A neutron in the pion angular distribution of the reaction \( pp \rightarrow pp^0 \) at 400 MeV

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The reaction \( pp \rightarrow pp^0 \) was studied with the WASA detector at the CELSIUS storage ring. The center of mass angular distribution of the \( pp^0 \) was obtained by detection of the decay products together with the two outgoing protons, and found to be anisotropic with a negative second derivative slope, in agreement with the theoretical prediction from a microscopic calculation.

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I. INTRODUCTION

The highest precision measurements of single neutral pion production in nucleon-nucleon collisions, using storage-ring technology, were done more than a decade ago. Still, the theoretical interpretation of the dominant production mechanisms remains uncertain. The magnitude of the total cross section of the \( pp \rightarrow pp^0 \) reaction in the threshold region, where only angular momenta equal to zero are important in the final state, was measured to be about 5 times larger than what was predicted by the theoretical models available at the time. However, the energy dependence was found to be consistent with the widely accepted Koltun and Rellman model based on s-wave pion production and rescattering. The experimental result was combined with the large theoretical activity that was triggered by the new high precision data, leading to the acceptance of a new model that predicted the production of different mesons. The theoretical model was also compared with the high precision data, leading to the acceptance of a new model that predicted the production of different mesons. The theoretical model was also compared with the high precision data, leading to the acceptance of a new model that predicted the production of different mesons.

The first successful remedy to the discrepancy between experiment and theory was to take into account the exchange of heavy mesons. The s-wave pion rescattering (together with the Born term) was also suggested to be the gap in the cross section. Both of these theories could not be right unless there were more additional effects. Further, one, approaches using chiral perturbation effective field theory (ChPT) reached a different conclusion than meson effective field theory and found the interference between the direct term and the pion scattering to be destructive. Improved calculations carried out in momentum space increased the rescattering amplitude for the ChPT treatment by a factor of three. Considerable progress has since been made developing the ideas of ChPT, using an ordering scheme that takes into account the large momentum transfer typical for meson production in N N collisions.

A calculation taking into account the exchange of two different heavy mesons, pion rescattering and the \( P_{11}(1440) \) nucleon resonance produced the total cross section numbers. Relativistic effects were studied in the impulse approximation in Ref. 19. The exchange of the mesons and \( \pi \) with the nucleon and the \( (1232) \) isobar as intermediate states, using a relativistic treatment in a covariant one-boson exchange model over an energy range from near threshold to 2 GeV, gave reasonable agreement with data. The effect of the \( P_{11}(1440), S_{11}(1535) \) and \( D_{13}(1520) \) together with the impulse and pair diagram terms were studied in Ref. 21.

The possible influence of the differential cross sections due to contributions from higher partial waves, including d-waves, was studied experimentally at CELSIUS. Angular distributions as well as total cross sections were recently measured from threshold up to 10 MeV above, by the TOF collaboration using an extracted beam.

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The angular distributions were isotropic as expected close to threshold. The total cross section obtained was about 50% larger than the IUCF [2] and CELSIUS data [3]. The reason for the large deviation compared to the previous storage ring experiments was suggested to be due to a significant loss of events in the internal experiments where the very forward going protons escape down the beam pipe undetected. At threshold a strong no-state interaction could cause the loss of a large number of protons that would not be properly accounted for.

The data set was drastically increased when the reaction pp → pp was measured at beam energies between 325 and 400 MeV by the P T TEX collaboration at IUCF [24, 25, 26, 27]. All possible polarization observables were deduced in the kinematically complete experiment and a general formism was developed from a partial wave analysis in order to obtain an expansion of the observables in terms of a complete set of functions mapping the angular dependence [17]. Thus an analysis method was realized with all the physics information contained in the deduced three-couplings. However, contributions from D and S to the no-state were not taken into account. The only theoretical model that so far has been compared to these data is the microscopic model developed by the Jülich group [28, 29]. The phenomenology of the model includes direct production, s- and p-wave rescattering of the pion, pair diagrams and excitation of the (1232). Angular momenta up to L = 12 and between the two protons and the pion with respect to the NN subsystem, are included. The same group has recently performed a partial wave analysis using the data and the assumptions of [21] and compared the extracted quantities to those of their m e - e x hange model [30]. Most of the amplitudes are shown to be reproduced fairly well by the model, except for the amplitude 3P 1 , which deviates significantly from what is extracted from the data. For a quantitative assessment of pp → pp and it also turns out that the excitation plays a major role. For a summary on near threshold m e - e x hange production experiments see [31]. The status of the theoretical eld is reviewed in [32].

In spite of the interest in the reaction pp → pp during the last 15 years, the reports on pion angular distributions at energies up to 400 MeV, s e r from low statistics and/or small acceptance. We have measured the unpolarized angular cross section of the 0 at 400 MeV, with the aim to resolve some of the ambiguities and complement the partial wave analysis based solely on polarized data.

II. MEASUREMENT

The experiment was done using the WASA 4 detector facility [33] situated in the CELSIUS accelerator and storage ring at Uppsala, Sweden. A stored circulating proton beam of energy 400 MeV was let to interact with a stream of small (30 cm) frozen hydrogen pellets. All three outgoing particles from the reaction pp → pp were detected. The protons were fully stopped either both in the Forward Detector (FD), or one in the FD and one in the Central Detector (CD). The FD consists of a stack of scintillator and wire chamber planes, primarily adapted to measure the four momentum of recoiling nuclei. The CD is constructed for measuring m e - e x hange decay products, and consists of the Scintillating Electromagnetic Calorimeter (SEC) made up of 1012 CsI detector elements, a Plastic Barrel (PB) for charged particle detection and a M inidrift Chamber (MDC) for measuring the momentum of charged particles. In the current experiment only the FD and the SEC were used for energy measurement and the PB for the rejection of charged particles. Since the energy and angular resolution for protons was relatively poor in the CD, a no-state analysis was based on the detection of the 0 ! 2 decay in the CD.

A. Data Analysis

The event selection was handled using two different sets of criteria based on two different track types, which were either both protons detected in the FD (2FD-type), or one in the FD and one in the CD (1FD1CD-type). The requirements were coincident fast signals from either two hits in one scintillator layer of the FD or one in the FD and one hit in the forward part of the PB. These triggers gave an unbiased acceptance of the CD but yielded very
the constraint that the sum of the energies of the two is within the kinematic limits for $^0$ production, is shown by the dashed line. The solid line depicts what is cut on based on the relation between the opening angle and the planarity of the two $^0$, representing largely backgournd from elastic scattering. Right panel: The combination of the two cuts is shown by the dashed line and the residual invariant mass of the two $^0$, is drawn by the bold line.

**Fig. 3:** The experimental center-of-mass $^0$ angular distribution, arbitrarily normalized. The shaded area is the result of a simulated phase space generated isotropic distribution of the pp $^0$ after passing through the detector system. The solid line corresponds to the predicted histogrammed values from a simulation weighted with the microscopic calculation by Hanhart et al. 28, 31. The statistical uncertainties are negligible.

The geometric acceptance for detection of the outgoing protons from the reaction pp $^0$ is shown in Fig. 3. The angular coverage was 3 $^\circ$ to 17$^\circ$ and 20 $^\circ$ to 155 $^\circ$. For the FD and the CD respectively. Since there were no triggers set for the case when both protons are emitted at $\text{lab} > 17^\circ$, these events escape the current analysis.

However, the full range of the relative momentum of the two protons is covered by the experiment, (c.f. the right panel of Fig. 3), which is crucial from the physics interpretation point-of-view.

The basic condition for an accepted event of the 2FD type was particle identification of the protons in the FD done by $E_p$ technique, and the presence in the CD of two neutral tracks from the decay of $^0$ $^2$. Additional constraints were based on the comparison of the reconstructed polar and azimuth laboratory angles, plus cuts in the center-of-mass energy, with respect to the missing mass of the two protons and the invariant mass of the two $^0$'s from the $^0$ decay. The conditions applied were: $\sqrt{M \times E} < 15$, $\sqrt{M \times E} < 15$ and $\sqrt{M \times E} < 30$ MeV, where $M$ is the missing mass of the two protons and $IM$ the invariant mass of the two $^0$'s. The consistency of the $^0$ angle reconstructed from the missing mass and the invariant mass, respectively, was investigated. The two approaches agreed and thus the conclusion was drawn that analysis of the 1FD 1CD type prongs could be done using CD information only.

The selection of event candidates for the type of events with one forward and one central prong (1FD 1CD type) was done by particle identification of the FD proton. Furthermore, for the two $^0$ cuts a cut based on the relation between the opening and planarity angles. An additional constraint applied was that the sum of the energies of the two $^0$'s was within the kinematic limits for $^0$ production, i.e. 135 < $E$ < 238 MeV. The $^0$ peak obtained from the invariant mass of the two $^0$'s, before and after track requirements are fulfilled, is shown in Fig. 3.

The two sets of selected pp $^0$ events were weighted together according to their relative trigger preselback factor. The experimental angular distribution of the $^0$ in the center-of-mass, uncorrected for acceptance, is seen in Fig. 3. Displayed are also simulations using either isotropically distributed events according to phase space or events weighted with the theoretical calculation of the Julich model by Hanhart et al. 28, 31. More details on the data reduction procedure can be found in 34.

**III. RESULTS**

The acceptance corrected $^0$ angular distribution is shown together with the prediction by the Julich model in Fig. 3. The experimental data points and the theoretical curve are normalized to $\text{tot} = 93.72$ barn from 32. The systematic uncertainties dominate, primarily emanating from the acceptance varying with the central detector's geometry. In order to obtain an estimate of the magnitude of this error the outermost layers in the forward and the backward parts respectively, were excluded in the analysis.

In previous experimental reports 23, 35, 36, 37, 38, 39, 40, 41 concerning the angular distribution a slope parameter $b$ was defined according to $d^2 \rho / d^2 \cos^2 \theta$, see
One recent experiment [22] yielded a negative slope up to 360 MeV beam energy but at 400 MeV the slope was reported to be positive in discrepancy with the present result \( b = -0.016 \pm 0.010 \). However, the acceptance of [22] was limited with respect to \( p \), with a coverage similar to the 2D type case, and a model dependence was introduced by extrapolating into unmeasured regions of phase space. It should be noted that events with both proton angles larger than 17° were not detected within the current acceptance, see Fig. 4. There are indications that the inclusion of such events would slightly affect the distribution [22]. Whereas the 0° angular distribution integrated over all \( p \) displays discrepancies among the different experiments, a selection of S-wave protons might shed some light. At very low relative momenta between the protons, \( p < 53 \text{ MeV}/c \), the two CELSIUS measurements agree at least qualitatively, see Fig. 5. At 800 MeV beam energy using the same cut in \( p \), an even larger negative second derivative was found [23], which was also predicted by a phenomenological calculation [24].

A direct comparison between the present experiment and the expansion deduced from the double polarization data [23] can be done by using the same fitting method [45], that allows to integrate the prediction of a theoretical model over the experimentally accessible phase space region, see Fig. 6. The corresponding combination \( H_{0}^{0} + I \) and the dependency on the \( \cos^{2} \phi \)-term (Eq. 11 [27]) have been taken into account, all other variables are ignored. See Table I for the correspondence between the slope parameter \( b \) and \( H_{0}^{0} + I \).

The prospect of improving the accuracy of certain co-
In the determination of the coefficients, as well as pinning down the only remaining coefficient, as well as in the determination of the coefficients, as well as pinning down the only remaining coefficient, H_{00}^0, using the present experimental sample, is now a highly feasible plan for the immediate future. Thus another advancement has been made towards a complete characterization of the amplitudes of the fundamental reaction pp. The dashed lines correspond to the uncertainty in the experimental data and the expansion developed in \[27\].

FIG. 7: Using the sampling method [45] for direct comparison between the experimental data and the expansion developed in [27].

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