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Pion-pion *p*-wave dominance in the $pd\rightarrow{}^3\mathrm{He}\ \pi^+\pi^-$ reaction near threshold

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The cross section for the $pd\rightarrow{}^3\mathrm{He}\ \pi^+\pi^-$ reaction has been measured in a kinematically complete experiment at a c.m. excess energy of $Q=70$ MeV. The striking energy and angular distributions are reproduced in a simple model calculation where it is assumed that the reaction is dominated by *p*-wave $\pi^+\pi^-$ pairs. This is in complete contrast to the results of inclusive measurements at somewhat higher beam energies which show a strong *s*-wave ABC enhancement at low $\pi\pi$ masses. [S0556-2813(99)51111-4]

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Measurements of inclusive meson production in the $pd\rightarrow{}^3\mathrm{He}\ X^0$ reaction are surprising, in that they show a strong enhancement at a missing mass of around 310 MeV with a width of only 50 MeV [1]. No similar effect is seen for the ${}^3\mathrm{H}\ X^+$ final state and this suggests that this ABC anomaly [1] is to be associated with the isospin-zero *s*-wave $\pi\pi$ system. More detailed studies [2] confirmed the results but showed that the mass and width of the peak both varied with beam energy T_p. In view of this, and because the corresponding isoscalar $\pi\pi$ scattering length is small [3], it has generally been assumed that the anomaly must be kinematic in origin, possibly being associated with the production of two Δ isobars in the reaction [4].

These inclusive measurements were carried out for $T_p \geqslant 745$ MeV [1,2], corresponding to two-pion production with c.m. kinetic energies in the final state $Q\geqslant 190$ MeV. To investigate such pion production closer to threshold and in greater detail, with the objective of deducing also angular distributions, we have carried out an exclusive measurement of the $pd\rightarrow{}^3\mathrm{He}\ \pi^+\pi^-$ reaction at $Q=70$ MeV ($T_p=546$ MeV). At this energy a possible ABC enhancement would be located near the center of the available two pion invariant mass range.

The MOMO (Monitor-of-Mesonic-Observables) facility was installed at the external proton beam of the COSY COoler SYnchrotron of the Forschungszentrum Jülich [5]. The setup consists of a high granularity meson vertex detector near the target, with the high resolution 3Q2DQ magnetic spectrometer Big Karl [6] being placed in the forward direction. The horizontal and vertical acceptances of this spectrometer were then ± 25 mrad and ± 100 mrad about the beam direction. The charged particle tracks were measured in the focal plane by two stacks of multiwire drift chambers (MWDC) which yield position information in both the horizontal and the vertical directions. The ^{3}He's were unambiguously identified by their time-of-flight and energy loss, as measured with two scintillator hodoscopes behind the MWDC's, separated 2 m from each other. The spectrometer alone gave a missing mass resolution in the $pd\rightarrow{}^3\mathrm{He}\ X$ reaction of typically 1 MeV/c^2.

In order to obtain kinematically complete information on the events, the directions of the two outgoing pions were measured in the MOMO vertex detector [7]. This consists of 672 scintillating fibers, of circular profile with diameters of 2.5 mm, arranged in three planes inclined at 60° with respect to each other. The fibers are individually read out by 16-anode multichannel photomultipliers. The detector was placed perpendicular to the beam direction at 20 cm downstream of the target, subtending an opening angle of $\pm 45°$. A 4 cm diameter central hole allowed the ^{3}He's and the undeflected proton beam to pass. The kinematical situation is depicted in Fig. 1.

A liquid deuterium target, 4 mm thick and 6 mm in diameter with 1 μm mylar windows [8], was placed in the MOMO vacuum chamber. A phosphorus screen, which could be lowered directly behind the target, showed the

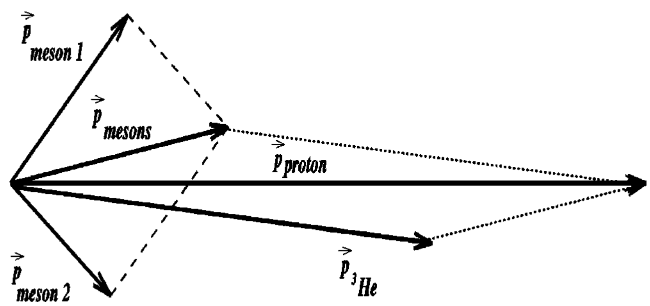

FIG. 1. Momentum diagram of the MOMO detection method. The directions of the pions are measured in the scintillating fibers detector, the ^{3}He momenta are determined in the spectrometer.

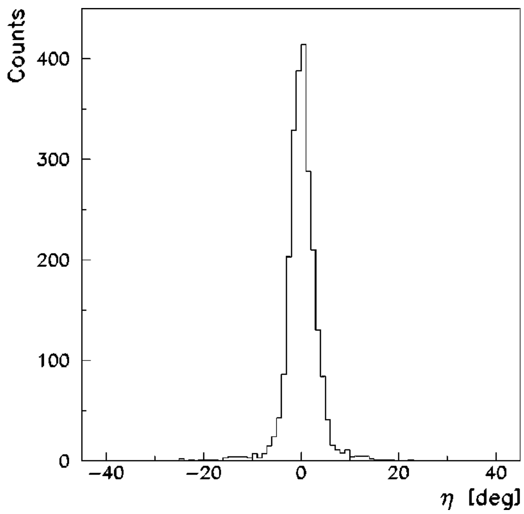

FIG. 2. Distribution in coplanarity angle η. Here η is the angle between the missing momentum, defined by Big Karl, and the plane defined by the directions of the two hits in the MOMO detector.

beam spot to be about 1 mm in diameter. A typical beam intensity of 10^9 particles per second was used in the experiment.

An event with two charged particles in the vertex detector and a ^{3}He in Big Karl was considered to be a candidate for the $pd \to {}^3\mathrm{He}\ \pi^+\pi^-$ reaction. Its identification and complete reconstruction involved a two-constraint kinematic fit. Good events must be coplanar with respect to the total meson momentum axis, which is defined by the beam and the ^{3}He momenta. The distribution in coplanarity of the coincident hits, shown in Fig. 2, demonstrates that any background due to four-body reactions or random coincidences is at most a few percent.

About 15 000 fully reconstructed $pd \to {}^3\mathrm{He}\ \pi^+\pi^-$ events were obtained at a beam energy of 546 MeV. Although the overall acceptance of the MOMO apparatus is only about 2% of 4π, it is well distributed over the complete invariant mass range, with the exception of the maximum excitation energy of the pion pair, where at least one of the pions escapes the vertex detector. This limits the maximum practical MOMO energies to $Q < 100$ MeV. The measurements were performed with three settings of the Big Karl magnet; the consistency of the results obtained in the overlapping regions shows that the acceptance of the spectrometer is well understood. The absolute normalization was determined with the help of scattering monitors placed behind the target and near the beam exit channel of the spectrometer, where the protons traversed a thin foil. Using a fast scintillator, which could be moved into the beam at reduced intensities, they were calibrated to about $\pm 7\%$, which is by far the largest contribution to the systematic error.

The differential cross sections, corrected for acceptance, are displayed in Fig. 3 in terms of four of the possible kinematic variables. The only variable accessible in single-arm experiments [1,2] is the pion-pion excitation energy $T_{\pi\pi} = m_{\pi\pi} - 2m_\pi$, where $m_{\pi\pi}$ is the two-pion invariant mass. The distribution in $T_{\pi\pi}$ is shown in Fig. 3(a). In marked contrast to the original ABC experiments [1], which showed an enhancement over phase space in the region of $T_{\pi\pi} \approx 30$ MeV, our data are pushed closer to the maximum values of excitation energy. On the other hand, the distribution in the π-^{3}He excitation energy, shown in Fig. 3(b), is fairly consistent with phase space. This is a further indication that the MOMO acceptance is sufficiently well understood and that

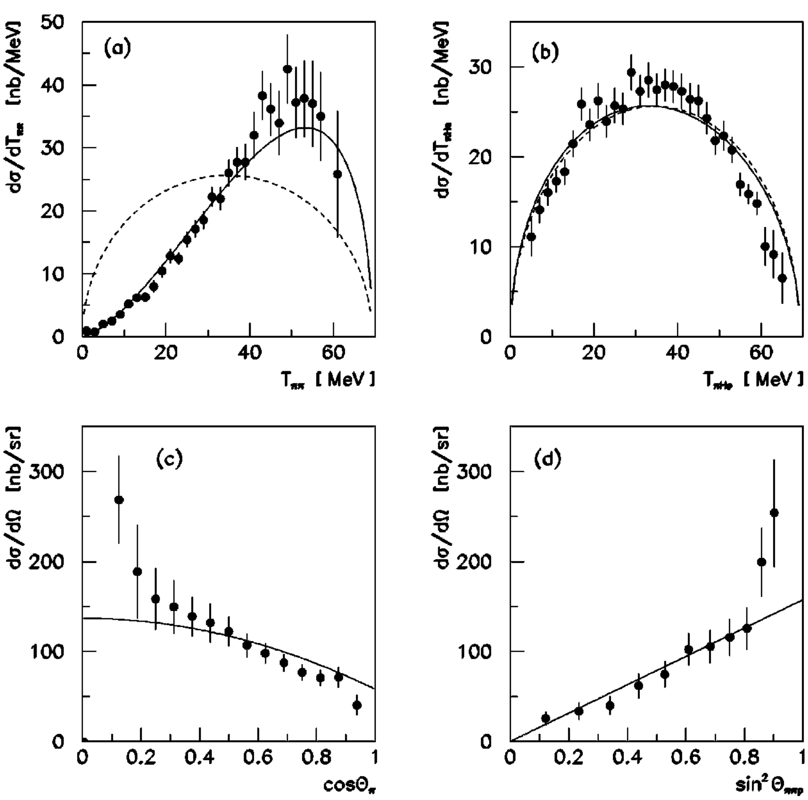

FIG. 3. Differential cross sections for the $pd \to {}^3\mathrm{He}\ \pi^+\pi^-$ reaction at $T_p = 546$ MeV as a function of (a) the pion-pion excitation energy $T_{\pi\pi}$, (b) the excitation energy in the π-^{3}He system, (c) the angle θ_π between one of the pions and the beam direction in the overall c.m. system, and (d) the angle $\theta_{\pi\pi p}$ between the two-pion relative momentum and the beam axis, also in the c.m. system. In the first two cases the dashed curves represent the predictions of phase space normalized to the data, whereas in all cases the solid curves are predictions assuming that the pion pair emerges in the relative p wave described by the matrix element of Eq. (1). The linear deviations in $T_{\pi\pi}$ from phase space in (a) and the linearity of the cross section with $\sin^2\theta_{\pi\pi p}$ in (d) are clear indications of the dominance of pion-pion p-wave effects.

the unexpected behavior in $T_{\pi\pi}$ is not an experimental artifact.

If all the final particles were in relative s waves, there would be no dependence upon θ_π, the angle between the proton and one of the pions in the overall c.m. system. The significant anisotropy shown in Fig. 3(c) is therefore direct confirmation of the importance of higher partial waves. It should be noted that events with pions in the backward hemisphere would not in general be detected in the MOMO apparatus. A particularly interesting angular variable for the subsequent discussion is that between the relative $\pi\pi$ momentum and the beam axis in the overall c.m. system; the corresponding distribution is shown in Fig. 3(d). As no distinction is made in MOMO between the π^+ and π^-, such a distribution must be symmetric about 90°. It is striking that over most of the range the cross section is in fact linear in $\sin^2\theta_{\pi\pi p}$.

It is seen that the $\pi\pi$ excitation energy distribution of Fig. 3(a) is broadly compatible with phase space (dashed curve) multiplied by $T_{\pi\pi}$ to give the solid curve. This, together with the linearity shown in Fig. 3(d), indicates that the two-pion system is mainly produced with $\pi\pi$ internal angular momentum $l=1$. To make this hypothesis more quantitative, consider the simplest matrix element for the production of a p-wave $\pi\pi$ pair which is in an s wave relative to the ^{3}He;

$$M=\sqrt{3}\,C\,\overline{u_\tau}\,\vec{\epsilon}\cdot(\hat{K}\times\vec{k})\,u_p. \qquad (1)$$

Here $\vec{\epsilon}$ is the deuteron polarization vector, u_p and u_τ are Pauli spinors describing, respectively, the initial proton and final ^{3}He, and C is a constant. The beam momentum is denoted by $\vec{K}$ and the relative momentum of the two pions as $\vec{k}=\frac{1}{2}(\vec{k}_1-\vec{k}_2)$.

This matrix element only allows for pion pairs with $m_l=\pm 1$ along the beam direction. Squaring and averaging M over spins, leads to

$$\overline{|M|^2}=|C|^2\,|\hat{K}\times\vec{k}|^2=k^2|C|^2\sin^2\theta_{\pi\pi p}, \qquad (2)$$

which reproduces the angular dependence observed in Fig. 3(d).

After averaging over $\theta_{\pi\pi p}$, the differential cross section becomes

$$d\sigma=\overline{|M|^2}\;dLips=\frac{2}{3}|C|^2k^2\;dLips, \qquad (3)$$

where *dLips* is the Lorentz-invariant phase space. Since nonrelativistically $T_{\pi\pi}=k^2/m_\pi$, Eq. (3) leads immediately to the $T_{\pi\pi}$ times phase space behavior that we have observed in the data. This is shown as the solid curve in Fig. 3(a), which was however calculated including the small relativistic effects.

Despite the $\pi\pi\,p$ wave hypothesis resulting in a large deviation from phase space for the distribution in pion-pion excitation energies, the modifications to the π-^{3}He relative energy distribution are extremely small and would actually vanish in the limit of infinite ^{3}He mass. This agrees well with the results shown in Fig. 2(b). Note that our data cannot distinguish between the distributions of the π^+ and π^-.

Experimentally, the pions are seen to be preferentially emitted at large angles with respect to the beam direction [Fig. 2(c)]. The $\pi\pi\,p$ wave hypothesis of Eq. (1) corresponds to a mixture of s and p waves for a single pion relative to the ^{3}He. This then leads to an effect of the right kind (solid curve), although not quite as large as that exhibited by the experimental data shown in Fig. 2(c).

Although s wave two-pion production has been observed in the $pd\to{}^3\text{He}\,\pi^+\pi^-$ reaction very close to threshold [9], and at $Q\approx 200$ MeV s wave pion-pion pairs again dominate the spectrum through the ABC enhancement [1], it is clear from the present data that there is an intermediate Q range where p waves are dominant. Similar behavior has, however, been observed in other reactions. The missing-mass distributions obtained for the $np\to dX$ reaction at $Q\approx 200$ MeV show a striking ABC effect [10], whereas at 70 MeV no ABC is seen [11]. In the latter case the events are pushed to the maximum missing mass, which is consistent with the p wave production seen in Fig. 2(a). Furthermore, recent data on the comparison of pion production in the $\pi^+d\to\pi^+\pi^+nn$ and $\pi^+d\to\pi^+\pi^-pp$ reactions at $Q\approx 100$ MeV show that, whereas the $\pi^+\pi^+$ spectrum broadly follows phase space modulated by detector acceptance, the $\pi^+\pi^-$ data are again heavily biased towards the maximum value of $T_{\pi\pi}$ [12,13].

Kinematically our results are indistinguishable from the production of the low-mass part of the ρ-meson in $pd\to{}^3\text{He}\;\rho^0$, with the ρ mesons being formed with polarizations ± 1 in the beam direction. Though there is some evidence from photoproduction for the ρ mass being depressed in the mass-3 system [15], it is hard in our case to see why such production should become less important at the higher energies where the original inclusive measurements were performed [1]. One possibility is that the effect is due to a rare decay of the Δ isobar. At $Q=70$ MeV the invariant mass with respect to a single nucleon is only 1290 MeV, which is well within the Δ width, whereas at $Q=200$ MeV it is outside. Moreover, the decay of the Δ into an s-wave pion pair is forbidden by isospin. However, due to the p-wave nature of the $\Delta\to N\rho$ coupling, in any dynamical model based on this idea one would have to transfer one unit of angular momentum from the final to the initial state through the action of a recoil term.

Conventional models of ABC production [4,14,16] suggest that this arises through two independent p-wave pion productions, mediated by two Δ resonances, combining to give s-wave pion-pion pairs. At low energies one of these productions might be through an s-wave πN system, leaving only one unit of angular momentum in the final state. However, given the importance of the Δ almost down to threshold, this is unlikely to play a major role here and, in any case, would tend to lead to p waves between the pion and the ^{3}He.

Experiments are currently being performed on exclusive

$pd\rightarrow{}^3\mathrm{He}\ K^+K^-$ production at similar Q values. It will be very interesting to see whether the ϕ's produced in this reaction have a similar alignment to that observed for the p-wave pion-pion pairs.

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