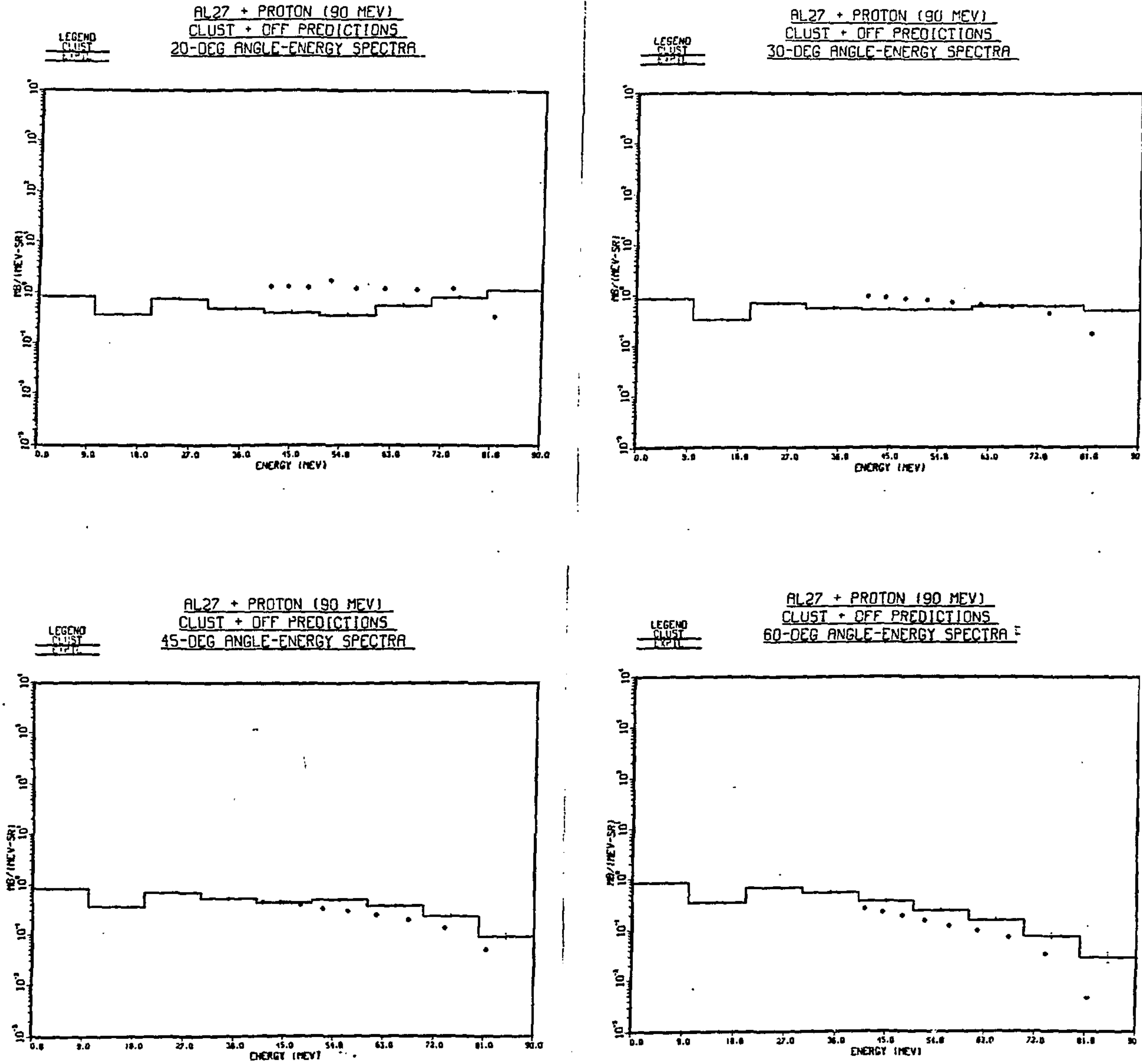
AL27 + PROTON (90 MEV)
CLUST + OFF PREDICTIONS
20-DEG ANGLE-ENERGY SPECTRA
30-DEG ANGLE-ENERGY SPECTRA
45-DEG ANGLE-ENERGY SPECTRA
60-DEG ANGLE-ENERGY SPECTRA
LEGEND
CLUST
EXPTL
MB/(MEV-SR)
ENERGY (MEV)
0.0
9.0
18.0
27.0
36.0
45.0
54.0
63.0
72.0
81.0
90.0

Figure 4

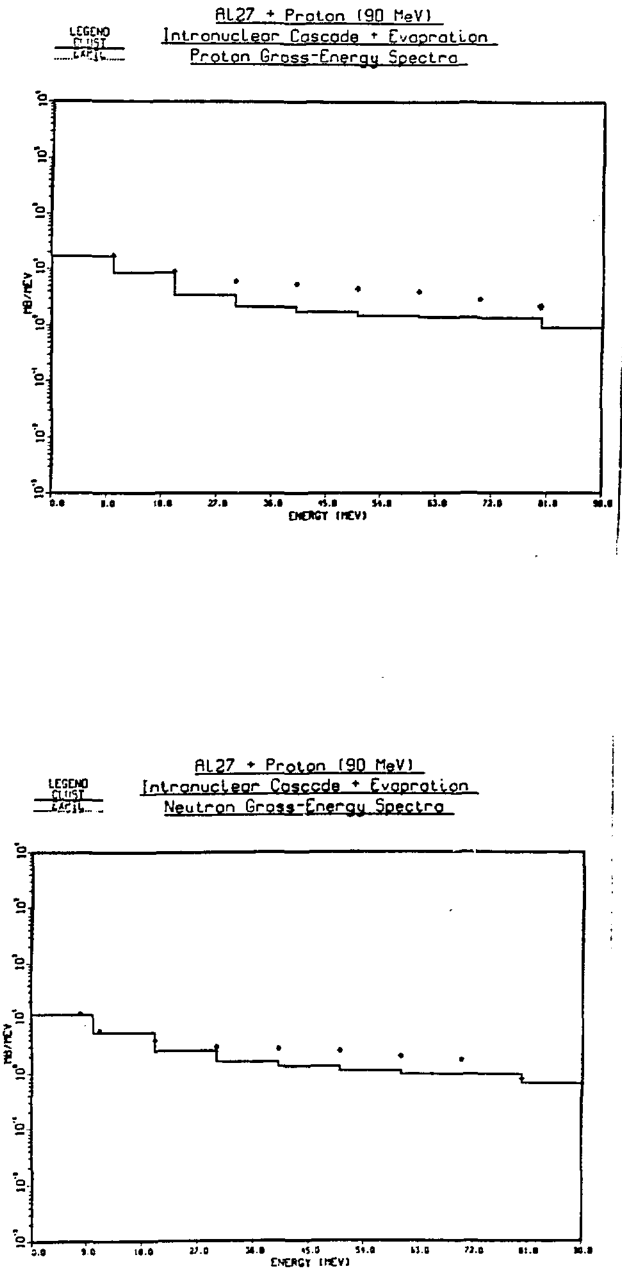
AL27 + Proton (90 MeV)
Intranuclear Cascade + Evapration
Proton Gross-Energy Spectra
LEGEND
CLUST
EXPTL
MB/MEV
10^{4}
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
0.0
9.0
18.0
27.0
36.0
45.0
54.0
63.0
72.0
81.0
90.0
ENERGY (MEV)
AL27 + Proton (90 MeV)
Intranuclear Cascade + Evapration
Neutron Gross-Energy Spectra
LEGEND
CLUST
EXPTL
MB/MEV
10^{4}
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
0.0
9.0
18.0
27.0
36.0
45.0
54.0
63.0
72.0
81.0
90.0
ENERGY (MEV)

Figure 5