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A STUDY OF THE REACTION $p+d \rightarrow {}^3He+\pi^0$ IN THE RESONANCE REGION †

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Abstract: The reaction $p+d \rightarrow {}^3He+\pi^0$ 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.

E | NUCLEAR REACTIONS ${}^2H(p, \pi^0)$, E = 377, 462 and 576 MeV; measured $\sigma(\theta)$.

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

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can be readily inferred. The simplest non-trivial reaction of this sort is pion production from deuterium leading to either ^3He or ^3H in the final state. The reaction $p+d \rightarrow {}^3H+\pi^+$ 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, in the reaction $p+d \rightarrow {}^3He+\pi^0$, as part of a comprehensive study of radiative final states in ^3He formation from proton-deuteron interactions at incident proton energies of of 377, 462 and 576 MeV [ref. [10])].

The experiment was performed at the 4.6 m cyclotron of the Lawrence Berkeley Laboratory. A complete description of the experimental apparatus is given in ref. [10]); here we restrict ourselves to a brief description. 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 (σ) 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 ref. [11]). A thin energy-loss scintillator situated 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 two radiation lengths thick slab of lead glass which served as an "active converter" for the photon, a scintillation counter to detect the conversion electrons, an array of magnetrostrictive wire spark chambers to define their trajectories, and 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 $p+d \rightarrow {}^3He+\pi^0$ hypothesis, and a Monte Carlo program was used to calculate the geometric acceptance. The only non-negligible background reaction is $p+d \rightarrow {}^3He+\gamma$, 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

TABLE 1

Differential cross sections measured in this experiment

Incident proton kinetic energy	Pion $\langle\theta^*\rangle_{\pi^0}$ (bin width ≈ 10°)	Cross section (10^{-32} cm^2/sr)
377 MeV	124.5	51.9±6.5
	115.0	41.4±4.3
	117.8	46.8±3.6
	107.0	41.8±2.8
	96.4	37.6±2.6
	85.4	30.6±2.2
462 MeV	123.5	33.2±2.3
	112.4	28.9±2.2
	101.3	30.9±2.6
	109.1	33.3±2.0
	99.6	31.4±1.9
	90.0	27.8±1.7
	80.5	29.8±1.8
	70.9	27.9±2.0
	74.6	35.7±3.9
	66.9	43.4±4.0
	57.4	94.4±6.5
	102.5	34.6±7.0
576 MeV	114.8	24.0±2.5
	105.3	24.1±2.5

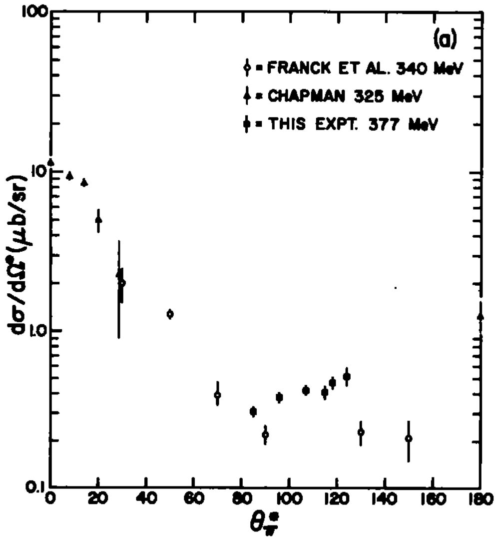

Fig. 1a. Center-of-mass differential cross section for $p+d \rightarrow {}^3He+\pi^0$ at T_p = 377 MeV. The other data points are Franck *et al.* at 340 MeV and Chapman *et al.*, at 325 MeV. θ^*_π is the c.m. angle between pion and proton.

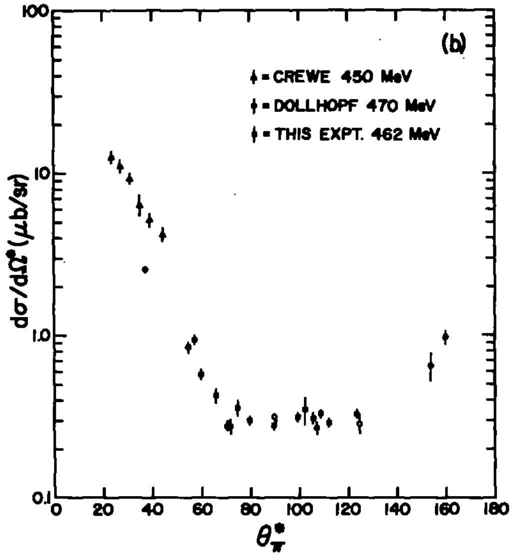

Fig. 1b. Same as fig. 1a for T_p = 462 MeV. The data of Dollhopf *et al.* is multiplied by $\frac{1}{2}$ as required by isospin.

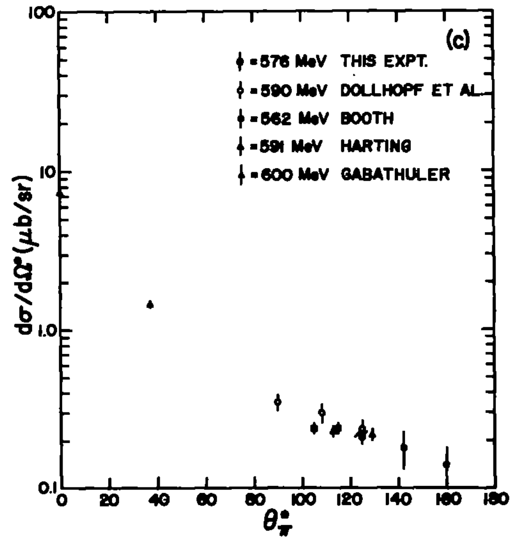

Fig. 1c. Same as fig. 1a for T_p = 576 MeV. Also included is the data of Gabathuler *et al.* (600 MeV), Harting *et al.* (591 MeV), Dollhopf *et al.* (590 MeV), and Booth (562 MeV).

^{3}He particle. These corrections were typically less than 5 %. The empty target contribution to the cross section was measured to be negligible.

The results of this experiment are given in table 1, and displayed in figs. 1 and 2. In addition to the quoted statistical error, there is an additional, overall systematic

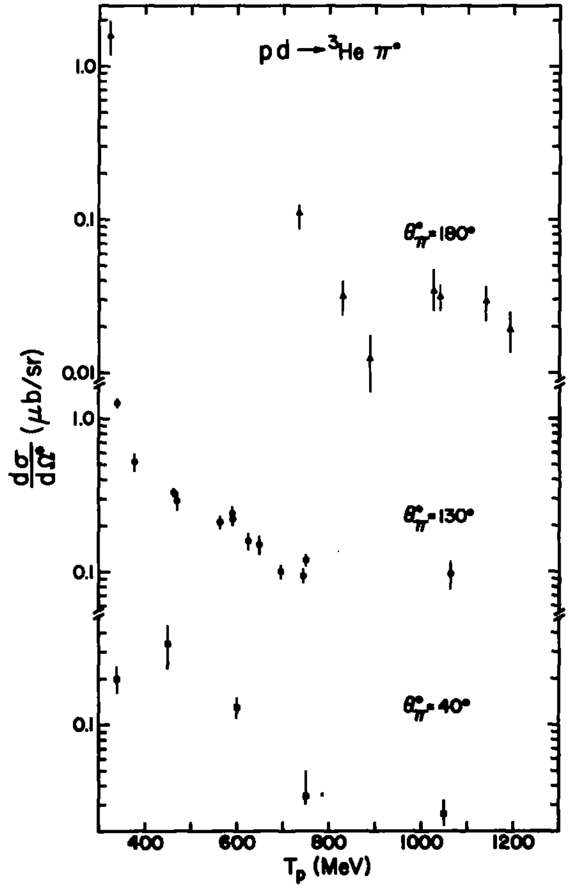

Fig. 2. Excitation functions at several angles. The 750 MeV points are from Banaigs *et al.* and Booth.

error of (+7, −2) % due to uncertainties in target thickness and absolute beam normalization. Widths of angular bins are typically 10°. Subgroups as indicated within the 377 and 462 MeV data refer to different kinematic settings, with the last 462 MeV subgroup representing data in which both photons from the π^0 were detected in coincidence. There is good internal consistency between the data from different kinematic settings, and between the one- and two-photon data.

The 377 MeV data are shown in fig. 1a, together with the results of several older experiments. The angular dependence of the cross section measured here at 377 and 462 MeV shows, between θ = 80° and 120°, a fairly flat behavior. This is in contrast to smaller angle data from several older experiments shown for comparison in fig. 1. The cross sections of Frank *et al.* (as well as those of Dollhopf *et al.* in fig. 1b) were derived from the reaction $p+d \rightarrow {}^3H+\pi^+$ by multiplying by $\frac{1}{2}$ as required by isospin. The three experiments in fig. 1a taken together suggest not only the expected backward peak, but also a peak at backward pion angles. This backward peak also appears at 470 MeV in the data of Dollhopf *et al.*, as shown in fig. 1b. The existence of a possibly sharp peak in this angular region is so far unexplained. A possible mechanism based on one-pion exchange has been considered by Barry [12]) and by Bhasin and Duck [13]), but they obtain a broad enhancement rather than the sharp peak which is observed. Fearing [14]) 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 [15]) to $p+d \rightarrow t+\pi^+$ in the nucleon resonance region. The results of these earlier calculations are summarized in ref. 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 [16]) and Fearing [17]), which include corrections for spin, rescattering (distortion) and exchange diagrams, reproduce the experimental cross sections quantitatively with the exception of 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 on 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. Fig. 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 $p+d \rightarrow {}^3He+\pi^0$, show a pronounced peak near 450 MeV. An explanation of this phenomenon has been provided by Fearing [18]) in a recent article: since the distortion effects in the exit (pion) channel are predominantly absorptive, the $\Delta(1236)$ tends to reabsorb the pion and surpress 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 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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