Observation of the Interaction $p+d \to He^3+\pi^0$ at a Proton Energy of 1.5 BeV*

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Using nuclear emulsions as a detector, the reaction $p+d\to He^3+\pi^0$ was studied at an incident proton energy $T_p=1.515$ BeV. The differential cross section in the c.m. system at 0^0 was found to be $(d\sigma/d\Omega)_{\text{c.m.}} = (4.1_{-2}^{+4})\times10^{-32}\,\text{cm}^2$.

THE reactions (1) $p+d\to He^3+\pi^\circ$ and (2) $p+d\to H^3+\pi^+$ have been of interest because they provide a test of charge independence in strong interactions.[1–3] Such experiments have been performed at incident proton energies around 600 MeV, and become more difficult at higher energy because of the decreasing cross section. We have measured the differential cross section for the process $p+d\to He^3+\pi^\circ$ at 0° and for a proton energy of 1.515 BeV.

The experiment was performed using the external beam III of the Brookhaven cosmotron. The experimental setup[4] is shown in Fig. 1. At the first focus of the external beam was placed a solid CD_2 target (deuteriated polyethylene) 2.5 cm thick with a cross-sectional area of 2×2.4 cm^2. Particles emerging at 0° were momentum analyzed in a 28° bend and then focused with a quadrupole doublet onto the detector; an additional stage of momentum analysis after the shielding wall helped to remove background particles. The characteristics of the spectrometer are given in Table I.

A nuclear emulsion stack consisting of 15 pellicles 8 in.×3 in. by 600 μ thick, Ilford K2, was exposed in the focal plane of the spectrometer with the tracks parallel to the 3-in. side and the 8-in. side horizontal. The K2 emulsion has very low sensitivity to minimum-ionizing particles, and it was possible to identify helium tracks by virtue of their ionization. For calibration purposes, control pellicles from the same batch were exposed to a 92±3 MeV proton beam. The observed "blob density"[5] versus β is shown in Fig. 2(a). If we extrapolate to $\beta=0.683$, which is the corresponding velocity of the He^3 particles, and multiply by four because of the double charge of the He^3, we would expect blob densities of $(44\pm6)/100\ \mu$ on their tracks. The average blob density on the tracks identified as due to He particles of the correct momentum was $38.1/100\ \mu$, a typical distribution for one plate being shown in Fig. 2(b).

TABLE I. Spectrometer characteristics.

Solid-angle acceptance	$\Delta\Omega=3.28\times10^{-4}$ sr
Dispersion (in focal plane)	$\Delta p/p=0.63\%$/cm
Magnification horizontal	$m_h=0.57$
Magnification vertical	$m_v=2.2$

Multiple-scattering measurements were performed on several tracks satisfying the scanning criteria. These yielded a mean scattering angle (in degrees) for 100 μ of

$$\bar{\alpha}_{100}=(3.82\pm0.27)\times10^{-2},$$

and using a scattering constant[6] $k=32$, we obtain

$$p\beta=1670\ \text{MeV}/c \quad \text{for} \quad Z=2 \text{ particles},$$

or

$$p\beta=835\ \text{MeV}/c \quad \text{for} \quad Z=1 \text{ particles}.$$

The spectrometer was set for particles with $p/Z=1320$ MeV/c, and the expected values of $p\beta$ and relative ionization are shown in Table II. Therefore, combining the multiple scattering and ionization data, we conclude that the selected tracks are mostly He^3 with a possible contamination of He^4 nuclei.

The developed emulsion plates were scanned "on-line" in a direction parallel to the long edge of the emulsion (normal to the tracks) and at a distance of 2 cm from the leading edge. Tracks with densities between

TABLE II.

	$Z=1$			$Z=2$	
	$p\beta$ (MeV/c)	blobs/100 μ		$p\beta$ (MeV/c)	blobs/100 μ
He^4	1510	55	π	1310	8
He^3	1750	44	p	1070	9
			d	756	14
			H^3	560	26

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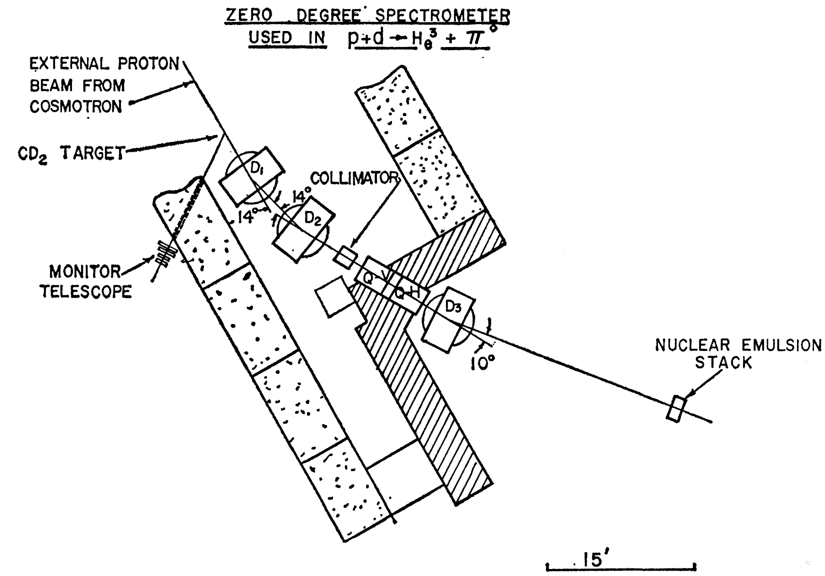

FIG. 1. The experimental setup in the external beam III of the cosmotron. D_1 and D_2 provide the main momentum analysis whereas D_3 is used to remove background. The nuclear emulsions are placed in the focal plane of the quadrupole doublet.

25–50 blobs/100 μ, with entrance angle $\pm 3°$ from the mean beam direction, and with dip angle less than 5° were picked up. These tracks were then followed to the entrance of the stack to be rejected if they originated in an interaction.

A total of four emulsion plates were scanned (two at the University of Rochester and the other two at the University of Ceylon). The combined results are shown in Fig. 3, which is a histogram of the number of tracks as a function of length along the emulsion. Half of the plates were scanned a second time in order to determine the scanning efficiency, which was found to be 85%.

The nominal momentum of the spectrometer was set as stated earlier at $p/Z=1320$ MeV/c and the emulsion stack located so that the central ray would be incident at grid coordinate 80, with higher momenta towards smaller grid numbers. The width of the He^3 peak is due mainly to two causes: (a) the width of the target image and (b) the energy loss in target. The energy spread of the primary beam[7] and the angular acceptance of the spectrometer which was $\pm 0.5°$ in the laboratory contribute negligibly. The target image at the focal plane is 1.36 cm, which corresponds to a width of ± 12 MeV/c for He^3 and the mean energy loss in the target is 19 MeV/c. We therefore expect a resolution curve of the order of ± 22 MeV half-width at half-maximum.

In order to fit the data shown in Fig. 3 we estimate our background as follows: Above 2600 MeV/c, the threshold for the reaction $p+d \rightarrow He^3+\pi^+ +\pi^-$, the background is flat and normalized to the events in the high-momentum region; below that threshold the background rises linearly towards the yield found at the low-momentum side. The resulting estimate is shown as the dashed curve (2) in Fig. 3. After subtracting this background, a two-parameter Gaussian fit to the data in the region from $p=2690$ to 2580 MeV/c yields a central value $p(He^3)=2626$ MeV/c and $\sigma=22$ MeV/c, both in good agreement with the expected values. From the kinematics, we expect that He^3 particles from the reaction $p+d \rightarrow He^3+\pi^0$, produced in the forward direction, will have a momentum $p=2640$ MeV/c. The χ^2 for this fit is 18.1 for three degrees of freedom,[8] which reflects our uncertainties in background subtraction and the exact shape of our resolution functions. The Gaussian fit when added to the background yields curve 1 of Fig. 3. Integrating the area under the Gaussian resolution curve obtained as discussed above, the yield is 263 tracks (excluding background). After correcting for scanning efficiency, this number becomes 310 tracks.

A few more comments on the data of Fig. 3 are appropriate: (1) Towards the high-momentum side of the emulsion no tracks are to be found, which constitutes further evidence that we observe He^3 particles from the above reaction. (2) On the low-momentum side we have indicated the threshold for double-pion production in reactions like $p+d \rightarrow He^3+\pi^+ +\pi^-$, which accounts for the tracks found at $p<2600$ MeV/c. (3) We expect a background mainly from He^4 nuclei which can appear from breakup interactions of the carbon in the target when hit by the beam protons; from the

[7] Fast ejection was used for the primary beam and thus $\Delta T/T < 0.001$. For our particular application $dp/p \sim d\bar{\gamma}/\bar{\gamma}$ and $d\bar{\gamma}/\bar{\gamma} \sim 0.3dT/T$. Similarly one obtains $dp/p \sim \tan\theta d\theta$; in our case $\theta \sim 10^{-2}$.

[8] We have also attempted a Gaussian fit with six degrees of freedom in the same momentum interval, again seeking the best value of σ and of the mean. We then obtain for the center of the peak $p_{He^3}=2634$ MeV/c and $\sigma=32$ MeV/c. The χ^2 for six degrees of freedom is $\chi^2=34.8$, which is of the same statistical significance as the value mentioned in the text for three degrees of freedom, and does not alter our conclusions.

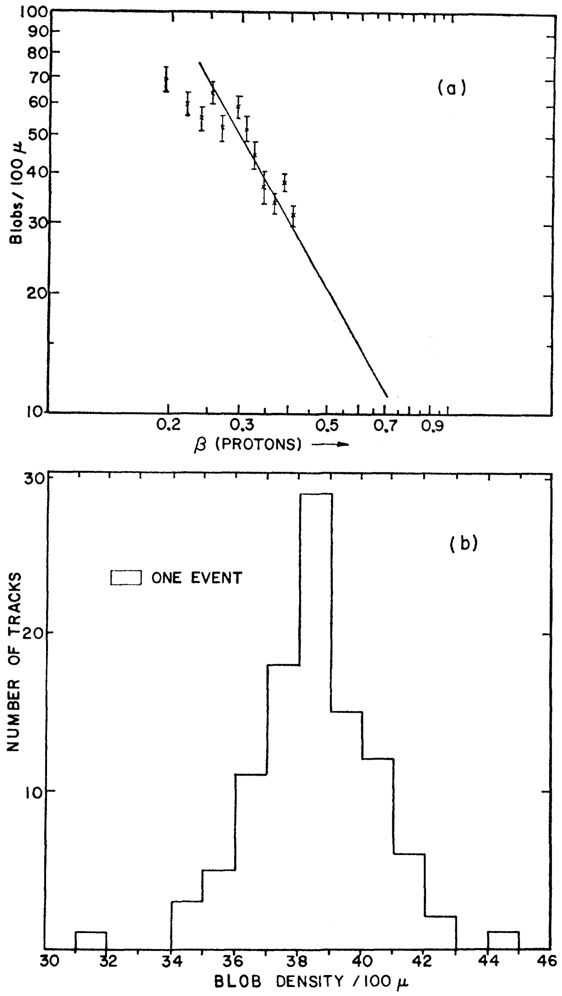

FIG. 2. (a) Plot of blob density/100 μ versus β as obtained from stopping proton tracks; these were obtained by exposing control pellicles in a proton beam of energy 92 ± 3 MeV. (b) Blob density/100 μ for all tracks (in one plate) accepted as He^3 on the basis of the scanning criteria. The average of the distribution is at 38.5/100 μ.

data of Fig. 3 it appears that such background does not exceed 10%.

To obtain the differential cross section we need to know the density of the incident beam. The total flux for this exposure was 1.5×10^{14} protons, as determined from the external beam monitor. The beam size, as determined from polaroid exposures, was found to be 4 cm^2 and was of the same order as the size of the target. We use for the beam density 4.25×10^{13} protons/cm^2 and a total number of 8.25×10^{23} deuterons in the CD_2 target. The four pellicles that were scanned presented a vertical aperture in the focal plane of 0.24 cm; since the vertical image of the target was $2\times2.2=4.4$ cm, we must correct our yield by a factor $\epsilon_v=(4.4/0.24)=18.3$. No such correction is needed in the horizontal plane since the entire peak has been included. Combining the above data and using $\Delta\Omega=3.28\times10^{-4}$, we obtain

$$(d\sigma/d\Omega)=0.51\times10^{-30}\ \text{cm}^2/\text{sr}.$$

The Jacobian for 0° and $T_p=1.515$ BeV is $J=12.47$, so that the differential cross section in the c.m. system becomes

$$(d\sigma/d\Omega)_{\text{c.m}}(\theta=0)=4.1\times10^{-32}\ \text{cm}^2.$$

The main error in the above cross section comes from the uncertainty in background and in the exact shape of the He^3 peak. The total incident flux is known to 20% and the same holds for $\Delta\Omega/m_v$ which characterize the spectrometer. Finally the exact shape of the beam spot and of its density contribute further to the uncertainty.

Scanning and detection losses are minor. From the above considerations we conclude that the errors on the cross section calculated above might be as large as +100% on the high side but not more than −50% on the low side. Hence

$$(d\sigma/d\Omega)=(4.1_{-2}^{+4})\times10^{-32}\ \text{cm}^2 \quad \text{at} \quad \theta=0^\circ.$$

The most striking conclusion of this work is the very rapid decrease of the cross section with increasing

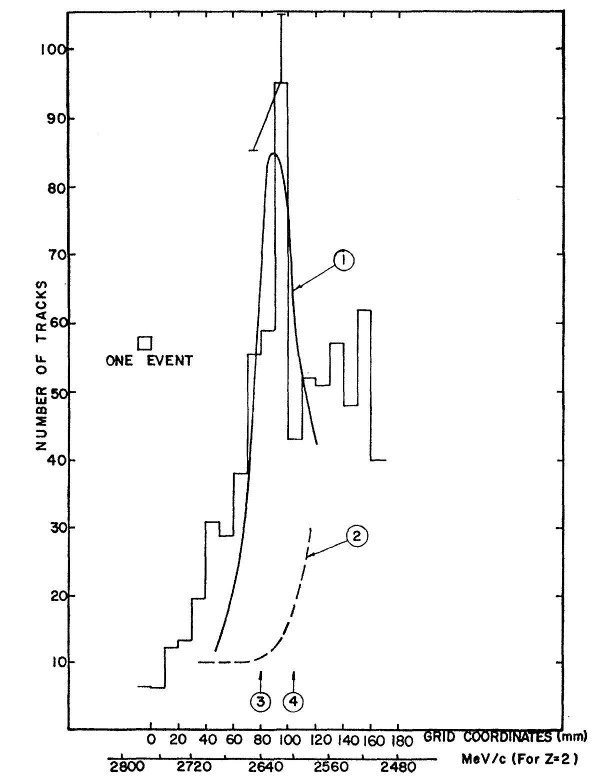

FIG. 3. Histogram of all He^3 tracks as a function of grid coordinate. The momentum for $Z=2$ particles is also indicated. Curve 1 is the fitted Gaussian with $p_0=2626$ MeV/c and $\sigma=22$ MeV/c. It is shown superimposed on the background given by curve 2. Arrows 3 and 4 indicate the expected positions for the He^3 peak from $p+d\rightarrow He^3+\pi^0$ and from the threshold of $p+d\rightarrow He^3+\pi^++\pi^-$, respectively.

proton energy. In Ref. 1 the cross section for $T_p=600$ MeV at $\theta_{c.m.}=52°$ is

$$(d\sigma/d\Omega)=(6.2\pm1)\times10^{-30}\ \text{cm}^2,$$

which is two orders of magnitude larger than our result at $T_p=1515$ MeV and $\theta=0°$. Since no other measurement of this reaction has been reported at $\theta=0°$, one may not exclude the possibility of a rapid angular variation of the cross section.[9]

We note that He^3 nuclei have been observed in the interaction of high-energy protons with complex nuclei. For example, for 3-BeV incident protons on beryllium at 30°, the laboratory cross section is of the order[10] of $d\sigma/d\Omega\sim2\times10^{-30}$ cm^2 per nucleon; similarly, He^3 nuclei have been observed at 30-BeV incident energy.[11] The production mechanism, however, is presumably different from reactions (1) or (2).

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Λ Polarization at 90° in $K^+\Lambda$ Photoproduction*

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The Λ polarization and the differential cross section for the reaction $\gamma+p\rightarrow K^++\Lambda$ have been measured, using the Caltech synchrotron, at 90° in the c.m. system and at laboratory photon energies of 1100, 1200, and 1300 MeV. Protons from the asymmetric decay of the Λ were detected by counters placed above and below the production plane. Kaons were identified by their behavior in a thick range telescope. Polarization results were $P_\Lambda=+0.34\pm0.09$ at 1100 MeV, $+0.30\pm0.07$ at 1200 MeV, and $+0.08\pm0.07$ at 1300 MeV, where P_Λ was measured in the $\hat{p}_\gamma\times\hat{p}_\Lambda$ direction. The differential cross section was constant with energy at 0.14 ± 0.01 μb/sr. Although the apparent bump in the polarization at 90° at a total energy of ≈1700 MeV adds support to models which invoke a resonance here, no really new conclusions can be reached.

I. INTRODUCTION

Over the past several years, experimenters have measured the differential cross section for the reaction

$$\gamma+p\rightarrow K^++\Lambda$$

from near its threshold at 911 MeV to about 500 MeV above threshold.[1–8] In contrast to the violent behavior of the cross section in such reactions as pion photoproduction, the results have a simple appearance. The total cross section at first rises linearly with the kaon center-of-mass momentum, then flattens to remain essentially constant at 2.2 μb between laboratory photon energies of 1000 and 1400 MeV. In the corresponding pionic production reaction

$$\pi^-+p\rightarrow K^0+\Lambda,$$

there is a broad, prominent bump at a total energy of about 1700 MeV[9]; no trace of it appears here. The photoproduction angular distribution is isotropic near threshold, peaks increasingly forward with increasing energy to 1200 MeV,[1–4,6,7] and appears to have flattened somewhat at 1400 MeV.[8] All of the data are very well fitted by quadratics in cosθ.

The polarization of the Λ hyperons has also been measured in several experiments.[5,10] Most measurements have been made near 90° in the c.m. system. The results indicate that the polarization rises to about +0.4 in

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