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INTRANUCLEAR CASCADE STUDY OF THE HADRON-NUCLEUS INTERACTIONS AT 1 GeV/c

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ABSTRACT

The proton inclusive spectra measured with 800 MeV/c π^+ beam (BNL) on light nuclei, and the 600 MeV/c $\bar{p}$ beam (LEAR) on ^{6}Li and ^{63}Cu have been successfully interpreted in terms of the Intranuclear Cascade (INC) Model. According to the INC model predictions the $\bar{p}$ induced reaction results in high pion yield for the light ^{6}Li target case. This is attributed to the nonavailability of nucleons to be knocked out by the pions produced following the $\bar{p}$ annihilation. While in the case of the heavier ^{63}Cu target some of the internally produced pions are subsequently absorbed leading to thermal equilibration of the nuclear medium, resulting in a softer proton spectrum at the high energy end. Based on the INC model predictions the K$^+$ induced reactions could be studied to search for the "true resonances" beyond 1 GeV K$^+$ energy.

I. INTRODUCTION

The hope that a relativistic quantum mechanical many–body problem could reliably calculate exotic processes that take place with high and medium energy projectile induced reactions is very remote. A number of models[1] that identify the conventional and the exotic processes with suitable approximations are able to predict most of the experimentally observable quantities. Among these the Intranuclear Cascade Model (INC) is the most convenient model at intermediate energies for conceptual simplicity, with fewer approximations, and including multiple scattering processes. The model is suitable for different kinds of projectiles, projectile energy and in principle for almost all target nuclei except the very light ones.

Recently, a π^+ 800 MeV/c investigation at BNL[2] was undertaken to search for the η–meson nuclear bound states superimposed on the (π^+, p) continuum spectrum. The experimental search for sharp η–meson nuclear bound states failed to observe such states.

Analogous to the BNL π^+–nucleus study, the search for $\bar{p}$–nucleus states was carried out[3] at the LEAR $\bar{p}$ beam facility with the expectation of finding sharp well–defined $\bar{p}$–nucleus states, superimposed on a continuous proton spectrum arising from the annihilation of the antiprotons, and the subsequent proton knockout by the annihilation of pions. For the initial study the 600 MeV/c LEAR beam was used on several targets to measure the 0° proton spectra. No evidence for the narrow bound or resonant $\bar{p}$–nucleus states could be found. The small angle proton spectra measured in both the reactions $\bar{p}$–nucleus at 600 MeV/c and π^+–nucleus at 800 MeV/c are similar in shape.

In the present study a theoretical interpretation of the ($\bar{p}$, p) and (π^+, p) spectra was undertaken within the framework of the INC model. The INC model calculations were extended to include the (K$^+$, p) reaction even though data are not available. Details

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of the INC model calculations and a comparison of the INC model predictions with the corresponding experimental data are presented.

II. INTERMEDIATE-ENERGY REACTION MECHANISM

IIa. Intranuclear Cascade and Evaporation Model

Serber[4] in 1947 proposed the idea that the high energy nucleon induced reactions may be described in terms of essentially a two-step model. At high energies ($E_{proj} \geq$ 100 MeV/nucleon) the reaction is assumed to proceed in two steps; 1) a fast process, and 2) a slow process based on the interaction time scale. In the first step, the incident nuclear interaction develops a series of binary nucleon-nucleon collision cascades with allowance for some particles to escape. At the end of the first step, the residual nucleus deexcites (after immediate equilibration) through the second step or statistical evaporation of other nucleons/light ions. In this second step, it is tacitly assumed that the residual nucleus is in statistical equilibrium prior to the commencement of the evaporation process.

We used two different INC model codes; 1) MECC7 developed by Bertini[5] at ORNL in the sixties and early seventies, and 2) ISABEL,[6] the generalized version of the original BNL code VEGAS eveloped by Chen et al.[7] The modification and improvements were made by Yariv and Frankel[5] and later by Clover et al.[8] Joseph Cugnon[9] has developed his own version of the INC model at the University of Liege. Monte Carlo techniques are used to simulate the intranuclear interactions.

In the ISABEL code the nuclear density distribution is approximated by a series of sixteen concentric shells of constant density which approximate the measured nuclear charge distribution functions. Whereas in MECC7 the nuclear density distribution is approximated by 3 concentric shells. The details of the models may be found in references 6 and 8 on ISABEL and 5 on MECC7.

At the end of the cascade process described above, the intermediate nucleus after ejecting a few nucleons is in an excited mode which can deexcite via evaporation process. The statistical evaporation theory was used in conjunction with MECC7 and ISABEL to calculate the process of deexcitation via evaporation by using Monte Carlo method. Relative probability of emission of the particles is based on the statistical theory of a fermi gas model. The step-wise Monte Carlo method has been adopted for following the fate of a given excited nucleus and the average behavior is deduced from analysis of a large number of cascades. Six particles n, p, d, t, h and α are allowed to be emitted from the excited nucleus.

III. MODEL CALCULATIONS AND COMPARISON TO EXPERIMENT

IIIa. 800 MeV/c π^+ Induced Reaction on Light Nuclei

As pointed out in the introduction π^+ induced proton inclusive spectra were measured at BNL on ^{6}Li, C, O and $A\ell$ at 15° with the π^+ beam momentum at 800 MeV/c. The MECC7 code was used to predict the proton inclusive spectra besides other quantities. The INC calculations were performed with 30,000 to 50,000 cascades. Due to space limitation the discussion is restricted to the $A\ell + \pi^+$ reaction.

DISCLAIMER

In Figure 1 a comparison is shown between the INC model calculated 15° double–differential proton inclusive spectrum for the $A\ell$ 800 MeV/c (π^+, p) reaction. The agreement between theory and experiment is very good both in shape and magnitude. Unfortunately, the experimental data covers a very limited energy range; a similar situation holds for ^{6}Li, carbon and oxygen. Figures 2a and 2b show the 5° proton and neutron double–differential inclusive spectra. The energy integrated angular distribution for (π^+, p) and (π^+, π^+) inclusive reactions are displayed in Fig. 3. The (π^+, n), (π^+, π^o) and (π^+, π^-) angular distributions are also similar in trend and magnitude. The angular distributions are forward peaked. There are no corresponding experimental data at this medium energy to compare with theory.

IIIb. 600 MeV/c $\bar{P}$ Induced Reactions on ^{6}Li and ^{63}C

The ISABEL results which predict the relative inclusive production of various outgoing particles is displayed in Figs. 4a and 4b for ^{6}Li + $\bar{p}$ and ^{63}Cu + $\bar{p}$ reactions respectively. In the case of the light target ^{6}Li, since there are not enough nucleons that could be knocked out by pions produced after the initial $\bar{p}$–nucleon annihilation takes place, we notice a copious production of pions. The situation is reversed in the case of the ^{63}Cu target. Lighter targets like ^{9}Be + $\bar{p}$ reaction would produce abundant π^- which would decay into μ mesons suitable for μ meson catalyzed fusion process and subsequent energy release.

Figures 4c and 4d display a comparison of the INC model predictions for the inclusive proton production at 0° and the corresponding LEAR experimental data. The energy dependence and magnitude observed in the LEAR experiment are well reproduced. Increasing the number of cascades from 15,000 to a higher figure might improve the statistics for the predicted double differential cross sections.

The angular distributions for ($\bar{p}$, n), ($\bar{p}$, p), ($\bar{p}$, π^+) and ($\bar{p}$, K$^+$) are shown in Fig. 5a. The angular distributions, are rather isotropic implying equilibration of the nucleus after the initial annihilation of the incident antiproton. This feature is also evident in fig. 5b, which displays the inclusive proton energy spectrum. The histogram could be fitted with two Maxwellian distributions with different temperatures. The spectrum up to about 40 MeV (or less) corresponds to the evaporation spectrum and the rest of the spectrum does not correspond to a typical fast–particle spectrum as observed in nucleon induced reactions or the K$^+$ induced reaction to be discussed in the next paragraph. After the incident $\bar{p}$ is annihilated, the subsequent pion production and some absorption leads to equilibration of the nuclear medium. The ($\bar{p}$, p) spectrum beyond 40 MeV demonstrates this point.

Due to space limitations a detailed discussion of $P_\perp$ distribution vs. rapidity, energy deposition description, particle multiplicities etc. is deferred to a later publication.

IIIc. 1 GeV K$^+$ + $A\ell$ Reaction

Figure 6 displays the K$^+$ induced reaction total cross sections[10] for the (K$^+$, p), (K$^+$, d) and (K$^+$, n) reactions. The variation of the total cross section with the K$^+$ incident energy increases slowly with energy beyond 1 GeV and the difference σ_t–$\sigma_{o\ell}$ for the (K$^+$, p) case increases with K$^+$ energy. This indicates that several reaction channels are opening beyond 1 GeV K$^+$ incident energy. The ISABEL calculations at 1 GeV were performed to check the relative inclusive production of the several outgoing particles. Figure 7a presents the ISABEL predicted relative production cross sections for p, n, π, K^+, K^o etc. It is noticeable that in addition to the production of K^+ and the nucleons, the K° production cross section is not negligible as is the situation for the other particles. It would be interesting to look into the K^+ induced reaction "true resonances" in the K° channel, i.e. delta and N-stars resonances.

Figure 7b displays a comparison of the (K^+, p) and (K^+, K^+) production cross section angular distributions, which are forward peaked-typical of hadron induced reactions other than the $\bar{p}$ projectile.

Experimental data is lacking for a comparison with ISABEL predictions.

IV. SUMMARY AND CONCLUSIONS

Theoretical interpretation of the 15° BNL 800 MeV/c (π^+, p) inclusive spectra from light target nuclei and the 0° LEAR 600 MeV/c ($\bar{p}$, p) inclusive spectra from ^{6}Li and ^{63}Cu targets was undertaken within the frame-work of the Intranuclear Cascade (INC) Model. The INC model codes MECC7 and ISABEL were used in predicting the relative production cross section and the doubly-differential cross section besides several other related quantities. The INC model predictions compare very well with the BNL and LEAR measured low angle proton spectra. The ^{6}Li + $\bar{p}$ and ^{63}Cu + $\bar{p}$ reaction study reveals interesting features regarding the relative pion production vs. nucleon production. The phenomena of phase transition in terms of equilibration temperatures in the case of ^{63}Cu + $\bar{p}$ reaction reveals that the pion production and absorption and subsequent thermalization of the nuclear system leads to a higher energy softer spectrum compared to the spectra observed in non-antiparticle induced reactions. The K^+ + $A\ell$ reaction was considered as a test case to explore the possibility of measuring the reaction products beyond 1.4 GeV/c. Beside the nucleon and K^+ production cross sections, the K° production cross section is non-negligible compared to the rest of the particle production cross sections.

In conclusion, it is demonstrated that quantitative reproduction of proton inclusive spectra measured both in 800 MeV/c pion and 600 MeV/c $\bar{p}$ induced reactions on light to medium mass target is possible within the framework of the INC model. It would be desirable to compare the ISABEL and MECC7 predictions for the π^+ induced reactions.

The ISABEL predicted (K^+, p), (K^+, n), (K^+, K^+) and (K^+, K°) inclusive spectra for the 1 GeV K^+ induced reaction on $A\ell$ suggest the use of one of these channels to measure the "true resonance structure" with K^+ beam momenta above 1.4 GeV/c.

Experimental data are in general sparse for the π^+, $\bar{p}$ and K^+ induced reactions for a critical test of the INC model predictability in the intermediate to high energy region.

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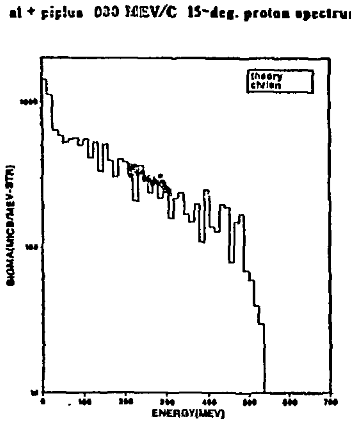

Fig. 1a. 15° inclusive proton spectrum; INC model calculations with 30000 cascades.

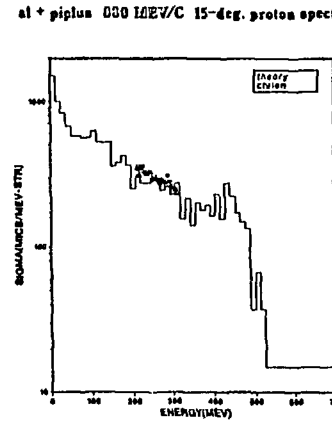

Fig. 1b. Inclusive proton spectrum; INC model calculations with 40000 cascades.

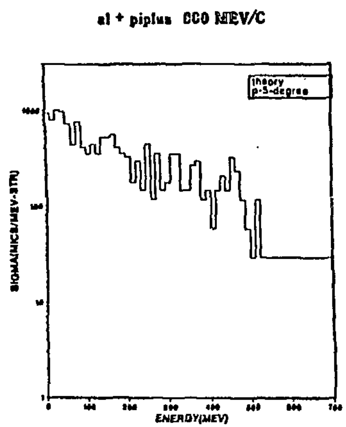

Fig. 2a. 0-5° inclusive neutron spectrum.

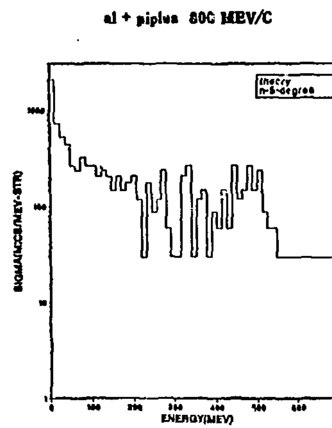

Fig. 2b. 0-5° inclusive proton spectrum.

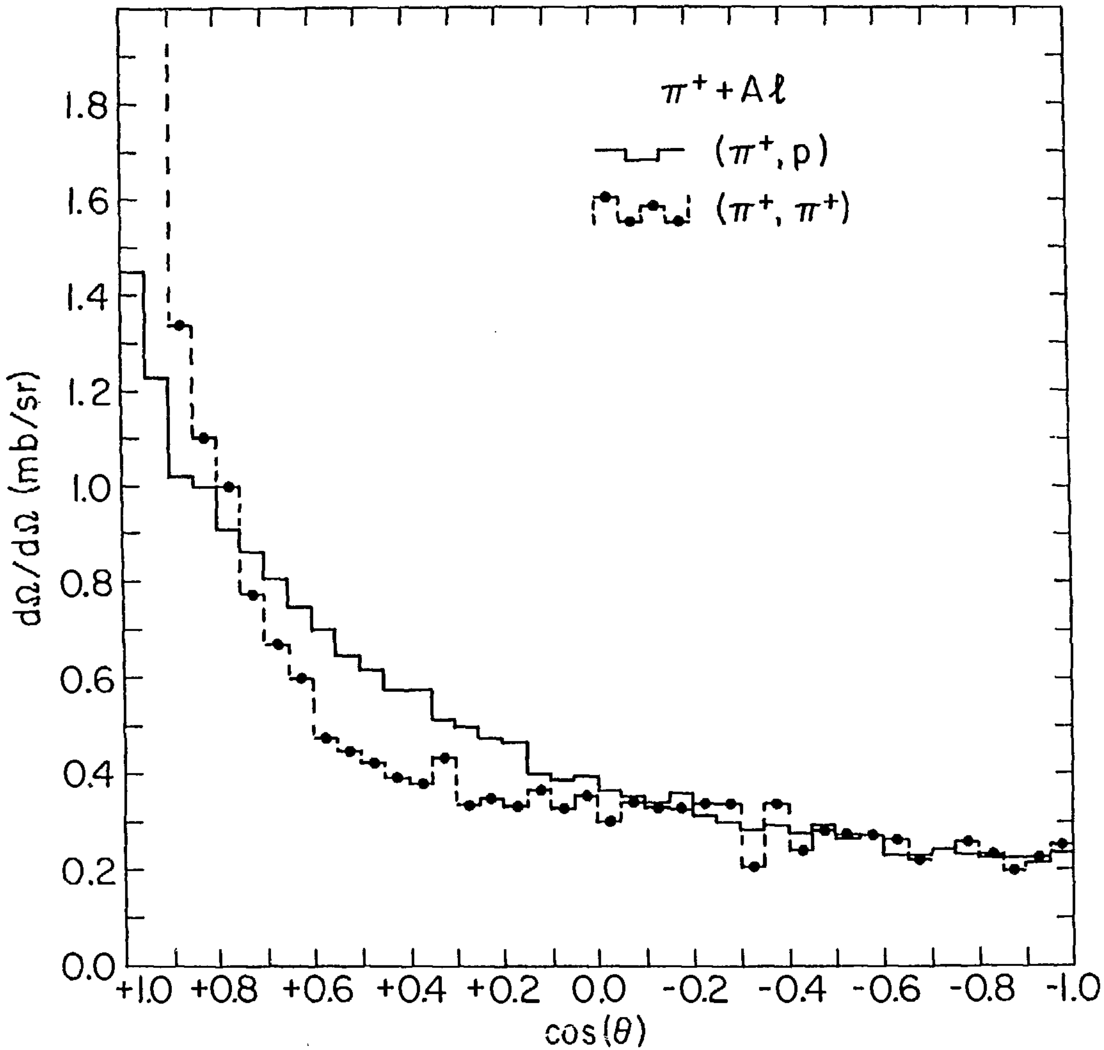

Fig. 3. $A\ell(\pi^+, p)$ and $A\ell(\pi^+, \pi^+)$ INC model predicted angular distributions.

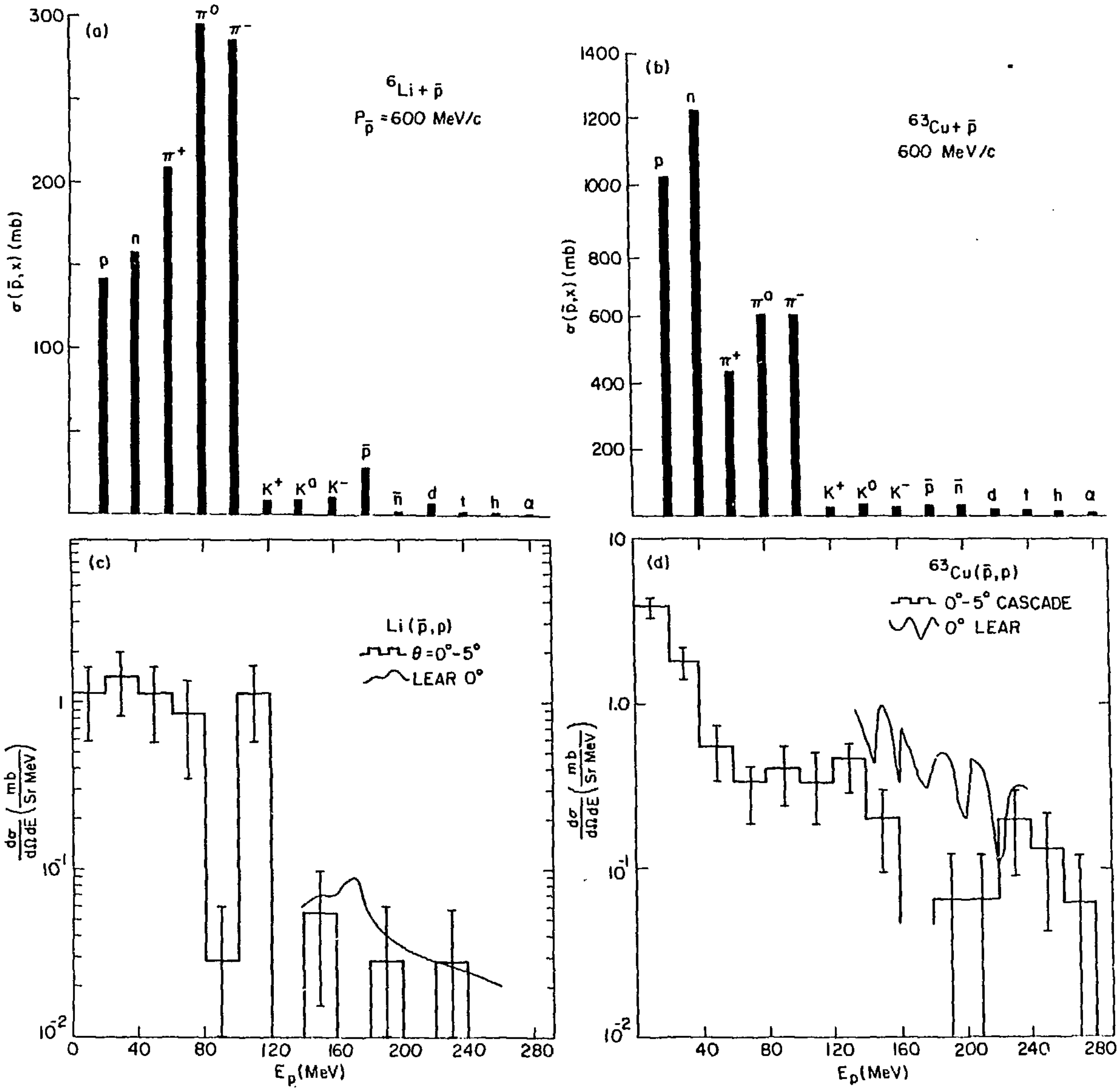

Fig. 4a. ^{6}Li + p̄ 600 MeV/c reaction-product cross sections: INC model predictions.
Fig. 4b. ^{63}Cu + p̄ 600 MeV/c reaction-product cross sections: INC model predictions.
Fig. 4c. ^{6}Li (p̄, p) 0° inclusive proton spectrum: comparison of theory with experiment.

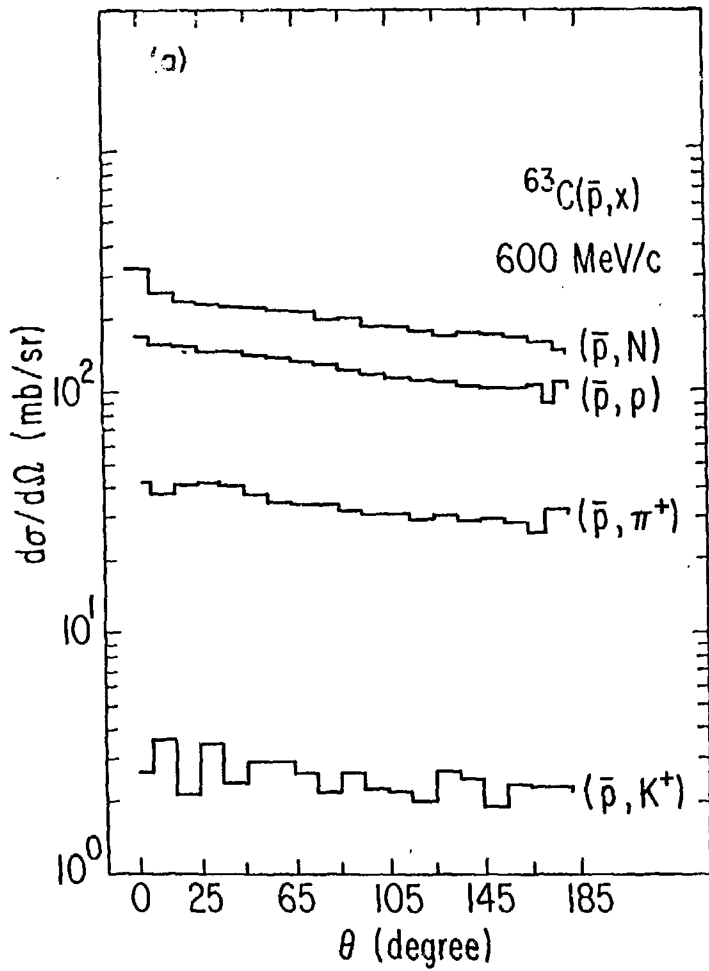

Fig. 5a. ($\bar{p}$, n), ($\bar{p}$, p), ($\bar{p}$, $\bar{\pi}^+$) and ($\bar{p}$, K^+) INC model predicted angular distributions for ^{63}Cu.

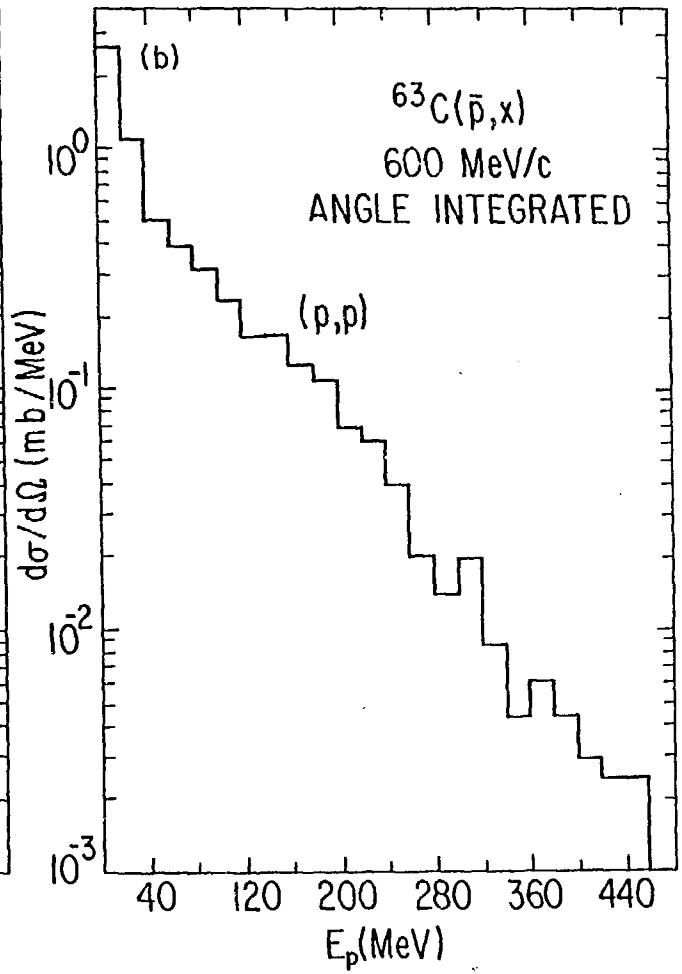

Fig. 5b. ^{63}Cu target ($\bar{p}$, p) inclusive proton gross energy spectra.

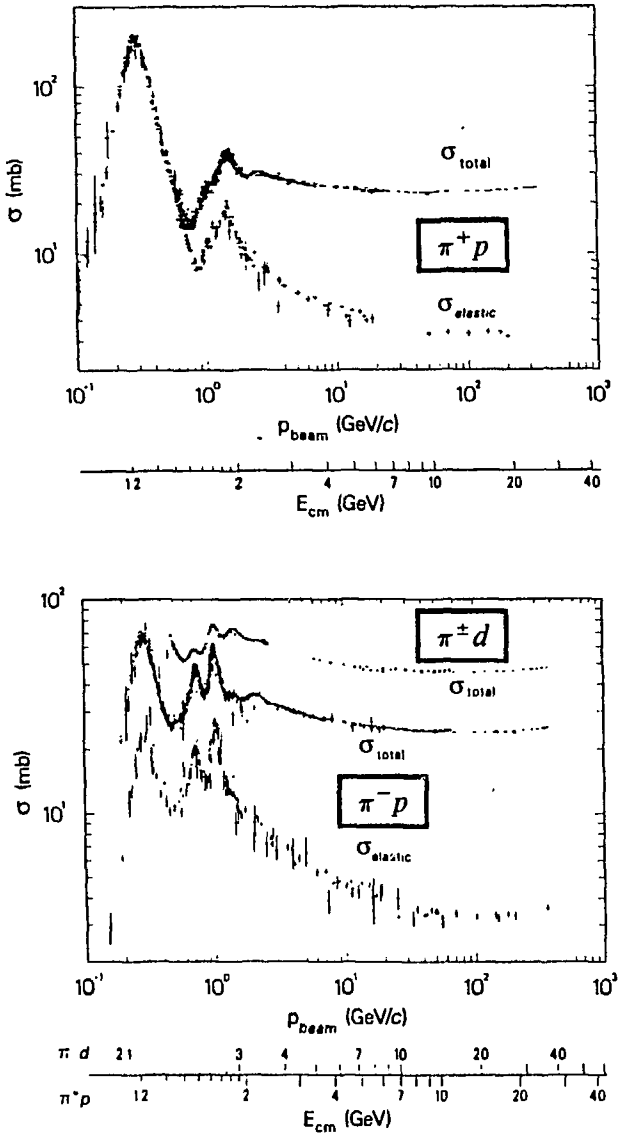

Fig. 6. K^+p, K^+d, K^+n cross sections. Plots reproduced from reference 10.

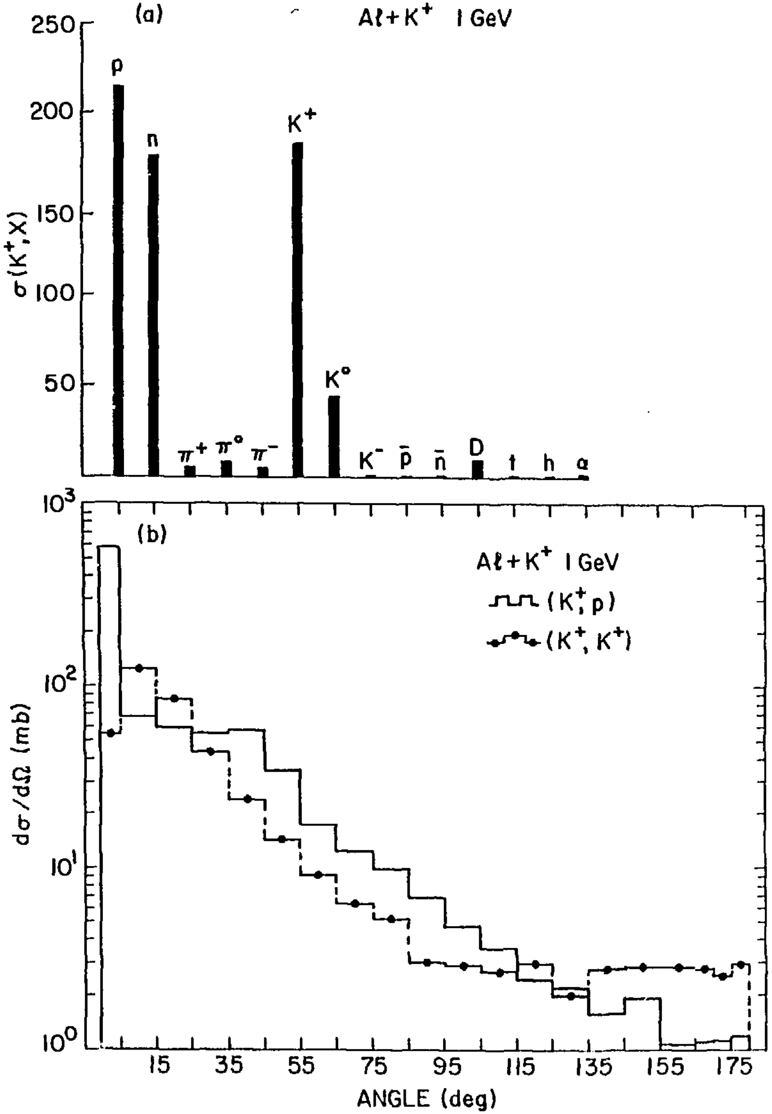

Fig. 7a. $A\ell + K^+$ 1 GeV reaction–product cross sections: INC model predictio

Fig. 7b. $A\ell(K^+, p)$ and $A\ell(K^+, K^+)$ angualr distributions: INC model predictions.