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DEUTERON PRODUCTION IN p-p COLLISIONS IN THE RANGE 1.5 TO 2.5 BeV†

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In a recent counter experiment[1] carried out at the Cosmotron, a general search for $I=1$ pion resonances was conducted by measuring deuteron energy spectra produced at an angle of 0° as a result of p-p interactions. A by-product of this search was the absolute differential cross section for the channel

$$p+p\rightarrow d+\pi^+ \tag{1}$$

for a range of incident kinetic energy from 1.5 to 2.5 BeV. We report here a sharp rise in the cross section along with a quantitative interpretation of the effect in terms of a one-pion-exchange (O.P.E.) model and the $I=\frac{3}{2}$ resonance in π^+p scattering at 1.35 BeV, the N_{37}^* isobar.[2]

A plan view of the apparatus is given in Fig. 1; it is basically a double-focusing magnetic spectrometer with a momentum resolution of 2.3% and solid angle of 4.7×10^{-3} sr, which analyzes particles produced at 0°± 0.5° with respect to the incident beam. The deuteron content of the analyzed beam is about 1%; hence a precise measurement of the number of deuterons requires a separation factor of 10^{-4}. This was accomplished by first rejecting ~99% of the protons and pions with a threshold Cherenkov counter and then performing a time-of-flight measurement with a resolution of ±0.6 nsec over the 15-ft flight path between counters S_1 and S_2 of Fig. 1. The absolute proton flux through the liquid hydrogen target was obtained by means of the polyethylene foil technique.[3]

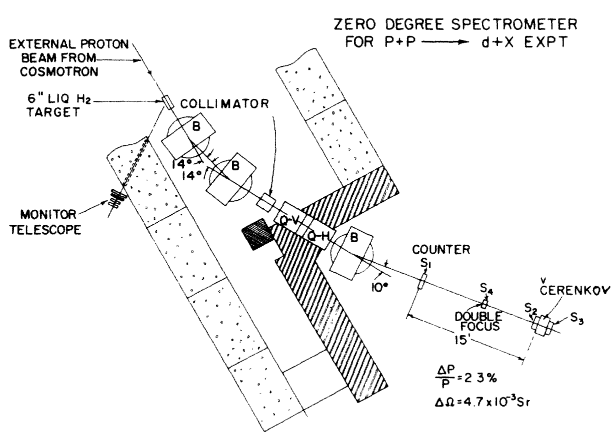

FIG. 1. Experimental arrangement. B signifies bending magnet, QV vertically focusing quadrupole, S_i scintillation counter.

The laboratory momentum spectrum (background subtracted) obtained at an incident kinetic energy of 2.5 BeV is shown in Fig. 2. This range of laboratory momentum corresponds to deuterons produced at 180° in the c.m. system, which must, of course, be equivalent to 0° in the c.m. system due to the symmetry of the initial state. The impressive peak at 1.1 BeV/c arises from $d\pi^+$ production and the area under this peak gives the cross section. Table I gives the cross sections at the four incident energies measured, viz. 1.55, 1.93, 2.11, and 2.50 BeV; the errors shown represent the total uncertainty in the absolute cross section, the error in the ratio of any two points being only ±15%. The c.m. values are plotted as a function of incident laboratory energy in Fig. 3; one notes that the cross section increases by nearly a factor of three between 1.93 BeV 2.5 BeV. Since it is generally expected that deu-

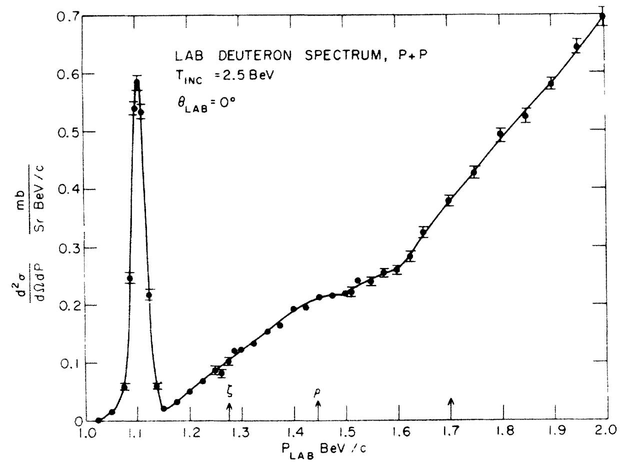

FIG. 2. Laboratory differential cross sections for deuterons produced at 0° for an incident kinetic energy of 2.50 BeV.

teron formation decreases at high energy, this behavior strongly suggests that a peak occurs in the 0° excitation curve. The total cross section for $d\pi^+$ at 2.05 BeV is[4] 53 ± 8 μb and at 2.9 BeV is[5] 110 ± 60 μb; hence the evidence for a corresponding rise in the total production is less certain.

From the point of view that the controlling interaction is due to the exchange of a single pion followed by a relatively weak final-state nucleon-nucleon interaction leading to deuteron formation, one can represent the interaction in terms of the triangle diagrams of Fig. 4. Using the O.P.E. formula of Chew and Low[6] in crudest approximation for Fig. 4(a), one arrives at an expression of the form

$$\left.\frac{d\sigma}{d\Omega}\right|_{d\pi}(0^\circ, T_p) = A(T_p)\left[\frac{t_1\Gamma^2(t_1)}{(t_1+\mu^2)^2}\left.\frac{d\sigma}{d\Omega}\right|_{\pi p}(180^\circ, T_\pi) + \frac{t_2\Gamma^2(t_2)}{(t_2+\mu^2)^2}\left.\frac{d\sigma}{d\Omega}\right|_{\pi p}(0^\circ, T\pi)\right], \quad (2)$$

Table I. Differential cross sections for $p+p\to d+\pi^+$ at 0° in the laboratory, 180° in the c.m. T_p is the incident proton kinetic energy in the lab.

T_p (BeV)	$(d\sigma/d\Omega)_{\text{lab}}$ (μb/sr)	$(d\sigma/d\Omega)_{\text{c.m.}}$ (μb/sr)
1.55	16.8 ±3.4	5.1 ±1.0
1.93	10.4 ±2.1	4.05 ±0.8
2.11	13.9 ±1.7	6.0 ±0.7
2.50	22.6 ±3.4	11.8 ±1.8

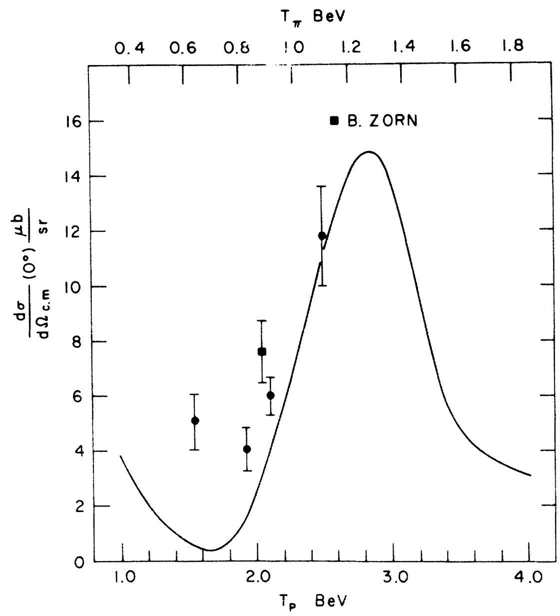

FIG. 3. C.m. differential cross section at $\theta_{\text{c.m.}}=0°$ for $p+p\to d+\pi^+$ as a function of incident kinetic energy in the laboratory. The scale at the top gives the equivalent incident energy in πp scattering. The point at 2.05 BeV is from Sechi Zorn (reference 4).

where T_p = incident proton laboratory kinetic energy; T_π = equivalent incident pion laboratory kinetic energy for the π-p scattering at the lower vertex of Fig. 4; $t_1^{1/2}, t_2^{1/2}$ = four momenta transferred by the pion. Formation of the deuteron implies that T_p and T_π are uniquely related by the equation

$$T_\pi = \tfrac{1}{2}T_p - 145\text{ MeV}. \quad (3)$$

In Eq. (2), $\Gamma(t)$ is the correction to the O.P.E. model due to off-mass-shell effects and the pionic form factor as introduced by Ferrari and Selleri.[7] For our energy range t_1 varies from 12-$15\mu^2$, whereas t_2 varies from 60-$105\mu^2$ with increasing energy, μ being the π^+ mass. The quantity $A(T_p)$ contains common kinematic factors multiplied by

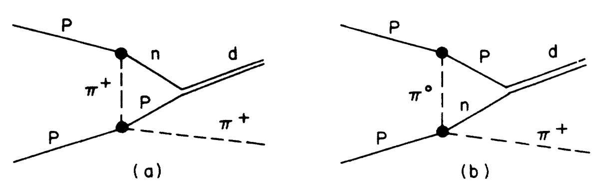

FIG. 4. Feynman diagrams for the reaction $p+p\to d+\pi^+$.

a range of c.m. energy for the πp scattering vertex; this range is determined by the internal motion of the deuteron.

The curve drawn in Fig. 3 is the prediction of Eq. (2), taking into account only diagram 4(a), i.e., π^+p scattering, assuming that a nucleon in the deuteron has a momentum ± 100 MeV/c in the direction of the deuteron's motion.[8] The shape of the curve is largely that of $d\sigma/d\Omega_{\pi p}(180°)$[9]; the peak in the 180° cross section occurs at $T_\pi = 1.25$ BeV (hence $T_p = 2.8$ BeV), but the factor $A(T_p)$ shifts it to slightly higher energy, $T_p = 2.85$ BeV. The 0° term contributes only 7% at the peak due to the fact that $t_2 \gg t_1$ and that $\Gamma(t)$ decreases as t increases. Diagram 4(b) presumably also makes a contribution to the cross section; however, the important πp cross sections at 180° have yet to be measured ($\pi^0 p \to \pi^+ n$ is equivalent to $\pi^- p \to \pi^0 n$ by charge symmetry). There are available 0° charge-exchange cross sections from dispersion relations[10]; and from these one can draw the likely conclusions that (i) diagram 4(b) contributes relatively little in the region $T_p > 2.2$ BeV, (ii) it will certainly help to fill in the valley between $T_p = 1.2$-2.2 BeV by bringing in the $I = \frac{1}{2}$ πp state. This diagram may, in fact, give rise to two additional variations in the $d\pi^+$ cross section at $T_p = 1.5$ BeV and 2.1 BeV due to the $I = \frac{1}{2}$ resonances at $T_\pi = 600$ and 900 MeV. In summary, the proposed model for $d\pi^+$ production appears able to explain the sharp increase in the 0° excitation curve; furthermore, it clearly predicts the occurrence of a peak at $T_p \sim 2.8$ BeV.[11] It seems likely that a corresponding peak will occur in total cross section for $d\pi^+$ production due to the implied proportionality to π^+p elastic scattering.

It is undoubtedly true that the O.P.E. model with final-state nucleon-nucleon interaction does not provide a unique explanation for the predicted peak; for example, one can argue that any mechanism that excites the N_{33}^* isobar would give a contribution at approximately the same position. However, the O.P.E. model does have the advantage of being amenable to making a quantitative prediction; in this connection it should be pointed out that experimental information in a closely related channel (viz., $pp \to pn\pi^+$) is used in determining a parameter in $\Gamma(t)$.[7,12] Mandelstam[13] was able to make a rather good three-parameter theory for explaining the maximum at 650 MeV in the $d\pi^+$ total cross section by taking into account the final-state 3,3 pion-nucleon and nucleon-nucleon interactions, but without postulating an explicit mechanism for exciting the 3,3 resonance. It may be that a precise determination of the peak position and width, along with the complete $d\pi^+$ angular distribution in this energy range, would serve to choose between available models.

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