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C. A. Heusch, and R. V. Kline

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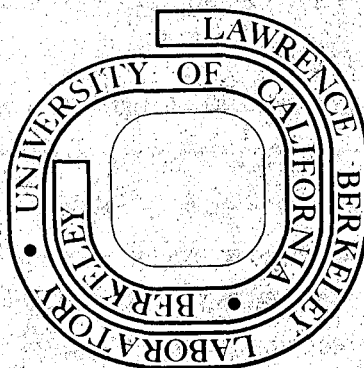
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A STUDY OF THE REACTION

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ABSTRACT

The reaction $p + d \rightarrow {}^3\text{He} + \pi^0$ was studied at incident proton energies of 377, 462, and 576 MeV. A comparison of our data with others suggests the existence of a sharp forward peak in θ_{He} at 377 and 462 MeV, which is unexplained by the theory and disappears at higher energies.

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Recent interest in the (p, π) reactions in nuclei stems from the work of the Uppsala group^[1] on low energy pion production from ^{12}C and ^9Be . It was generally felt that the detailed structure evident in these reactions together with the large momentum transfers involved would make (p, π) reactions a sensitive probe of the high momentum components of nuclear wave functions. The disappointing results of some of the early calculations, however, demonstrated a fundamental dilemma: it is difficult to understand the reaction mechanisms involved without detailed knowledge of the nuclear wave functions, and conversely, it is hard to obtain this information without first settling on the reaction mechanisms.

One way out of this dilemma is to study systems that are simple enough so that either the wave functions are known from other sources or the reaction mechanism can be readily inferred. The simplest non-trivial reactions of this sort are pion production from deuterium leading to either ^3He or ^3H in the final state. The reaction $p + d \rightarrow ^3\text{H} + \pi^+$ was investigated in the work of Dollhopf et al.^[2] as well as in several older experiments^[3-9]. We report here the results of π^0 production, which is part of a comprehensive study of radiative final states in ^3He formation from proton-deuteron interactions at incident proton energies of 377, 462, and 576 MeV.

The experiment was performed at the 4.6 meter cyclotron of the Lawrence Berkeley Laboratory. The 740 MeV external proton beam was degraded to the desired energy and refocused to obtain a secondary beam of 2×10^8 protons/sec at the target with a momentum spread (sigma) of 0.5%. The beam intensity was measured with ionization chambers, which

were calibrated by direct proton counting. The beam energy was determined by degrading the protons and measuring the range corresponding to the Bragg peak as detected in an ionization chamber. A 1.3 cm thick, gas ballasted, liquid deuterium target was used. The product of effective target thickness and beam intensity was monitored by measuring the proton-deuteron elastic scattering rate with two scintillation counter range telescopes in coincidence.

The momentum of the ^3He particle was measured by a spectrometer consisting of two magnetostrictive wire spark chambers for trajectory definition and a large plastic scintillator, which was used as a total absorption counter. The construction and calibration of this detector are described in reference 10. A thin energy-loss scintillator situated before before this counter aided in rejecting singly charged particles. One of the decay photons from the π^0 was detected in a photon spectrometer, consisting of a scintillation counter to veto charged particles, a slab of lead glass two radiation lengths thick to convert the photon, a scintillation counter to detect any resulting charged particles, an array of magnetostrictive wire spark chambers to define their trajectories, and finally a thick (8 radiation lengths) lead glass block to measure the energy of the electron shower.

An event was defined by requiring a trigger from the energy-loss counter, a stopped particle in the thick scintillator with a pulse height in a prescribed interval, and a conversion in the photon spectrometer. A conversion was defined as a signal in the second scintillator. The photon energy as measured in the lead glass was not used either in the trigger or in the subsequent analysis. The photon conversion

efficiency was calibrated as a function of energy in a separate experiment at the California Institute of Technology electron synchrotron.

A χ^2 minimization procedure was used to fit the events to the $p + d \rightarrow {}^3\text{He} + \pi^0$ hypothesis, and a Monte Carlo program was used to calculate the geometric acceptance. The only non-negligible background reaction is $pd \rightarrow {}^3\text{He} \gamma$, which is kinematically very similar but a factor of 20 lower in cross section. The data were corrected for this background as well as for accidental triggers and break-up of the ${}^3\text{He}$ -particle. These corrections were typically less than 5%. The empty target contribution to the cross section was negligible.

The results are shown in Figs. 1-2. The vertical error bars include statistical errors and an estimate of the systematic errors. The width of the angular bins (determined by multiple scattering of the ${}^3\text{He}$) is always less than $\pm 3^\circ$. The 377 MeV data are shown in Fig. 1a together with the results of several older experiments. The cross sections of Frank et al. (as well as those of Dollhopf et al. in Fig. 1b) were derived from the reaction $p + d \rightarrow {}^3\text{H} + \pi^+$ by multiplying by 1/2 as required by isospin. The three experiments in Fig. 1a taken together seem to suggest the existence of a sharp peak at forward θ_{He} angles. This peak also appears at 470 MeV in the data of Dollhopf et al. as shown in Fig. 1b. The existence of so sharp a peak in this angular region is so far unexplained. A possible mechanism based on one pion exchange has been considered by Barry^[11] and by Bhasin and Duck^[12], but they obtain a broad enhancement rather than the sharp peak which is observed. Fearing^[13] has studied the effect of D-state components

in the deuteron wave function, but again the effects are small and show no sharp structure. By 590 MeV the peak has totally disappeared as shown in Fig. 1c.

Although most of the calculations done so far on (p, π) reactions involve assumptions that limit their validity to threshold production, there have been some attempts to apply the impulse approximation model of Ruderman^[14] to $p + d \rightarrow t + \pi^+$ in the resonance region. The results of these earlier calculations are summarized in reference 2. In its simplest form the approach seems to give qualitatively correct results both for normalization and angular distributions. More recent calculations by Locher and Weber^[15] and Fearing^[16], which include corrections for spin, rescattering (distortion) and exchange diagrams, reproduce the experimental cross sections quantitatively except for the backward peak.

Since the data taken in this experiment span the energy of the $\Delta(1232)$ resonance it is of interest to display them as excitation functions. The energy at which the resonance peak occurs depends upon the diagrams that contribute to the reaction and upon distortion effects that tend to shift the peak toward lower energies. Estimates of the resonance position vary from 450 to 600 MeV. Unfortunately, uncertainties in the relative normalization of the different experiments have so far made the comparison inconclusive. Figure 2 shows excitation functions for several angles including data compiled from Refs. 2-9. (Some points on these curves were obtained by interpolation and were consequently assigned generous error bars). There is no sign of an enhancement; all the curves fall off smoothly with increasing energy.

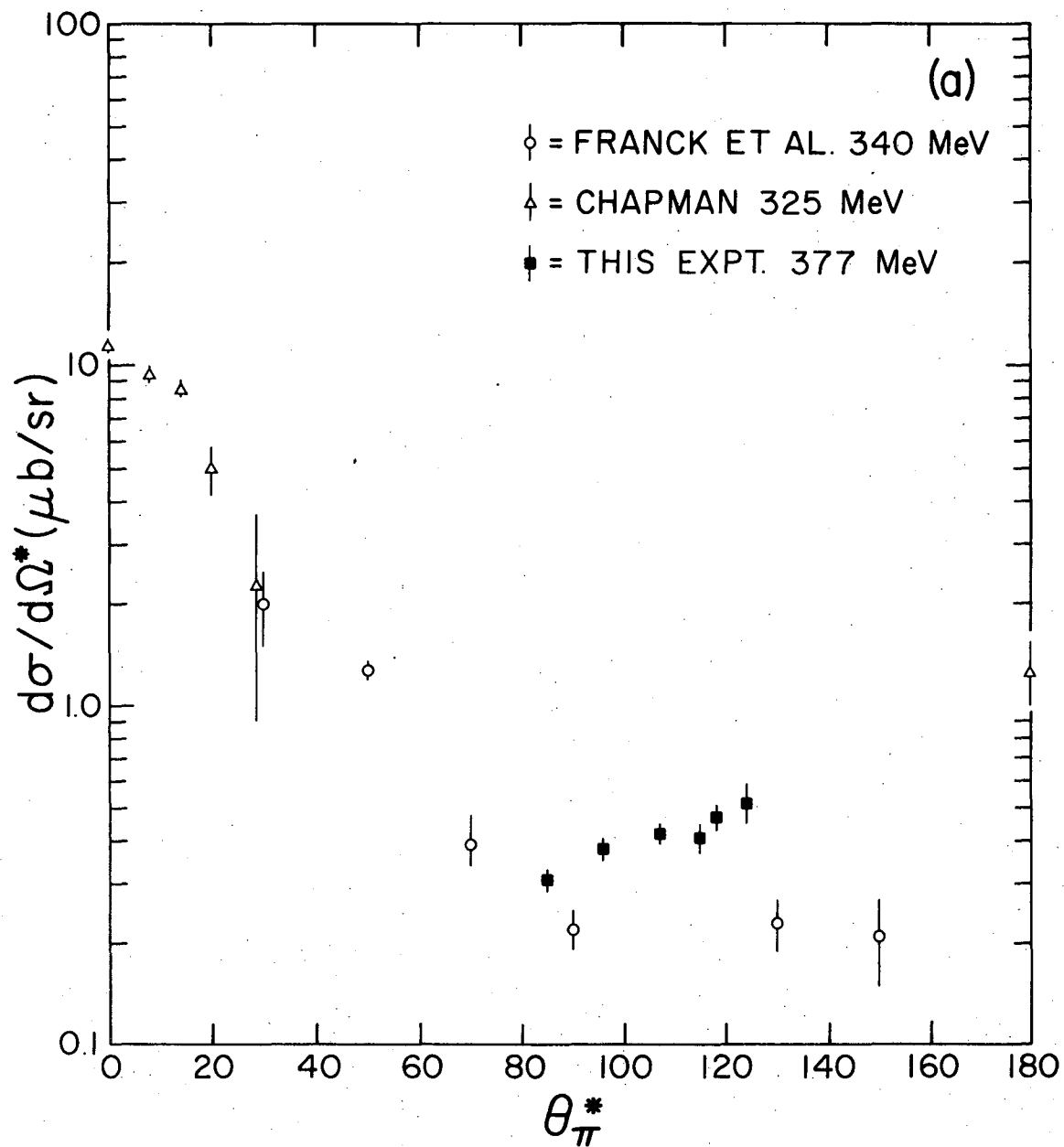
This behavior is surprising at first sight since the experimental data on the reaction $p + p \rightarrow d + \pi^+$, which was used as input for most of the calculations of $p + d \rightarrow {}^3\text{He} + \pi^0$, show a pronounced peak near 450 MeV. An explanation of this phenomenon has been provided by Fearing^[17] in a recent preprint: since the distortion effects in the exit (pion) channel are predominately absorptive, the $\Delta(1236)$ tends to reabsorb the pion and suppress the reaction in this energy range. Residual effects of this resonance would appear as a small enhancement at energies much below those measured in this experiment followed by a gradual fall off with energy above 360 MeV. If this is so it may be very difficult to extract any further information in this energy region either about the detailed reaction mechanism or the nuclear wave functions since the cross sections are dominated by relatively trivial absorption effects.

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FIGURE CAPTIONS

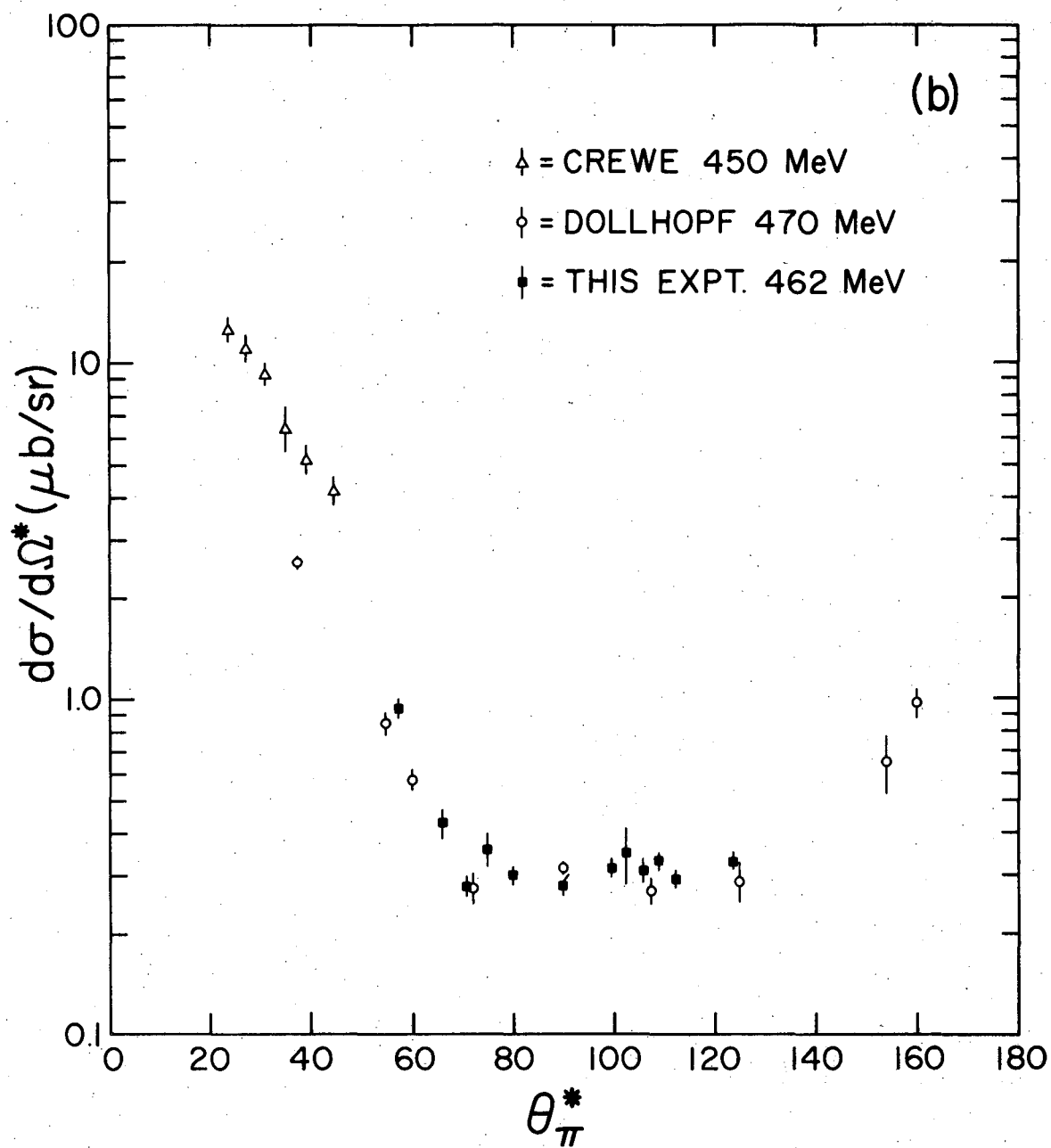
- Fig. 1. a) Center-of-mass differential cross section for $p + d \rightarrow {}^3\text{He} + \pi^0$ at $T_p = 377$ MeV. The other data points are Franck et al. at 340 MeV and Chapman et al. at 325 MeV. θ_π^* is the center-of-mass angle between pion and proton.
- b) Same as Fig. 1 for $T_p = 462$ MeV. The data of Dollhopf et al. is multiplied by $\frac{1}{2}$ as required by isospin.
- c) Same as Fig. 1 for $T_p = 576$ MeV. Also included is the data of Gabathuler et al. (600 MeV), Harting et al. (591 MeV), Dollhopf et al. (590 MeV), and Booth (562 MeV).
- Fig. 2. Excitation functions at several angles. The 750 MeV points are from Banaigs et al. and Booth.



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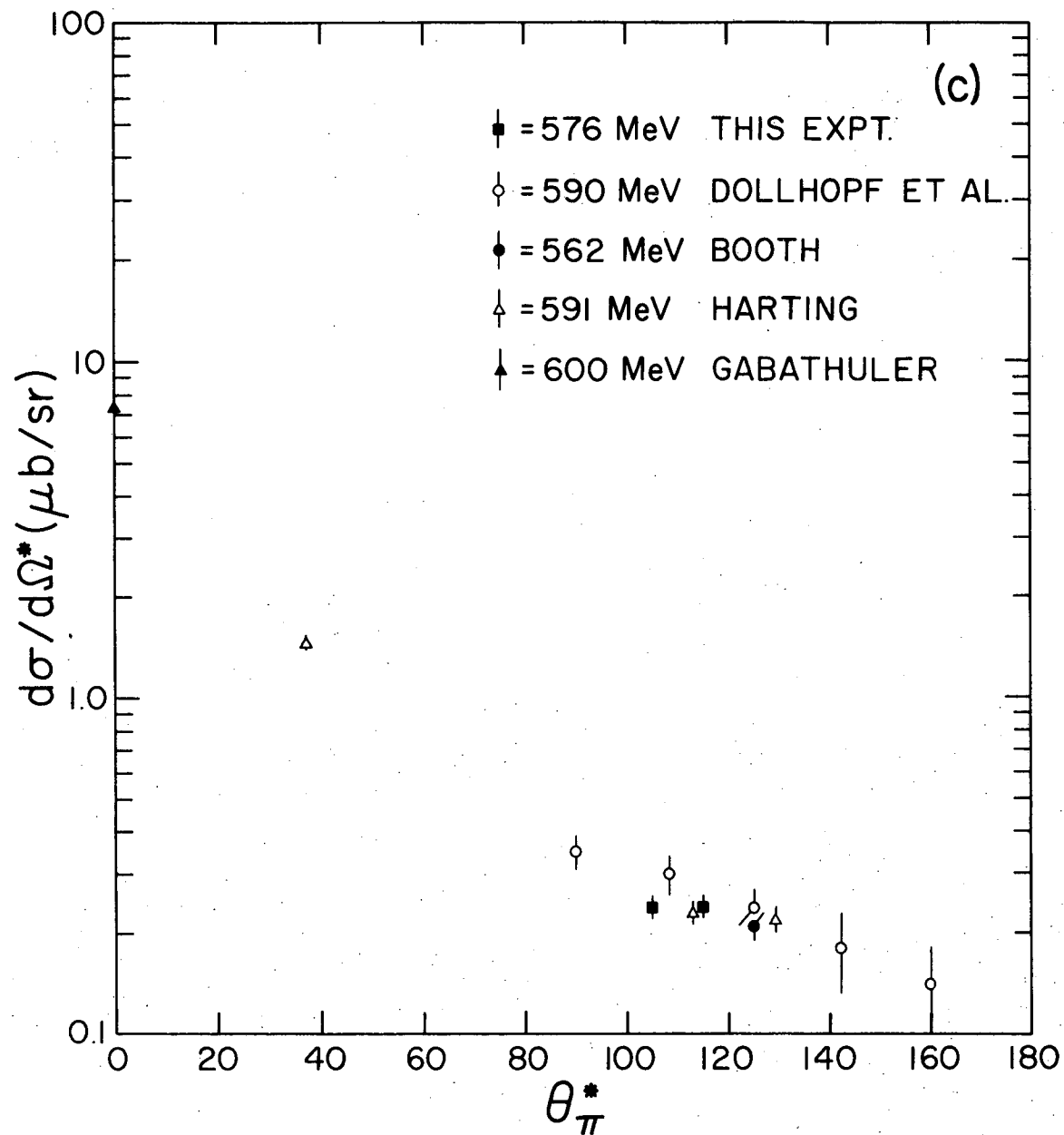
Fig. 1a

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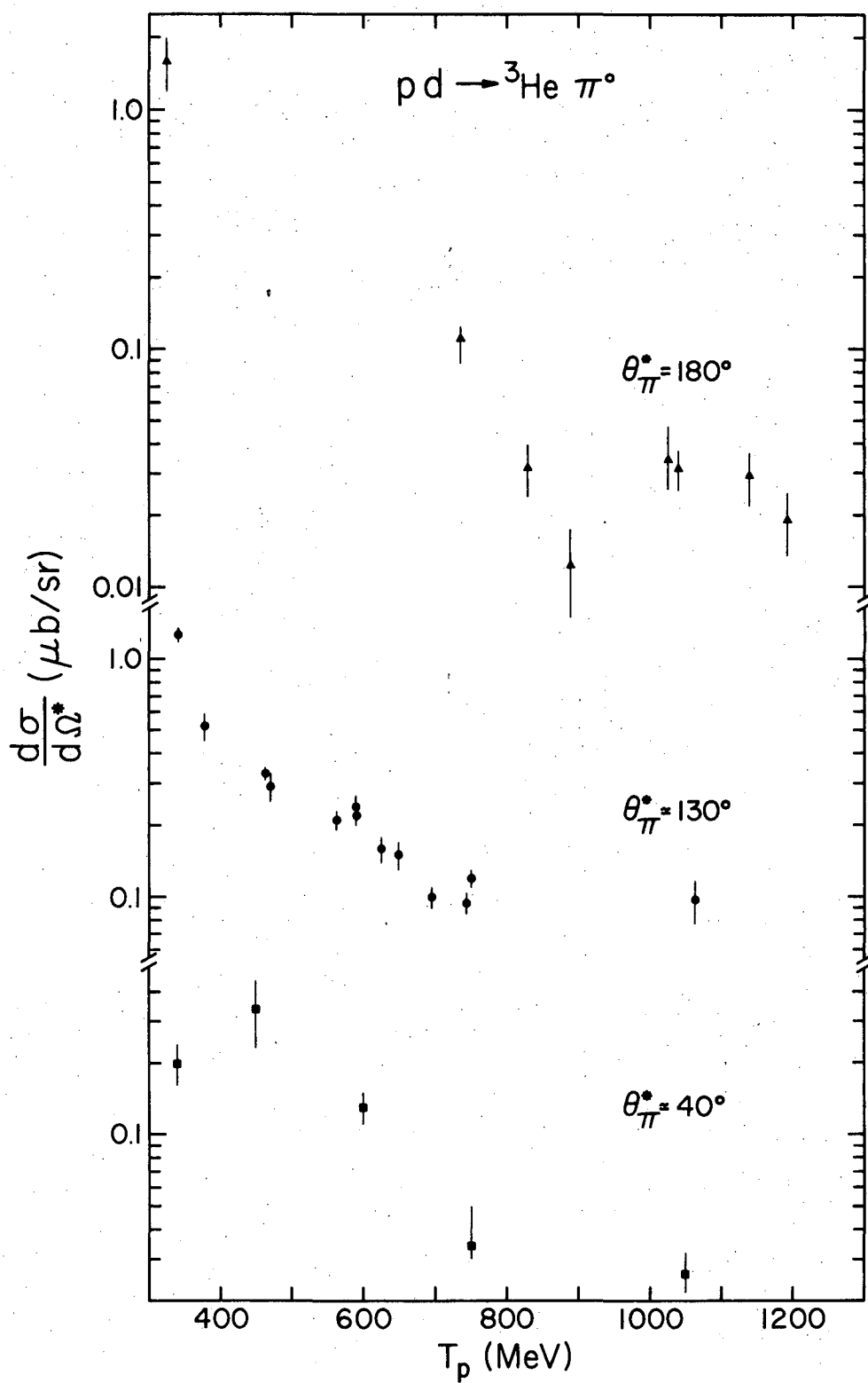
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Fig. 1b



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Fig. 1c



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Fig. 2

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