Total and Differential Cross Sections of $p + p \to \pi^+ + d$ Reactions Down to 275 keV above Threshold

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The $p + p \to \pi^+ + d$ reaction is studied at excess energies between 0.275 and 3.86 MeV. Differential and total cross section were measured employing a magnetic spectrometer with nearly 4π acceptance in the center of mass system. The measured anisotropies between 0.008 and 0.29 indicate that the p wave is not negligible even so close to threshold. The data are compared to other data offering no evidence for charge symmetry breaking or time reversal violation. The s-wave and p-wave contributions at threshold are deduced. [S0031-9007(96)00602-3]

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Threshold meson production reactions are characterized by large momentum transfer -370 MeV$/c$ for $p + p \to \pi^+ + d^-$ and dominant s wave in the exit channel with strong overlap at short distance. Both favor heavy meson exchange. Recently, this reaction close to threshold has again attracted theoretical interest. Horowitz [1] claims that the s-wave production should be increased by heavy meson exchange in addition to pion rescattering only. The need for such an additional cross section results from the use of a modern value of the π-NN coupling constant which reduces the fraction of the cross section due to the pion rescattering. His work is along similar paths as for $p + p \to p + p + \pi^0$ [2,3]. In contrast, Niskanen [4] claims that inclusion of the Δ isobar will produce a larger s-wave cross section. However, these findings are not based on data for the reaction of interest but on data from $n + p \to \pi^0 + d$ [5] and from time reversed $\pi^+ + d \to 2p$ [6]. Moreover, inconsistencies were recently found between these two reactions at small pion momenta [5]. As the Coulomb force does not affect the first reaction either in the entrance or in the exit channel, the data from the second reaction were corrected for some Coulomb effects. The validity of these correction procedures is questionable [5]. Usually the data were expressed in terms of the Gell-Mann and Watson model [7]

$$\sigma(p + p \longrightarrow \pi^+ + d) = \sum_{\ell_\pi} \alpha_\ell \eta^{2\ell+1}, \qquad (1)$$

which was derived from barrier penetration for the reversed reaction. In Eq. (1) $\eta = p_\pi/m_\pi$ and p_π denotes the pion momentum in the center of mass system and ℓ its angular momentum. The charged and neutral particle induced reactions yield $\alpha_0 = 0.24$ and 0.184 mb, respectively. A part of this discrepancy was cured by new data [8] for $\pi^+ + d \to 2p$ in the range $0.215 \le \eta \le 0.518$. However, if we fit the existing world data body (published after 1967) of charged particle reactions including the data of Ref. [8] with Eq. (1) for $\eta \le 0.8$, a value of $\alpha_0 = 0.22$ mb is obtained. In this analysis all data (including the ones of Rose [6]) were corrected for Coulomb effects by commonly applying Reitan's results [9]. A part of the discrepancy may result from the fact that the momenta ranges of the two data sets are different. The neutron induced reactions cover only the pion momentum range up to $\eta = 0.32$ which is dominated by s-wave production while the other data are mostly dominated by p-wave contributions. The aim of the present study is, therefore, to measure cross sections for $p + p \to \pi^+ + d$ close to threshold ($\eta \le 0.22$) over the full angular range. To the best of our knowledge no complete data for this reaction exist below $\eta = 0.85$. A few differential cross sections measured over a smaller angular range at somewhat higher energies than the present ones are reported in Refs. [10] and [11].

The experiment was performed at COSY in Jülich with proton beams between 789.75 and 800.5 MeV$/c$. This corresponds to excess energies of between 0.275 and

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3.36 MeV, respectively. The pion production threshold is at 788.85 MeV/c. Proton beams were focused onto the target point of a 3Q2DQ magnetic spectrometer. It has a ± 25 mrad acceptance in the horizontal direction and up to a ± 100 mrad acceptance in the vertical direction. The beam spot had dimensions of less than 2 and 1 mm (FWHM) and divergences of 1.8 and 3.8 mrad in the two directions, respectively. Its momentum spread was measured to be $\Delta p/p = 4 \times 10^{-4}$ and it had a duty factor of 10%. The target was a cell [12] containing liquid hydrogen, with 6 mm in diameter and a thickness of 4.4 ± 0.2 mm for the 801 MeV/c run and 2.2 ± 0.1 mm for the other runs. The windows made from Mylar were of 2 μm thickness each. In order to suppress beam-halo events an annular scintillator with a 3 mm diameter inner hole was used in front of the target cell as a veto counter.

The deuteron tracks were measured in the focal-plane area of the spectrometer by two stacks of multiwire drift chambers (MWDC) which allow measurements both in the horizontal and vertical direction. A track resolution of 0.2 mm was achieved. The spectrometer operated in the point-to-parallel mode in the vertical direction and in the dispersive image mode in the horizontal direction. The magnetic field was set to a central momentum which corresponds approximately to the mean momentum of the recoiling deuterons. The emerging deuterons have emission angles up to 40 mrad and momenta up to 775.4 MeV/c. Thus the beam protons have magnetic rigidities very close to those of the deuterons and an enormous background existed therefore in the focal plane area. This background was strongly suppressed as follows: Behind the MWDC's in the focal plane was a trigger detector consisting of four layers of scintillator paddles. By using pulse-height discrimination of the signals from the first layer the number of recorded protons was suppressed. An aluminum absorber with thickness sufficient to stop deuterons was mounted between the third and the fourth layer. The detectors in the last layer acted as a veto counter, while the first three layers operated in coincidence. In addition, pions from the reaction were detected in coincidence by another annular scintillator with a 5 mm diameter hole located behind the target. The pion detector and the scintillators of the third layer served as delayed stop and start detectors, respectively, for a time of flight (TOF) measurement over a flight path of approximately 18 m through the spectrometer. A permissible intensity of 5×10^6 protons per spill limited the total event rate. At this rate there was no measurable dead time in the fast trigger system nor in the data acquisition system.

From the measured tracks momentum vectors of the deuterons at the target were reconstructed. The procedure applied to the raw data yields the distribution shown in the upper part of Fig. 1. In order to suppress the background events further, we applied a gate on deuterons in the TOF spectrum. Further background remained, which was rejected by applying a gate with a width of four times the experimental resolution on the reconstructed pion mass. The resulting deuteron-momentum distribution of this procedure is shown in the lower part of Fig. 1. The distributions obtained in this way were projected onto the axis parallel to the beam ($p_{\|}$), which corresponds to integration over the azimuthal angle, and then transformed into the center of mass system. At low deuteron momenta for the higher beam momenta, data suffered from detector acceptance limits. They were excluded from the present data analysis. Differential cross sections were deduced by normalizing the count rate to target thickness and to the number of incident protons which was measured during each run by counting scattered protons with calibrated scintillator detectors. For the two higher beam momenta the geometrical acceptance of the spectrometer is truncated in the horizontal direction by the side yokes of the dipole magnets. This missing acceptance can be deduced from the data itself by the following prescription. All events of the present reaction are on the surface of a rotational ellipsoid. If $p_{\|}$ is transformed by the Lorentz boost γ, the ellipsoid transforms into a sphere. The surface of this

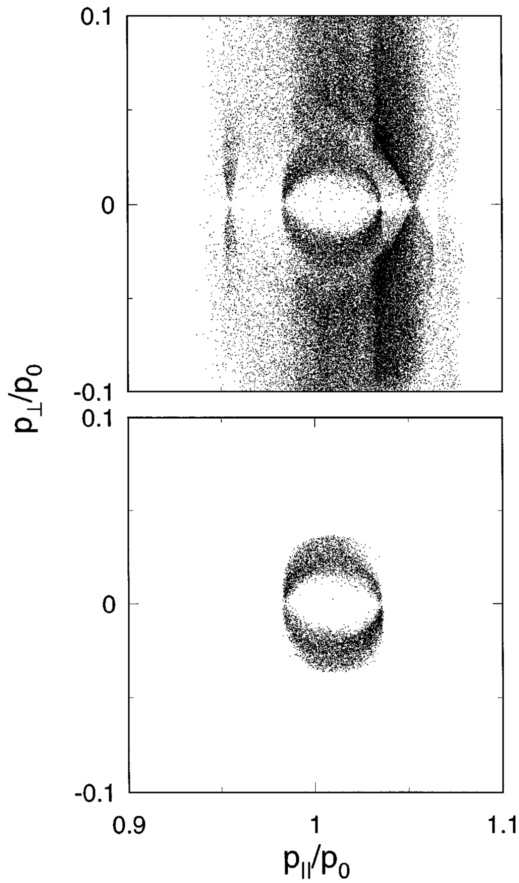

FIG. 1. Density distributions of emerging deuterons as functions of momentum parallel ($p_{\|}$) and perpendicular ($p_\perp$) to the beam axis. The magnetic spectrometer was set to a central momentum $p_0 = 730$ MeV/c. The upper part shows the raw data with the only constraints applied on-line by the hardware. The lower part shows the same data set after applying the constraints off-line as discussed in the text.

sphere can be plotted as a function of the azimuthal and polar angle (ϕ and $\cos\Theta$) yielding a rectangle with the same area as the sphere surface. The missing area is taken from such a graph. The measured angular distributions after acceptance corrections are shown in Fig. 2. The distributions become flatter for decreasing beam momenta. The data cover 75% (for 801 MeV/c) up to 100% of the c.m. angular range and are, therefore, ideally suited to extract s- and p-wave contributions to the cross sections. Absolute cross sections are fitted using the relation

$$4\pi(d\sigma/d\Omega) = A_0 + A_2 P_2[\cos(\Theta_{\mathrm{cm}})], \qquad (2)$$

where $P_2[\cos(\Theta_{\mathrm{cm}})]$ denotes the Legendre polynomial, A_0 the total cross section, and A_2 the p-wave contribution to the cross section. The fitted values of A_0 and A_2 are compiled in Table I and the corresponding curves are shown in Fig. 2.

The measured values of total cross sections are plotted in the upper part of Fig. 3 as a function of η together with all data published after 1967, to the best of our knowledge. Data for the same reaction are from Refs. [13] and [14]), for pion absorption transformed assuming time reversal invariance (Refs. [6,8,15–18]) and for $n + p \rightarrow \pi^0 + d$ reactions assuming isospin symmetry from Ref. [5]). All data with two charged particles in the exit channel were corrected for Coulomb effects employing the results of Reitan [9] which are almost identical for s and p wave. The

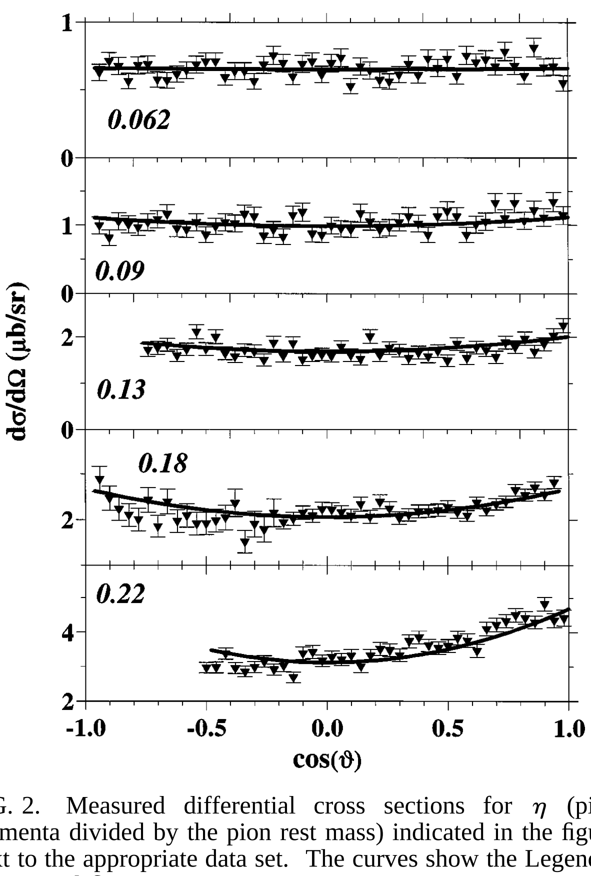

FIG. 2. Measured differential cross sections for η (pion momenta divided by the pion rest mass) indicated in the figure next to the appropriate data set. The curves show the Legendre polynomial fits.

TABLE I. Deduced parameters in Eq. (2) and the applied Coulomb correction factors. The errors include statistical errors and uncertainties in the measurements of the beam current (typically 5%), and target thickness and a 20% systematical error in A_2 from the acceptance corrections. For the two largest momenta a 10% systematical uncertainty due to the acceptance corrections has to be added additionally.

η	A_0 (μb)	A_2 (μb)	Coulomb correction
0.062	8.2 $\pm$ 0.4	0.066 $\pm$ 0.25	0.74
0.09	12.9 $\pm$ 0.9	1.1 $\pm$ 0.6	0.79
0.13	21.8 $\pm$ 1.6	2.7 $\pm$ 0.7	0.85
0.18	28.4 $\pm$ 2.1	5.2 $\pm$ 1.2	0.89
0.22	45.7 $\pm$ 3.3	13.3 $\pm$ 2.7	0.91

present data seem to be a smooth continuation of the earlier data for the charged-particle induced reactions towards threshold. They agree well with the neutron induced data.

Anisotropies (A_2/A_0) obtained from the Legendre polynomial fits are shown in the lower part of Fig. 3. Other data presented in the figure are for the same reaction [13],

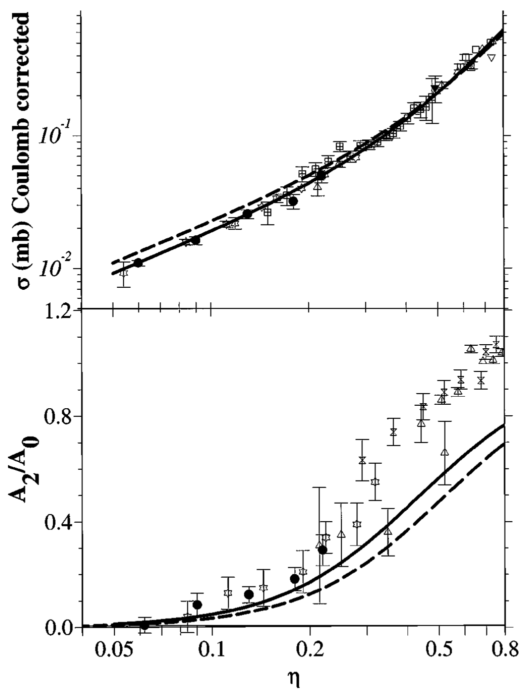

FIG. 3. Upper part: Total cross section deduced from the present measurement for the $p + p \rightarrow \pi^+ + d$ reaction (full dots) as a function of the relative pion momenta. Also shown are other data for the same reaction (full symbols [13,14]), pion absorption transformed assuming time reversal invariance (open symbols [6,8,15–18]), and $n + p \rightarrow \pi^0 + d$ reactions assuming isospin symmetry (open star [5]). The results obtained from the present fits [Eq. (1)] are shown as curves; dashed curve: charged particle reactions with $\eta \leq 0.8$ without the present data; full curve: charged particle reactions with $\eta \leq 0.5$ including the present data. Lower part: The anisotropy deduced from the present experiment is compared with earlier results. Symbols are as in the upper part, additional data [19] are shown as hourglasses. The curves are predictions from the barrier penetration model without interferences when applying the same parameters as in the upper part.

from the time reversed reaction [8,18] and the isospin related reaction [5,19]. It should be mentioned that the Coulomb correction applied cancels in this ratio. The presently deduced anisotropies agree with the data in the overlap range indicating again isospin and time reversal invariance to hold good.

As stated above old Coulomb corrected data yield values of $\alpha_0 = 0.22 \pm 0.01$ mb and $\alpha_1 = 0.79 \pm 0.01$ mb. The corresponding cross sections are shown as a dashed curve in Fig. 3. For this fit all data with $\eta \leq 0.8$ were taken into account. It was found that only two partial waves contribute in this range in agreement with earlier findings [13,20]. The curve definitely overpredicts the present data as well as the $n + p \rightarrow \pi^0 + d$ data. If the present data are added to the data sample, the new fit yields $\alpha_0 = 0.195 \pm 0.003$ mb and $\alpha_0 = 0.840 \pm 0.008$ mb. However, the χ^2 values obtained indicate poor fits. The first fit yields $\chi^2/n_{\text{free}} = 17.4$ and the one including the present data $\chi^2/n_{\text{free}} = 16.2$. Inclusion of d waves yields slightly worse fits. Also assuming an energy dependence of α_0 similar to Refs. [21,22] does not improve the fits significantly. The values contributing most to the large χ^2 values are those with large η values ($\eta > 0.5$). When these data are excluded from the analysis, a value of $\chi^2/n_{\text{free}} = 0.9$ is obtained for the data including the present ones with coefficients $\alpha_0 = 0.182 \pm 0.006$ mb and $\alpha_1 = 0.93 \pm 0.06$ mb. The s-wave strength is in nice agreement with the $\alpha_0 = 0.184 \pm 0.005$ mb obtained by Hutcheon *et al.* [5]. For the p wave their value of $\alpha_1 = 0.781 \pm 0.079$ mb agrees within two standard deviations with ours. The difference may arise from different momentum ranges as already discussed above.

The measured anisotropies are compared with those obtained from the above fits with and without the present data, assuming $A_2/A_0 = \alpha_1 \eta^2/(\alpha_0 + \alpha_1 \eta^2)$. The corresponding curves are shown in the lower part of Fig. 3. Such predicted anisotropies underestimate the experimental data. The discrepancy increases with increasing η. The difference between data and the curve is an indication of an interference between the s and d wave in the pp channel leading to a p wave in the πd system [7]. For the momentum range covered by the present data no serious difference is found giving evidence that the s-wave amplitude is rather small close to threshold. This is in agreement with previous findings [22–24].

In summary, we have measured total cross sections and full angular distributions for $p + p \rightarrow \pi^+ + d$ between $\eta = 0.062$ and 0.22. To the best of our knowledge these measurements are first in this energy range. They are the only ones for charged projectiles employing a magnetic spectrometer. Our high resolution spectrometer together with thin targets and small beam emittance allowed track reconstruction. The values of the total cross section are—when corrected for Coulomb effects—in agreement with results obtained from the time reversed reactions as well as from the isospin related reactions. The same is true for the anisotropies which do not need to be Coulomb corrected. Thus these findings are consistent with isospin symmetry and time-reversal invariance in the pionic sector. The deduced s-wave contribution to the cross section at threshold is $\alpha_0 = 0.182 \pm 0.006$ mb. This value is smaller then the so far accepted value of 0.27 ± 0.04 mb [21] but identical to the one recently found by Hutcheon *et al.* for the isospin related reaction [5]. The corresponding value for the p wave is $\alpha_1 = 0.93 \pm 0.06$ mb. The presently measured anisotropies are consistent with the barrier penetration model Eq. (1) indicating a very small s-wave amplitude in the pp channel. For larger η values there is a notable discrepancy between data and the model without considering interferences. These differences allow the determination of the ratio of the partial wave amplitudes (s and d wave in the pp channel) except for the phases. From presently measured anisotropies one can deduce that pion p-wave contribution to the cross section is still 30% at $\eta \approx 0.2$ and decreases smoothly to zero towards threshold.

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[1] C. J. Horowitz, Phys. Rev. C **48**, 2920 (1993).
[2] C. J. Horowitz, H. O. Meyer, and D. K. Griegel, Phys. Rev. C **49**, 1337 (1994).
[3] T. S. H. Lee and D. O. Riska, Phys. Rev. Lett. **70**, 2237 (1993).
[4] J. A. Niskanen, Phys. Rev. C **53**, 526 (1996).
[5] D. A. Hutcheon *et al.*, Phys. Rev. Lett. **64**, 176 (1990).
[6] C. M. Rose, Phys. Rev. **154**, 1305 (1967).
[7] M. Gell-Mann and K. M. Watson, Annu. Rev. Nucl. Sci. **4**, 219 (1954).
[8] B. G. Ritchie *et al.*, Phys. Rev. Lett. **66**, 568 (1991); Phys. Rev. C **47**, 21 (1993).
[9] A. Reitan, Nucl. Phys. **B11**, 170 (1969).
[10] F. S. Crawford and M. S. Stevenson, Phys. Rev. **97**, 1305 (1955).
[11] E. L. Mathie *et al.*, Nucl. Phys. **A397**, 469 (1983).
[12] V. Jaeckle *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **349**, 15 (1994).
[13] D. Aebischer *et al.*, Nucl. Phys **B108**, 214 (1976).
[14] F. Shimizu *et al.*, Nucl. Phys. **A386**, 571 (1982).
[15] D. Axen *et al.*, Nucl. Phys. **A256**, 387 (1976).
[16] S. I. Gogolev *et al.*, Phys. Lett. B **300**, 24 (1993).
[17] B. M. Preedom *et al.*, Phys. Lett. B **65**, 31 (1976).
[18] B. G. Ritchie *et al.*, Phys. Rev. C **24**, 552 (1981).
[19] E. Roessle *et al.*, in *Pion Production and Absorption in Nuclei*, edited by Robert D. Bent, AIP Conf. Proc. No. 79 (AIP, New York, 1982), p. 171.
[20] C. Richard-Serre *et al.*, Nucl. Phys. **B20**, 413 (1970).
[21] J. Spuller and D. F. Measday, Phys. Rev. D **12**, 3550 (1975).
[22] D. Bugg, J. Phys. G **10**, 46 (1984).
[23] B. Blankleider, Ph.D. thesis, Flinders University, 1980.
[24] B. Blankleider and I. R. Afnan, Phys. Rev. C **31**, 1380 (1985).