Observation of an ABC effect in proton-proton collisions

S. Dymov,1,2,3 M. Hartmann,3,4 A. Kacharava,3,4 A. Khoukaz,5 V. Komarov,1 P. Kulessa,6
A. Kulikov,1 V. Kurbatov,1 G. Macharashvili,7,1 S. Merzliakov,1,3,4 M. Mielke,5
S. Mikitychians,3,4,8 M. Nekipelov,3,4 M. Nioradze,7 H. Ohm,3,4 F. Rathmann,5,4 H. Ströher,3,4
D. Tsirkov,1,3,4 Yu. Uzikov,1 Yu. Valdau,3,4,8 C. Wilkin,9 S. Yaschenko,1,10 and B. Zalikhanov1

1Laboratory of Nuclear Problems, Joint Institute for Nuclear Research, 141980 Dubna, Russia
2Physikalisches Institut II, Universität Erlangen-Nürnberg, 91058 Erlangen, Germany
3Institut für Kernphysik, Forschungszentrum Jülich GmbH, 52425 Jülich, Germany
4Jülich Centre for Hadron Physics, 52425 Jülich, Germany
5Institut für Kernphysik, Universität Münster, 48149 Münster, Germany
6H. Niewodniczański Institute of Nuclear Physics PAN, 31342 Kraków, Poland
7High Energy Physics Institute, Tbilisi State University, 0186 Tbilisi, Georgia
8High Energy Physics Department, Petersburg Nuclear Physics Institute, 188350 Gatchina, Russia
9Physics and Astronomy Department, UCL, London, WC1E 6BT, UK
10Physikalisches Institut II, Universität Erlangen-Nürnberg, 91058 Erlangen, Germany
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The cross section for inclusive multipion production in the \( pp \rightarrow ppX \) reaction was measured at COSY-ANKE at four beam energies, 0.8, 1.1, 1.4, and 2.0 GeV, for low excitation energy in the final \( pp \) system, such that the diproton quasi-particle is in the \( ^1S_0 \) state. At the three higher energies the missing mass \( M_X \) spectra show a strong enhancement at low \( M_X \), corresponding to an ABC effect that moves steadily to larger values as the energy is increased. Despite the missing-mass structure looking very different at 0.8 GeV, the variation with \( M_X \) and beam energy are consistent with two-pion production being mediated through the excitation of two \( \Delta(1232) \) isobars, consistent to \( S^- \) and \( D^- \) states of the initial \( pp \) system.

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The ABC effect is a sharp enhancement of the two-pion invariant mass spectrum near its threshold that has puzzled hadron physicists for almost fifty years. First observed in a \( pd \rightarrow ^3\text{He}X \) missing-mass experiment [1], and subsequently confirmed using a deuteron beam [2], it was seen most spectacularly in the \( dd \rightarrow ^4\text{He}X \) reaction [3,4]. The ABC typically manifests itself as a peak at an invariant mass \( M_X \approx 310 - 330 \text{ MeV}/c^2 \) and it was first even speculated that it might be a scalar meson with isospin \( I = 0 \). However, the fact that the mass and width varied with experimental conditions [2] suggests that the ABC is a kinematic enhancement. This is consistent with the smooth behavior of the isoscalar \( \pi\pi \) phase shifts at low energies. To understand the nature of the ABC it is necessary to investigate the effect in simpler systems.

The ABC showed up very clearly in the zero-degree momentum spectrum of the deuteron from \( np \rightarrow dX \) [3]. Here it leads to two peaks, i.e. forward and backward production in the c.m. system, though the momentum spread of the neutron beam degraded the missing-mass resolution. This has recently been overcome by measuring the quasi-free \( pd \rightarrow d\pi^0\pi^0p_{sp} \) reaction semi-exclusively at beam energies of \( T_p = 1.03 \) and \( 1.35 \text{ GeV} \), with just the spectator proton \( p_{sp} \) escaping detection [5]. The only published study of the ABC effect in proton-proton collisions was carried out at \( T_p = 1.52 \) and \( 1.81 \text{ GeV} \) [3], though this concentrated on possible substructure.

Studies of the energy dependence of the \( pd \rightarrow ^3\text{He}X \) and \( dd \rightarrow ^4\text{He}X \) cross sections showed that the ABC effect is most prominent for energies where the maximum missing mass is about 600 MeV/c^2 [2]. Since this corresponds to the mass difference between two \( \Delta(1232) \) isobars and two nucleons, it is tempting to suppose that the two-pion production is mediated by the excitation and decay of two separate \( \Delta \) isobars. Such a model with \( \pi \pi \) and then \( \pi + \rho \) exchange [2] had semi-quantitative success in describing the existing \( np \rightarrow dX \) data. The dominant contribution to the cross section arises when the two \( \Delta \) are in a relative S-wave. For the production of an \( I_{\pi\pi} \) pion pair, isospin conservation requires \( I_{\Delta\Delta} = 0 \). It follows from the generalized Pauli principle that the two isobars must then couple to a total spin of \( S_{\Delta\Delta} = 1 \) or 3. In contrast, for \( pp \rightarrow \Delta\Delta \rightarrow pp\pi\pi \), \( I_{\Delta\Delta} = 1 \) so that \( S_{\Delta\Delta} = 0 \) or 2, and an s-wave pion pair can have \( I_{\pi\pi} = 0 \) or 2. The investigation of the ABC phenomenon in \( np \) and \( pp \) collisions is therefore largely complementary.

The aim of the present experiment is the measurement of the \( pp \rightarrow \{pp\}_sX \) reaction when the excitation energy in the final diproton system is low, \( E_{pp} < 3 \text{ MeV} \). This quasi-particle, denoted by \( \{pp\}_s \), will be almost exclusively in the \( ^1S_0 \) state. Under these conditions, the kinematics are similar to those of \( pn \rightarrow dX \), which facilitates a comparison of the two reactions. Of the four proton beam energies used, \( T_p = 0.8, 1.1, 1.4, \) and \( 2.0 \text{ GeV} \), the lowest is well below the nominal \( \Delta\Delta \) threshold, and by \( 2 \text{ GeV} \) much of the \( \Delta \) strength has passed.

The measurement of single and multipion production...
in pp collisions was performed using the ANKE magnetic spectrometer \cite{10}, positioned at an internal target station of the COSY synchrotron storage ring of the Forschungszentrum Jülich. The single pion results have already been reported \cite{11}. The proton beam was directed at a hydrogen cluster-jet target with an areal density of 2 × 10^{14} atoms/cm^{2}. The resulting positively charged particles were recorded in the ANKE forward detector system, consisting of three MWPCs and a two-layer scintillation hodoscope, the whole giving a horizontal acceptance of 12° and ±3.5° vertically. The particle momenta, deduced by tracing through the analyzing magnetic field, had typical uncertainties of ≈ 1%. The emerging proton pairs were identified by evaluating the difference \( \Delta t \) between the times of flight measured with the hodoscope and those calculated from the particle momenta, assuming the particles to be protons \cite{11}.

![Graph](image)

**FIG. 1:** Distribution in the square of the missing mass of the pp \(\rightarrow\) ppX reaction at 1.4 GeV. Imposing a \( \Delta t \) cut to select the two protons gives the open histogram. The lightly shaded plot corresponds to the additional requirement that \( E_{pp} < 3 \) MeV and the heavy shading reflects the further \( \cos \vartheta_{pp} > 0.95 \) cut to match the overall ANKE acceptance. The positions of the \( \pi^0 \) and \( \eta \) peak are indicated, as is the two-pion threshold (dotted line).

Figure 1 shows the spectrum in the square of the missing mass of the pp \(\rightarrow\) ppX reaction at 1.4 GeV. Selecting pp events on the basis of the \( \Delta t \) cut eliminates almost all \( d\pi^+ \) pairs, leaving a background of less than 0.1%. To ensure that the two protons are dominantly in the \(^1S_0\) state, a further cut on the pp excitation energy, \( E_{pp} < 3 \) MeV, was imposed. After weighting by detection efficiency, such pairs are distributed isotropically in their rest frame, as expected for an S-wave. The \( E_{pp} \) distributions also follow closely the expected S-wave final-state-interaction behavior. Since for low missing masses the c.m. angle of the diproton, \( \vartheta_{pp} \), is strongly limited by the ANKE acceptance, we imposed the extra cut \( \cos \vartheta_{pp} > 0.95 \) on the whole spectrum. Apart from peaks corresponding to the production of single \( \pi^0 \) and \( \eta \) mesons, the distribution shows a rapid rise from the two-pion threshold with a gentle decrease towards the upper kinematic limit.

![Graph](image)

**FIG. 2:** Distribution in missing-mass squared for the pp \(\rightarrow\) (pp)\(\rightarrow\)X reaction for \( E_{pp} < 3 \) MeV and \( \cos \vartheta_{pp} > 0.95 \) at a) 0.8, b) 1.1, c) 1.4, and d) 2.0 GeV. The \( \eta \) signal is seen at the expected position for the two higher energies. The curves represent normalized simulations within a phase-space model.

The development of the counting rate distribution with energy is displayed in Fig. 2 for the multipion region. Also shown there are the results of a phase-space Monte-Carlo simulation of the detector and analysis code, including effects of momentum resolution, and applying the same cuts as for the experiment. In no case does this approach reproduce the data.

A simulation was used to deduce the differential cross sections of Fig. 3 from the counting rate data, taking as input the double-\( \Delta \) model to be discussed with Eq. (3). The simulation also defines the momentum reconstruction uncertainties and this leads to a \( \pi^0 \) peak whose width is compatible with that shown in Fig. 1. The requisite luminosity was derived from the simultaneous measurement of pp elastic scattering \cite{11}.

As shown in Fig. 3 the strength at 0.8 GeV is pushed towards the maximum missing mass, while at the higher three energies there is a peak of the ABC type at low \( M_X \) and no sign of any enhancement at large masses. Above its threshold there are also contributions from \( \eta \) production, with cross sections integrated over our cuts of \( \sigma_\eta = 4.3\pm0.8 \) at 1.4 GeV and \( 4.5\pm0.9 \) nb at 2.0 GeV. The ABC position moves steadily to the right and gets broader as \( T_p \) increases above 1.1 GeV, a confirmation that the phenomenon is primarily a kinematic effect. The peak seems to be rather clearer than that observed at Saclay at 1.5 and 1.8 GeV \cite{2}. Although a previous exclusive measurement of pp \(\rightarrow\) pp\(\pi^+\pi^-\) at 0.8 GeV \cite{13} did not study in detail our kinematic configuration, the
the recoiling protons. The $S$ and $D$–wave amplitudes $A_S$ and $A_D$ are scalar functions that may depend strongly upon the kinematic variables because of the excitation of the two $\Delta$, though we shall neglect any variation with $M_X$. In terms of the relative $\pi\pi$ momentum, $2\vec{q}$, and that of the diproton, $-\vec{k}$, the pion c.m. momenta are $\vec{k}_{1,2} = \frac{1}{2}\vec{k} \pm \vec{q}$, and the matrix element becomes

$$
M = A_S(\alpha^2 k^2 - \beta^2 q^2) + \frac{1}{2} A_D(3\alpha^2 k^2 - 2k^2 - (\alpha^2 k^2 - \beta^2 q^2)) \, ,
$$

(2)

where the $z$-direction is taken along $\vec{p}$. In this approximation, $q^2$ and $k^2$ are linked by energy conservation. For simplicity of presentation, a Galilean transformation is used to evaluate the recoil factors $\alpha = \frac{1}{2} (m+2\mu)/(m+\mu)$ and $\beta = m/(m+\mu)$ in terms of the pion ($\mu$) and proton ($m$) masses. Only the part of the matrix element proportional to $3q^2 - q^2$ corresponds to a $d$-wave in the $\pi\pi$ system and this contributes very little to the ABC peak, which is $s$-wave in nature.

Since the direction of the $\pi\pi$ relative momentum is not observed in a missing-mass experiment, $|M|^2$ must be averaged over the angles of $\vec{q}$:

$$
< |M|^2 > = |A_S(\alpha^2 k^2 - \beta^2 q^2) + \frac{1}{2} A_D(3\alpha^2 k^2 - k^2)|^2 + \frac{1}{2}|A_D|^2 \beta^4 q^4 \, .
$$

(3)

Figure 3 shows the results of implementing the simple double–$\Delta$ model of Eq. (3). Since the charges of the pions were not measured, we assumed an $I_{\pi\pi} = 0$ ratio of $\pi^+\pi^- : \pi^0\pi^0 = 2 : 1$, with the corresponding masses being used in the two phase spaces. If there were only $S$-wave production, $< |M|^2 >$ would be maximal at $q^2 = 0$ (the ABC bump) and at $k^2 = 0$ (the maximum allowed missing mass), with a deep valley between these two structures. Such behavior is seen for $d\vec{d} \rightarrow 4\mathrm{HeX}$ [3, 4]. The $A_D = 0$ case is illustrated in Fig. 3 as is that of a pure $D$-wave, which gives a broad maximum at low $\pi\pi$ invariant masses and no sign of any high mass bump.

The general shapes of the spectra at the three higher energies are qualitatively reproduced by the pure $D$-wave model. However, the peaking towards maximum $M_X$ in the 0.8 GeV data shows the necessity for a substantial $S$-wave contribution at this energy. To investigate this, the uncorrected data of Fig. 2 were fitted to the Monte-Carlo simulations using as input Eq. (3) with free values of $A_S$ and $A_D$. The values of these parameters that best reproduce the spectra are given in Table II along with the resulting integrated cross sections. Only at 0.8 GeV is $A_S/A_D$ required to be large. The description of the data shown in Fig. 3 is much improved, especially at 0.8 GeV, but the model does not reproduce the sharpness of the ABC peaks seen at 1.1 and 1.4 GeV. The values of $A_D$ fall steadily with energy but, to understand the significance of this, would require a full dynamical model.

The special quasi-particle kinematics studied here are very similar to those of $pn \rightarrow d\pi^0\pi^0$ and so a com-

FIG. 3: The $pp \rightarrow ppX$ differential cross section with statistical errors as a function of the square of the missing mass at a) 0.8, b) 1.1, c) 1.4, and d) 2.0 GeV for $E_{pp} < 3$ MeV and $\cos \theta_{pp} > 0.95$. The $\eta$ peaks are indicated. Events were simulated using Eq. (3) with $A_D = 0$ (long dashes), with the best fit of Table II (solid line), and with the best fit of Table I (short-dashed), and with the best fit of Table I (solid line).
TABLE I: Cross section \( \sigma_X \) for the \( pp \rightarrow \{pp\}_X \) reaction integrated over \( \cos \theta_{pp} > 0.95, E_{pp} < 3 \text{ MeV} \) and over \( M_X \) up to the kinematical limit. The experimental acceptance is limited to less than \( M_X^{\text{max}} \), and \( \sigma_X \) is obtained by correcting the measured cross-section by an amount \( \xi \), as suggested by fits of the \( \Delta \Delta \) model to the differential data. In addition to the given statistical errors, there are systematic uncertainties of 7\%, coming principally from the luminosity and acceptance evaluations \[11\]. The parameters \( A_S \) and \( A_D \) are determined by fitting the spectra away from regions of rapid variation, where resolution questions arise, and at too high masses to avoid the tail from \( \rho \) production. The results for \( A_D \) are normalized at 1.1 GeV.

| \( T_p \) (GeV) | \( M_X^{\text{max}} \) (MeV/c\(^2\)) | \( \sigma_X \) (nb) | \( \xi \) | \( A_S/A_D \) | \( A_D \) |
|-----------------|-------------------|-------------|------|--------------|------|
| 0.8             | 351               | 12 ± 2      | 34   | -1.23 ± 0.10 | 1.09 ± 0.05 |
| 1.1             | 468               | 389 ± 6     | 2.3  | -0.20 ± 0.03 | 1.00 |
| 1.4             | 571               | 563 ± 6     | 2.4  | -0.10 ± 0.03 | 0.48 ± 0.01 |
| 2.0             | 741               | 456 ± 5     | 5.8  | -0.23 ± 0.02 | 0.17 ± 0.01 |

Comparison with the CELSIUS-WASA data \[6\] is instructive because of the different spin-isospin selection rules. The measurement of the Fermi momentum when using a deuterium target allowed the determination of cross sections as a function of the laboratory kinetic energy \( T_p \). The results suggested a resonance-like structure with a mass of 2.39 GeV/c\(^2\) and width of \( \Gamma \approx 90 \text{ MeV/c}^2 \) \( (T_p \approx 1.17 \text{ GeV}, \Gamma_T = 0.23 \text{ GeV}) \). Though our energy intervals are rather wide, no such behavior is obvious in the values given in Table I which would suggest a strong isospin dependence of the production mechanism.

Within the \( S \)-wave \( \Delta \Delta \) approach, the matrix element of Eq. \[1\] allows for both \( A_S \) and \( A_D \) terms. If two-proton production were driven instead by the excitation of \( S \)-wave \( N^*(1440)N \) pairs, where \( N^* \) is the Roper resonance, an \( A_S \) term is generated through the double \( p \)-wave cascade decay \( N^*(1440) \rightarrow \Delta \pi \rightarrow p(\pi \pi) \). However, this model requires that \( A_D = 0 \). Contributions from both \( N^*N \) and \( \Delta \Delta \) might therefore provide an explanation for the energy dependence of \( A_S/A_D \) shown in Table I. It should be noted that the \( \Delta \Delta \) model would lead to an ABC effect also in \( pp \rightarrow \{nn\}_X \pi^+ \pi^- \), which is forbidden in the \( N^*N \) model. Earlier studies of the ABC effect were not sensitive to any \( I_{\pi \pi} = 2 \) component.

In summary, we have measured the differential cross section for the \( pp \rightarrow \{pp\}_X \) reaction at four beam energies from 0.8 to 2.0 GeV under the specific kinematic conditions where the proton-proton excitation energy is below 3 MeV and the c.m. angle between the diproton momentum and the beam axis is less than 18\(^\circ\). The form of the \( E_{pp} \) spectra and isotropy of the angular distribution in the diproton frame are consistent with the two final protons being in the \( 1S_0 \) state. Strong deviations from phase space are observed in the missing-mass variable, with a peak in \( M_X \) whose position varies with beam energy, and no broad bump at maximum missing mass of the type observed in \( dd \rightarrow \alpha X \) \[3, 4\]. On the other hand, there is no sign of the resonance-like structure in the energy dependence of the integrated cross section that is reported for \( pn \rightarrow d\alpha \pi^0 n^0 \) \[3\].

The evidence presented here points towards to the ABC produced in \( pp \) collisions being a kinematic effect and this is backed up by our naive phenomenological description. The isospin structure of \( pp \rightarrow \{pp\}_X \) is much richer than in the \( pn \rightarrow dX \) case and it is quite likely that there will be significant contributions from both \( I_{\pi \pi} = 0 \) and 2; a kinematic enhancement does not have to have a definite isospin. On the other hand, the spin structure is much simpler and, after assuming that each of the two pions is emitted in a \( p \)-wave, there are only two amplitudes to be considered. Except for the 0.8 GeV data, the bulk of the \( M_X \) spectra are consistent with a dominant \( D \)-wave coupling to the incident protons, whereas at the lowest energy the \( S \)-wave is significant. The major discrepancies in the model are in the heights of the ABC peaks at 1.1 and 1.4 GeV, but a fully microscopic approach would be required to assess the origin of these.

Exclusive measurements of \( pp \rightarrow \{pp\}_X(\pi\pi)^0 \) over a wider range of angles would provide more stringent tests of the simple phenomenological description and the study of \( pp \rightarrow \{nn\}_X \pi^+ \pi^- \) would be particularly valuable.

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* Electronic address: sdymov@tue-juelich.de

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