# $\pi^-$-nucleus interactions for stopped and 45 MeV pions with $^{58,60,62}$Ni

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The spectra of residual nuclei produced by the interaction of stopped and 45 MeV $\pi^-$ has been studied as a function of neutron excess in the nickel isotopes. The similarity of results for stopped pions and pions in flight indicates that absorption is the dominant mode of interaction. While the data show substantial departures from trends observed in measurements reported previously at higher energies, the same mechanism appears to explain the reaction in all cases.

[NUCLEAR REACTIONS $^{58,60,62}$Ni, $(\pi^-, ?)\gamma$ inclusive $\gamma$ ray spectra, $E_\pi = 0$ and 45 MeV. Production cross sections for residual nuclei, quasideuteron pion absorption model.]

## I. INTRODUCTION

One of the first priorities in pion nuclear physics is the determination of the dominant features of the pion-nucleus interaction. These include the relative strength of pion capture and scattering; the mode of absorption, e.g., quasideuteron absorption or absorption on $\alpha$ clusters; and the extent to which the interaction is dominated by direct reactions or evaporative decay. A number of experiments have been reported recently[1-4] in which these questions are explored through the study of multinucleon removal spectra generated by interactions of pions in flight. Major features of the multinucleon removal spectra were determined in these studies from observation of the prompt $\gamma$-ray spectra; in effect, on-line activation analysis. A systematic study of the dependence on pion charge and energy in a single measurement[1] has been reported for two nickel isotopes, $^{58}$Ni and $^{60}$Ni. The results can be summarized in the statement that the multinucleon removal spectra are insensitive to the pion energy and charge. Relatively large numbers of nucleons are observed to be removed, suggesting that surprisingly large energies are transferred to the nucleus in the pion interaction. These data seem to contradict older $\pi^+/\pi^-$ comparisons reported for 65 MeV on Cu.[5] The discrepancy has been attributed to the fact that the prompt $\gamma$-ray spectra measurements are sensitive to stable residual nuclei where most of the total cross section is concentrated, while activation measurements identify only a small portion of the residuals off the line of stability. More important, however, none of the experiments have given an unambiguous answer to such questions as whether the pion is absorbed or scattered, not to mention the relative importance of quasideuteron absorption and absorption on clusters.

We wish to report results of a direct comparison of the spectra for stopped pions and pions in flight on three isotopes of nickel, which gives a measure of the importance of pion absorption. The range of targets permits a study of the spectra of residual nuclei as a function of neutron excess. The limited total pion energy available in our experiment compared to measurements at higher energy places a stronger limit on the amount of excitation energy the nucleus can receive in the usual models of pion absorption. In addition, such measurements are of major interest because of the possibility that the reaction mechanism for stopped pions will be different than that of pions in flight. In contrast to the situation for energetic pions, absorption of stopped pions may not be dominated by effects of a $\frac{3}{2}, \frac{3}{2}$ isobar doorway.[6,7] In exploring this question, Ullrich and co-workers[4] showed that the spectra for stopped and 60 MeV pions absorbed on $^{31}$P gave similar spectra. In this work we find a similar result for pion interactions with the nickel isotopes at 0 to 45 MeV. Ullrich *et al.* also compared somewhat indirectly the 0 and 60 MeV data for a range of targets with results at higher energy and concluded that the pion-nucleus interaction at 220 MeV is very different from absorption at rest. Here we draw quite a different conclusion. Our spectra for $^{58,60,62}$Ni can be compared directly with those[1] corresponding to higher pion energies. The results reported here indicate that the same reaction mechanism accounts for absorption at all pion energies below ~400 MeV.

## II. EXPERIMENTAL METHOD

The experiments were performed on the low energy pion channel PM2 at the 600 MeV Saclay linear accelerator. The technique is basically the same as that used in earlier experimental studies of pion induced multinucleon removal.[8] The spectra of residual nuclei are determined by measuring the prompt $\gamma$-ray spectra generated by all pion interactions. In this way one identifies those nuclei which are left without sufficient energy for further particle emission. These may be nuclei produced in the primary interaction of the pion with a target nucleus or the residue of particle evaporation after the primary process. These experiments are in many ways analogous to activation measurements from which much of our current knowledge of the details of pion interactions with nuclei originates, but with the important difference that from prompt measurements it is possible to identify stable daughters and thus a much larger fraction of the components of the total cross section.

The experimental arrangement is shown in Fig. 1. A beam of negative pions was focused on targets of separated isotopes of $^{58,60,62}$Ni. The spectra were measured by requiring a coincidence between the incident $\pi$ observed in one or more plastic scintillators and a Ge(Li) $\gamma$-ray detector whose resolution was ~3 keV at 1 MeV. Electron contamination in the incident beam was eliminated by biasing out the corresponding peak in the pulse height distribution from the beam scintillators. The pion beam consisted of 10 $\mu$sec bursts of pions delivered at a repetition rate of 1–2 kilocycles corresponding to a duty cycle of 1–2%. The pion flux was limited to an average value of $2.4\times10^4$ $\pi^-$/sec in order to limit electronic dead time resulting from the much higher instantaneous rates. In addition, the actual dead-time losses were monitored by connecting to the Ge(Li) preamplifier a pulser triggered by a counter viewing the scattered beam and comparing the number of triggers with the observed intensity of the pulser peak in the spectrum.

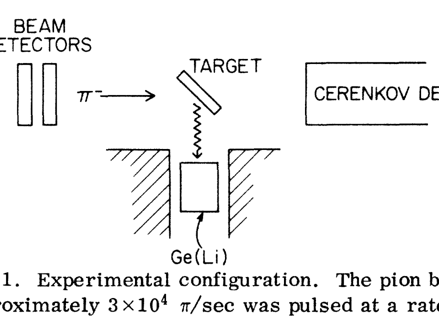


FIG. 1. Experimental configuration. The pion beam of approximately $3\times10^4$ $\pi$/sec was pulsed at a rate of 2000 pulses/sec. The pulse width was 10 $\mu$sec.

As a further precaution, in place of direct absolute determination of $\gamma$ ray intensities, all photon yields were measured relative to the intensities of characteristic lines of the pion spectra from aluminum targets, generated under the same conditions of incident pion flux and beam profile. The aluminum targets were constructed to have the same cross sections as the corresponding sample targets with the result that corrections for the fraction of the beam profile intercepted by the target cross section canceled out. The absolute calibration of the aluminum cross sections was accomplished in a subsequent measurement using a target whose dimensions were larger than those of the pion beam profile and a pion flux whose level precluded significant dead-time losses in the beam scintillators. Muon contamination estimated from the muonic x-ray yields to be $\le 10\%$ limited the accuracy of our absolute cross sections.

By examining $\gamma$-ray spectrum for Al we were able to estimate background contributions to intensities of most characteristic lines. They were found to be negligible. However, contamination of the in-flight spectra by stopped pion contributions to characteristic line intensities was a potentially serious problem. With the thickness of targets used the probability of interaction of pions in flight was typically ~0.05. Because every stopped pion interacts, the presence of even a small low energy tail in the pion energy distribution would have been serious. A 1% contamination of $E_\pi < 10$ MeV (appropriate to our targets) would have generated an interaction rate 20% of that due to pion in flight. To assess this problem the rate of stopped $\pi$ absorption was monitored by measuring the pion x-ray yield corresponding to the $4g$-$3d$ transition at 145 keV. The absence of any observable strength for this line in the 45 MeV spectra (not to be confused with a weak line at 143 keV which is due to $^{59}$Co) indicated that the stopped pion contribution to the in-flight spectra was negligible.

Absolute yields for stopped pions in photons per stopped pion were obtained directly from the observed intensity in the Ge(Li) spectrum by correcting the incident pion flux for the pion fraction stopping in the target. The full width at half-maximum of the range curve for incident pions was ~2.7 g/cm$^2$. Typically, about 65% of the pion beam incident on the individual targets was stopped. The absolute detection efficiency of the Ge(Li) spectrometer and corrections for target absorption were determined experimentally using calibrated $\gamma$-ray sources.

## III. RESULTS

Typical spectra are shown in Fig. 2 for spectra generated by fast pions and stopped pions incident

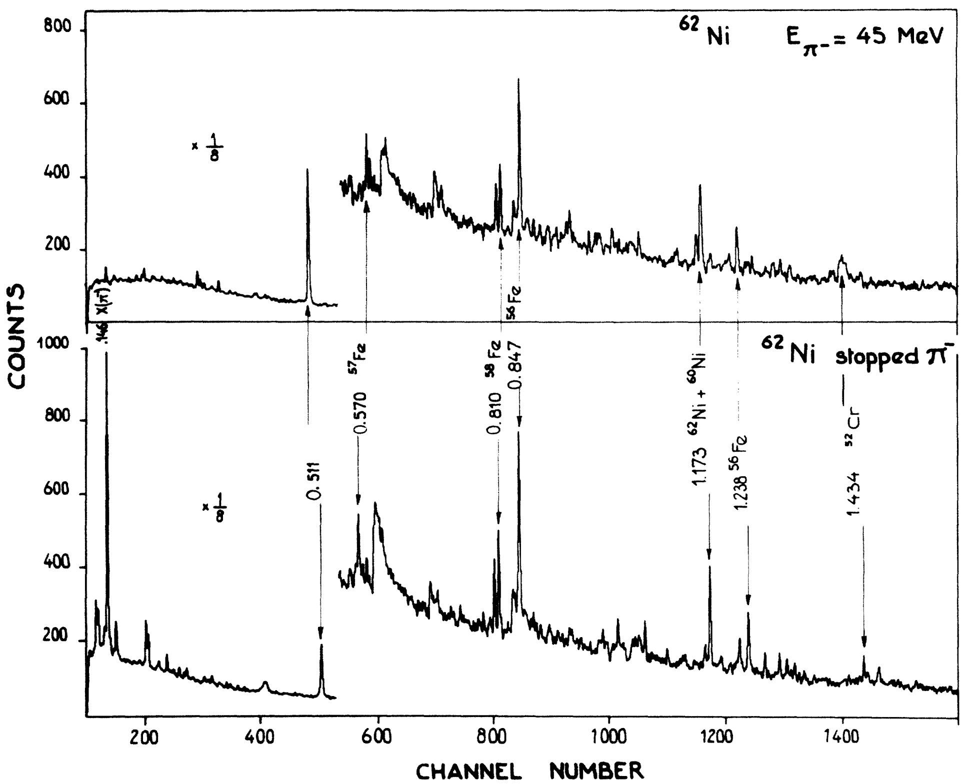


FIG. 2. $\gamma$-ray spectra from 45 MeV pions (upper curve) and stopped pions (lower curve) interacting with $^{62}$Ni.

on a target of $^{62}$Ni. Some of the stronger characteristic lines and their assignments made on the basis of $\gamma$-ray energy are indicated. In the spectra shown, the strongest lines corresponds to $^{56}$Fe, (i.e., removal of $\alpha + 2n$), the nucleus most favored on the basis of its stability. From these spectra the production cross sections for the corresponding residual nuclei are made.

Several remarks should be noted. First, cross sections were calculated on the assumption of isotropy for the $\gamma$-ray angular distributions. Second, any direct population of the ground state of the residual nucleus by particle emission will not be observed so the yields or cross sections are really lower limits. Third, there will be a variable experimental sensitivity to even-even, even-odd, and odd-odd nuclei because of the different character of the $\gamma$-ray cascades. In particular, the most favorable cases are the even-even daughter nuclei for which almost all the yield should cascade through the $2^+ \to 0^+$ transition from the first excited state to the ground state.

In spite of these limitations the results indicate that we have accounted for a major portion of the reaction yields and that the data reflect the major outlines of the multinucleon removal spectra for pions. For stopped $\pi^-$ the total assigned yield of known $\gamma$-ray lines ranges from 0.57 to 0.65 of the total number of stopped pions. The yields for the various nuclei inferred from the spectra are given in Fig. 3 for each of the nickel isotopes. In each case, while there are detailed differences in individual yields between stopped and 45 MeV pions, the dominant features of the mass distribution are very nearly the same. This is also evident from an inspection of the actual spectra (see Fig. 2) and of course suggests that the 45 MeV spectrum is dominated by pion absorption. For each target the distribution of residual nuclei indicates that the nucleon emission process populates states near or along the line of stability. Thus, as the target neutron excess increases, neutron emission is increasingly favored. In addition, $\alpha$ removal is not a favored process in pion-induced reactions beyond that due to the usual $Q$ dependence. For the $^{62}$Ni target the peak in the mass distribution is considerably to the left of the $N - 6 = z$ line, which would correspond to multiple "$\alpha$-equivalent" nucleon emission. For $^{58,60}$Ni, as at higher energy,[9] multiple equivalent $\alpha$ removal accounts for about 20% of the observed yield.

The comparison of stopped and 45 MeV spectra is put on a more quantitative basis in Table I, which presents average parameters characterizing the

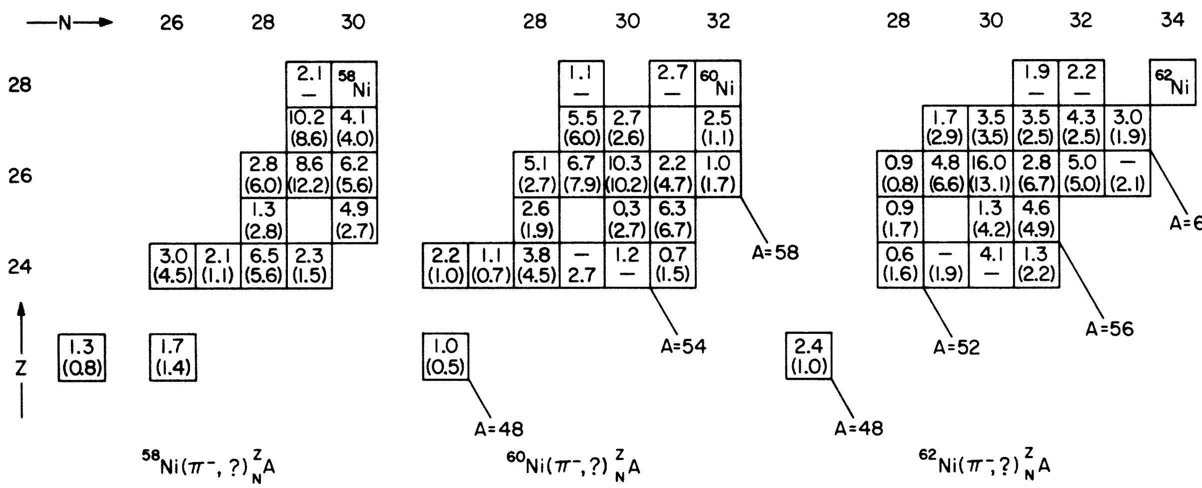

FIG. 3. Yields of various nuclei resulting from interactions of 45 MeV and stopped pions $^{62}$Ni. The latter are given in parentheses in percent. Total absolute yields and total identified cross sections are tabulated in Table II for each target.

spectra for all targets. Within the accuracy of the measurement there are no significant differences between stopped and 45 MeV values. However, their variation with neutron excess corresponds to the trends one would expect from nuclear evaporation. Decreasing neutron binding energy with increasing neutron excess is expected to favor neutron emission as one moves across the line of stability with the result that $\langle \Delta A \rangle$ and $\langle \Delta N \rangle / \langle \Delta Z \rangle$ should increase. It is of interest to compare these values with those obtained at higher energies where the removal cross sections show very little dependence on pion energy. As indicated in Table I, below ~50 MeV $\langle \Delta A \rangle$ decreases by about 1 unit relative to values at higher energy. This behavior indicates that the characteristics of the removal spectra are not independent of total pion energy.

The basic similarity of the spectra suggest a procedure for estimating the total reaction cross section from our 45 MeV measurements. Namely, one can assume that the stopped and in-flight spectra are the same and use the observed total identified yield for stopped $\pi^-$ as a measure of the overall detection efficiency of the system. Table II shows the result of such a procedure. The total yield for stopped $\pi^-$ and total cross section for identified lines in the 45 MeV spectra are shown for each target. The total reaction cross sections inferred from these data range between 0.8 and 1.0 b for the three targets studied.

## IV. DISCUSSION

To assess some of the implications of our data, we have compared our results with relative yields which were calculated using the simple "quasi-deuteron" absorption model of Monahan and Serduke.[10] In their approach one makes extremely simple assumptions about the preequilibrium phase of the reaction and calculates relative yields using

TABLE I. Average parameters for pion-multinucleon removal spectra of nickel isotopes. Inelastic scattering from the target is excluded in the determination of $\langle \Delta A \rangle$, the mean number of nucleons removed; $\langle \Delta Z \rangle$ and $\langle \Delta N \rangle$ are the corresponding averages for protons and neutrons.

| Target | $^{58}$Ni | | | $^{60}$Ni | | | $^{62}$Ni | | |
|---|---|---|---|---|---|---|---|---|---|
| $E_\pi$ (MeV) | 0 | 45 | 220[a] | 0 | 45 | 220[a] | 0 | 45 | 220[b] |
| $\langle \Delta A \rangle$ | 3.9 | 3.8 | 5.4 | 4.8 | 4.9 | 5.3 | 5.8 | 5.7 | 6.5 |
| $\langle \Delta Z \rangle$ | 2.4 | 2.5 | 3.0 | 2.3 | 2.3 | 2.3 | 2.2 | 2.1 | 2.1 |
| $\langle \Delta N \rangle$ | 1.5 | 1.3 | 2.4 | 2.5 | 2.6 | 3.0 | 3.6 | 3.6 | 4.4 |
| $\frac{\langle \Delta N \rangle}{\langle \Delta Z \rangle}$ | 0.6 | 0.5 | 0.8 | 1.1 | 1.1 | 1.3 | 1.6 | 1.7 | 2.1 |

[a]Data taken from Ref. 1.
[b]S. Tabor *et al.* (unpublished).

TABLE II. Total yields measured for $\pi^-$ interactions with $^{58,60,62}Ni$ targets. The total reaction cross section is calculated by assuming the removal spectra for stopped and 45 MeV pions are the same.

| Target | Yield $E_{\pi^-}=0$ (%) | Iden. $\sigma_{total}$ (mb) | Reaction $\sigma_{total}$ $E_{\pi^-}=45$ MeV (mb) |
|---|---|---|---|
| $^{58}Ni$ | 57 | 502 | 880 |
| $^{60}Ni$ | 59 | 598 | 1014 |
| $^{62}Ni$ | 65 | 525 | 800 |

well-established procedures to treat the evaporation phase. The incident pion is assumed to be absorbed with the ejection of two nucleons. Subsequent nucleon emission is assumed to result from evaporation. Two further simplifying assumptions are made. First, only one nucleus is assumed to be formed in the preequilibrium phase. Second, in the evaporation calculations a uniform distribution of excitation energies in the daughter nucleus is used with a maximum energy $E_{max}$, chosen to give the best fit to the data. Clearly such a model is a gross oversimplification but our purpose is to use its predictions as a guide in understanding the gross features and trends displayed by the multinucleon removal spectra. For further details of the calculation the reader is referred to Ref. 8.

In order to avoid ambiguities and uncertainties associated with our measurement sensitivity and lack of knowledge of $\gamma$-ray branching ratios, the comparison of experiment and calculation was restricted to yields of even-even final nuclei. Table III shows typical results of an evaporation calculation[11] appropriate to the preequilibrium pion reaction in which the incident $\pi^-$ is absorbed on a $pp$ pair and on a $np$ pair with the subsequent emission

TABLE III. Comparison of experimental and calculated relative yields of nuclei produced by $\pi^-$ interaction with $^{58}Ni$. The calculated yields are based on a quasideuteron absorption model (see text) with the maximum excitation energy $E_{max}=100$ MeV, and are assumed to result from evaporation of the compound nuclei $^{56}Fe$ or $^{56}Co$.

| Final nuclei | Relative yields (arbitrary units) Exp. | Cal. $^{56}Fe^*$ | Cal. $^{56}Co^*$ |
|---|---|---|---|
| $^{54}Fe$ | 2 | 3.5 | 5 |
| $^{52}Cr$ | 4.6 | 3.9 | 2.9 |
| $^{50}Cr$ | 2.1 | 2 | 2.5 |
| $^{48}Ti$ | 1.2 | 2.2 | 1 |
| $^{46}Ti$ | 0.9 | 0.9 | 0.3 |

TABLE IV. Comparison of experimental and calculated values of the average number of nucleons removed in populating even-even daughter nuclei. Calculated values are shown for two values of the maximum excitation energy in the evaporation phase $E_{max}$.

| Target | $\langle \Delta A \rangle_{even-even}$ Exp.[a] | Cal. $E_{max}=100$ MeV | Cal. $E_{max}=80$ MeV |
|---|---|---|---|
| $^{58}Ni$ | 7.0 | 6.6 | 5.8 |
| $^{60}Ni$ | 6.1 | 6.7 | 5.9 |
| $^{62}Ni$ | 7.1 | 6.8 | 6.2 |

[a] $E_\pi=45$ MeV.

of the absorbing pair. In this case the target is $^{58}Ni$ and the excited nuclei from which subsequent evaporation takes place are $^{56}Fe(pp)$ and $^{56}Co(np)$, respectively. From a comparison of experimental and calculated yields for different values of $E_{max}$ we found that the best fit is obtained with the values given in Table III corresponding to $E_{max}=100$ MeV. Furthermore, as in the analysis of earlier data at higher energy,[8] the assumption of $pp$ emission appears to give a better fit to the data in spite of the apparent favoring of $n,p$ emission implied by free pion-nucleon cross sections.

In general our data are best fitted with $90 < E_{max} < 110$ MeV. The value of $E_{max}$ inferred from data at higher energy is ~150 MeV. An indication of the sensitivity of the calculated yields to the value of $E_{max}$ is given in Table IV, where the average observed number of nucleons removed in generating even-even daughters is compared with values calculated for $E_{max}=100$ and 80 MeV. The values we observe for $E_{max}$ are surprisingly high when one notes that the maximum excitation energy expected in the nucleus corresponding to the target plus two nucleon holes should be ~60 MeV. They suggest that pion reactions are unexpectedly efficient in transferring energy to the compound system.

The decrease in the parameters of Table I relative to values reported at higher energy can be attributed to the decrease in excitation energy which we find for the pion reactions at low energy. Among the even-even daughters for which our experimental sensitivity is highest, the mean number of nucleons removed typically was observed to decrease by 0.7 mass units, while the best calculated fit to the data with $E_{max}=100$ MeV gave a decrease of 0.6 mass units.

In earlier experiments at higher pion energies the mean number of nucleons removed, $\langle \Delta A \rangle$, was found to be typically about 1 unit greater than the corresponding values observed in proton-induced reactions at comparable energies. Assuming pion absorption, proton energies equal to the inci-

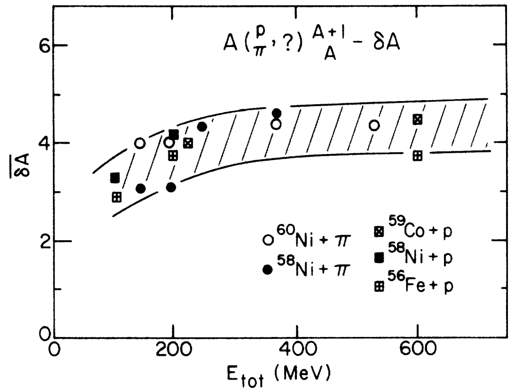


FIG. 4. Comparison of nucleon removal in proton- and pion-induced reactions. Data for pion-induced reactions above 200 MeV are taken from Refs. 1 and 8. The proton data are from Refs. 8, 12, and 13. $E_{tot}$ is defined as the total incident pion energy or incident proton kinetic energy, i.e., the excitation energy available in the compound system. $\overline{\delta A}$ is the average nucleon removal from the $A+1$ proton excited system or the $A$ pion excited system (see text).

dent pion total energy are taken as the point of comparison. This observation has led to a number of comparisons[12,13] of pion and proton-induced multinucleon spectra in a search for unique aspects of the pion-nucleus interaction. However, it is not all evident that such a study should be based on a direct examination of $\Delta A$. The relative success of the simple quasideuteron in explaining the gross features of the spectra suggests the contrary. In this picture the first stage of the pion-induced reaction is the generation of a highly excited nucleon pair by pion absorption. In the proton-induced reaction a reasonable supposition is that the proton-nucleus reaction begins with a simple incident nucleon bound-nucleon scattering which also generates an energetic dinucleon system. This suggests that any study of average nucleon removal should compare the $A+1$ proton excited system with the mass-$A$ pion excited system. We have done this in Fig. 4, using data available for nuclei near $A \approx 60$. It is immediately evident that, in this respect, proton-induced and pion-induced spallation reactions are quite similar. However, there is no reason to assume this implies anything concerning the character of the primary phase of the pion and proton-induced reactions. Rather, it is probable that the features of the multinucleon removal spectra are dominated by those properties of the evaporative phase of the reaction which are not to be strongly influenced by the initial phase of the reaction.

In conclusion, the similarity of stopped and in-flight-pion spectra which we have observed for the nickel isotopes indicate that pion-nucleus reactions in this mass region are dominated by pion absorption. While the data show detailed departures from trends in measurements of these isotopes at high pion energies, the broad outlines of the multinucleon are insensitive to pion energies. The same reaction mechanism appears to explain pion-nucleus reactions over the energy range 0–400 MeV, contrary to the conclusions of earlier experiments. However, while the gross features of the removal spectra are consistent with nuclear evaporation, a detailed model which explains the large excitation energies which are released in the evaporation phase remains to be established.

## V. ACKNOWLEDGMENTS

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