Proposal and beam request

Measurement of the cross section and analysing power of the $\vec{p}\,p \to \{pp\}_s\pi^0$ reaction

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Abstract

We propose to measure the differential cross section and proton analysing power of the $pp \to \{pp\}_s\,\pi^0$ reaction for excitation energies of the final di–proton less than 3 MeV. The experiment would be carried out at the ANKE spectrometer at several beam energies from 350 MeV up to 950 MeV. At the lowest energy the results will be of relevance for Chiral Perturbation Theory whereas at higher energies they will give valuable insight into Δ–nucleon dynamics. These experiments are in line with the proposals outlined in the ANKE spin document.

Contents

1 Introduction

Pion production in nucleon–nucleon collisions has been studied for many years [1]. The theoretical description is, however, considerably simplified if two final protons are detected at low excitation energy because, by the Pauli principle, their spins must align in opposite directions. The $pp \to \{pp\}_s\pi^0$ spin–structure, where $\{pp\}_s$ denotes such a ${}^1S_0$ state, is particularly simple since there are only two invariant amplitudes compared to the six for $pp \to d\pi^+$. Thus at any angle one needs only to measure the differential cross section, proton analysing power, and one spin correlation to carry out an amplitude analysis in order to disentangle the underlying dynamics.

At low energies, pion production can be described in terms of Chiral Perturbation Theory (ChPT) [1] and we have suggested in the ANKE SPIN proposal [2] that the combined study of several observables in the $pp \to \{pp\}_s\pi^0$ and $np \to \{pp\}_s\pi^-$ reactions could be used to isolate one important parameter in this theory. Such experiments should be carried out at fairly low energies in regions where only terms up to second order in the pion cm momentum contribute significantly to the observables. One obvious choice is the vicinity of 350 MeV, where data on π^0 [3] and π^- [4, 5] production are already available.

At higher energies one has to rely on much more phenomenological approaches for guidance. The simple $N\Delta$ model of Ref. [6, 7] predicts that there should be a minimum of the $pp \to \{pp\}_s\pi^0$ differential cross section in the forward direction and that is precisely what is seen both in data below 425 MeV [3, 8] and in our own measurement with ANKE at 800 MeV [9]. Furthermore this model reproduces the size of the steep near–forward slope, though not the magnitude of the 800 MeV cross section. Between 425 and 800 MeV the model predicts considerable structure in the forward cross section, its slope, and the proton analysing power as functions of the beam energy [6,7]. Measurements in this region should therefore provide interesting tests of nuclear dynamics involving Δ degrees of freedom.

We have shown in our first experiment in this field [9] that one can measure the small–angle $pp \to \{pp\}_s\pi^0$ reaction very effectively in ANKE and this capability should be equally valid for experiments with a polarised proton beam. It is therefore proposed to measure $\mathrm{d}\sigma/\mathrm{d}\Omega$ and A_y for the $pp \to \{pp\}_s\pi^0$ reaction at several beam energies, starting at 350 MeV to provide the ChPT information, and linking up with our previous 800 MeV measurement. We expect to propose to a later PAC experiments, $\vec{p}\vec{p} \to \{pp\}_s\pi^0$ and $\vec{p}\vec{d} \to p_{\rm sp}\{pp\}_s\pi^-$, where both the beam and target will be polarised.

2 Detailed physics case

The spin structure of the $pp \to \{pp\}_s\pi^0$ (or $np \to \{pp\}_s\pi^-$) reaction is that of $\frac{1}{2}^+\frac{1}{2}^+ \to 0^+0^-$. There are only two independent spin amplitudes and these may be written in terms of unit vectors along $\boldsymbol{m} = \boldsymbol{k} - \boldsymbol{k}'$, $\boldsymbol{n} = \boldsymbol{k} \times \boldsymbol{k}'$, and $\boldsymbol{l} = \boldsymbol{n} \times \boldsymbol{m}$ as

$$\mathcal{F} = \frac{i}{\sqrt{2}}\, u_2^T\, \sigma_y \left\{ A\, \boldsymbol{\sigma} \cdot \hat{\boldsymbol{l}} + B\, \boldsymbol{\sigma} \cdot \hat{\boldsymbol{m}} \right\} u_1\,, \tag{2.1}$$

where $\boldsymbol{k}$ is the initial proton cm momentum and $\boldsymbol{k}'$ that of the emerging di–proton, and the u_i are Pauli spinors describing the initial protons. Taking a coordinate system where $(\hat{\boldsymbol{l}},\, \hat{\boldsymbol{n}},\, \hat{\boldsymbol{m}}) = (\hat{\boldsymbol{x}},\, \hat{\boldsymbol{y}},\, \hat{\boldsymbol{z}})$, the double–polarised differential cross section becomes

$$\begin{aligned} \frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} = \left(\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}\right)_0 \times & \qquad\qquad (2.2)\\ \left[1 + P_y^b A_y^b + P_y^t A_y^t + P_y^b P_y^t C_{yy} + P_x^b P_x^t C_{xx} + P_z^b P_z^t C_{zz} + P_x^b P_z^t C_{xz} + P_z^b P_x^t C_{zx}\right]\,, & \end{aligned}$$

where $\boldsymbol{P}^b$ and $\boldsymbol{P}^t$ are the beam and target polarisations. The observables are then expressed in terms of the two amplitudes through [10]

$$\begin{aligned} \left(\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}\right)_0 &= \tfrac{1}{4}\left(|A|^2 + |B|^2\right), \quad A_y^b = A_y^t = -\frac{2\, Im(A^*B)}{|A|^2+|B|^2} \\ C_{xx} = -C_{zz} &= \frac{|B|^2 - |A|^2}{|A|^2+|B|^2}\,, \quad C_{yy} = 1, \quad C_{xz} = C_{zx} = -\frac{2\, Re(A^*B)}{|A|^2+|B|^2}\,\cdot \end{aligned} \tag{2.3}$$

From this it is seen that, up to a two–fold ambiguity, the measurement of the differential cross section, the analysing power, and one spin correlation coefficient is sufficient to extract magnitudes of the two amplitudes and their relative phase. Such amplitude information can then be compared with theoretical models in a much more transparent way than through the direct use of observables. The present proposal is limited to the study of $\mathrm{d}\sigma/\mathrm{d}\Omega$ and A_y for the $pp \to \{pp\}_s\pi^0$ reaction. Double–spin observables and the reaction $np \to \{pp\}_s\pi^-$ will be the subject of a later proposal to the PAC.

It was argued in the ANKE spin proposal [2] that experiments in the 350 MeV region would be particularly interesting because, taken in conjunction with data on $np \to \{pp\}_s\pi^-$, a valuable test of chiral perturbation theory could be deduced. The detailed theoretical motivation for this is given in the spin document and only the phenomenology is presented here.

Due to spin–parity constraints applied to the $pp \to \{pp\}_s\pi^0$ reaction, the orbital angular momentum of the pion must be even and that of the initial protons odd. Therefore at low energies one can expect the dominant partial–wave contributions to the amplitudes of Eq. (2.1) to come from the transitions ${}^3P_0 \to {}^1S_0 s$, ${}^3P_2 \to {}^1S_0 d$, and ${}^3F_2 \to {}^1S_0 d$. It is interference between these s– and d–waves that gives rise to the forward dip seen in the $pp \to \{pp\}_s\pi^0$ cross section [3, 8, 9].

In Ref. [1] it was shown that the differential cross section and analysing power for the reaction $np \to \{pp\}_s\pi^-$ is sensitive to an interference of the s–wave pion–production amplitude, ${}^3P_0 \to {}^1S_0 s$, and the p–wave amplitudes, ${}^3S_1 \to {}^1S_0 p$ and ${}^3D_1 \to {}^1S_0 p$. The four–nucleon contact interaction, with strength parameter d, contributes to both. Thus, once a proper chiral perturbation theory calculation is available for the s–wave pion production, the reaction $np \to \{pp\}_s\pi^-$ close to the production threshold might well be the best reaction from which to extract the parameter d. The contributions from isovector initial states can be deduced from the $pp \to \{pp\}_s\,\pi^0$ measurements being discussed in this proposal. For the isoscalar initial state, the Δ–nucleon intermediate system does not contribute before pion emission. Secondly, the leading p–wave amplitude is the one of interest, in contrast to $pp \to pn\pi^+$, where p–wave pion production is completely dominated by the transition ${}^1D_2 \to {}^3S_1 p$ involving production through the Δ.

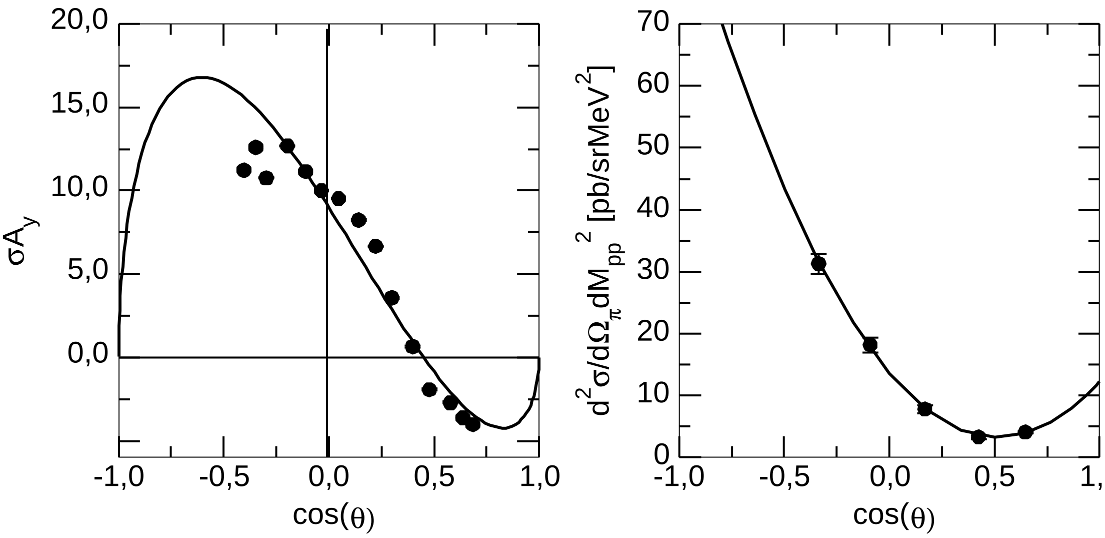


Figure 1: Analysing power and differential cross section of the $np \to pp\pi^-$ reaction at $T_n = 353\,\mathrm{MeV}$ and $E_{pp} < 1.5\,\mathrm{MeV}$. The experimental data are from Ref. [4] and [5]. The curves are polynomial fits up to second order in the pion momenta.

One eventual goal of the ANKE pion–production measurements is therefore to provide the missing observables needed to extract unambiguously the amplitudes for the transitions ${}^3S_1$–${}^3D_1 \to {}^1S_0 p$ [2]. The TRIUMF $np \to \{pp\}_s\pi^-$ data [4, 5], shown in Fig. 1, are consistent with the assumption that at a neutron beam energy of $T_n = 353\,\mathrm{MeV}$ only terms up to quadratic in the outgoing pion momentum need to be kept in the expressions for the observables and the same is true for the $pp \to \{pp\}_s\,\pi^0$ differential cross section [3]. Such terms can arise from the square of p–wave amplitudes or from s–d interference and both have to be taken into account.

To extract the two p–wave amplitudes, nine independent observables are required, of which the TRIUMF data provides five (here each angular structure is counted as an individual observable). The TSL measurement of the $pp \to \{pp\}_s\,\pi^0$

differential cross section [3] furnishes the values of another two observables. At least two further measurements are required and it would be preferable to measure more in order to eliminate discrete ambiguities and improve the statistical and systematic precision. The measurement of $A_y(pp \to \{pp\}_s\pi^0)$ would provide one though the rest will require studies with polarised beam and target, including a quasi–free neutron target.

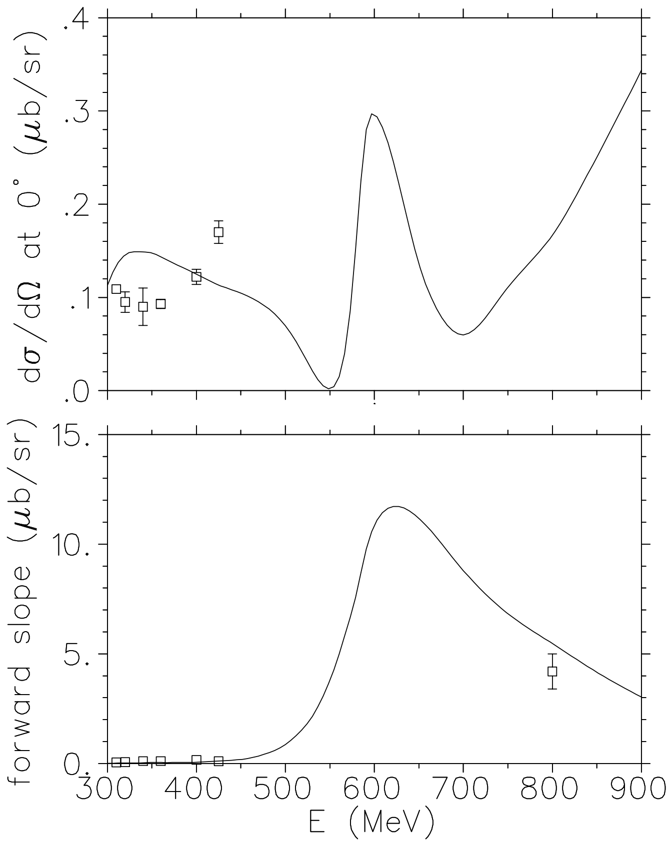


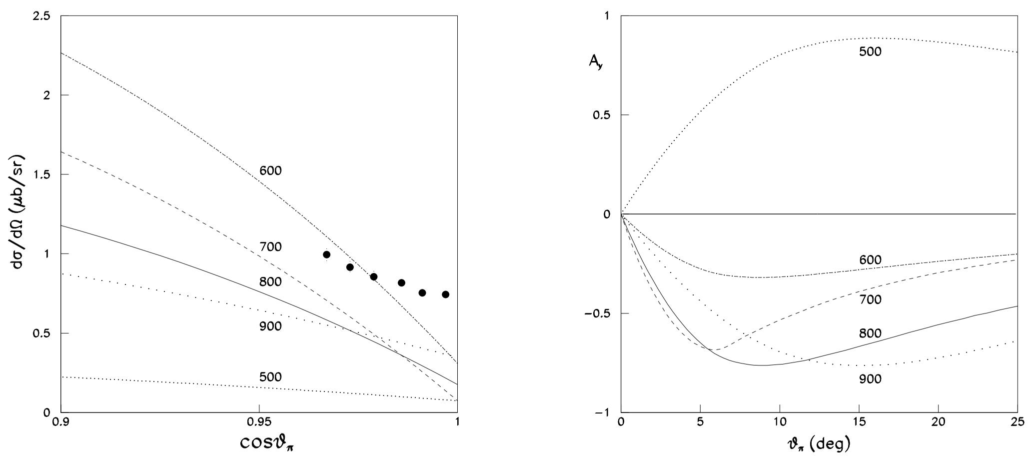
Figure 2: Upper frame: Forward differential cross section for the $pp \to \{pp\}_s\pi^0$ reaction as a function of beam energy predicted by the $N\Delta$ model [6]. Shown are the experimental values obtained from TSL at low energy [3]. Our results at 800 MeV gave about 0.7 μb/sr. Lower frame: Value of the forward slope with respect to $\cos^2\theta$ of the differential cross section as a function of beam energy.

At higher energies, one has to rely rather on more phenomenological approaches, such as the $N\Delta$ model of Ref. [6]. Now conservation laws forbid the S–wave $N\Delta$ intermediate state and the P–waves will feed both s–wave and d–wave pion production and the structure of the observables will depend very sensitively on their relative contributions. The phenomenological model [6] predicts violent oscillations in the forward cross section as a function of energy with a width that is even smaller than that of the Δ itself, as illustrated in fig. 2a. Due to the delicate nature of the cancellation between pion s and d–waves, this calculation underestimates our 800 MeV result and so one must take the details of these predictions with caution.

Nevertheless the model does reproduce the order of magnitude of the low energy data [3] and the result that the forward cross section will change fast with T_p is likely to remain true.

More reliance can be placed on the value of the forward slope, which is shown in Fig. 2b. This gives a reasonable description of the low energy data [3] as well as of our 800 MeV results. The width of the structure here is much more characteristic of that of the Δ, though it is shifted to slightly higher energies, probably because of the presence of the P–wave in the $N\Delta$ system [6].

The rich structure in the predictions of the differential cross section with respect to angle and beam energy is matched or even surpassed by that for the proton analysing power [6, 7]. On general grounds $A_y(\theta{=}0) = 0$ but, in the $N\Delta$ model, it approaches its maximum value at quite small angles. Furthermore, below 550 MeV (the minimum in Fig. 2) the analysing power is strongly positive but this changes to negative for higher energies due to the change in sign of the ${}^3P_0 \to {}^1S_0 s$ amplitude in this region. The remarkable behaviour of the differential cross section is illustrated in Fig. 3(a), while the corresponding analysing power is shown in Fig. 3(b). It should, however, be noted that if the forward cross section is larger than that shown in Fig. 3(a) the slope of the analysing power near $\theta_\pi = 0$ might be less than that of Fig. 3(b).



(a) Differential cross section. The 800 MeV ANKE results [9] are shown by circles.

(b) Proton analysing power

Figure 3: Predictions for small–angle observables of the $pp \to \{pp\}_s\pi^0$ reaction at 500, 600, 700, 800, and 900 MeV derived within a phenomenological $N\Delta$ model [6,7].

Experimental data on neutral pion production in pp interactions at 350–950 MeV beam energy, with selection of a ${}^1S_0$ diproton in the final state, would thus provide extremely valuable information for comparison with theoretical models and approaches.

3 Experimental considerations

3.1 Experimental set–up

The ANKE set–up [11] is well suited for the study of meson production at small angles. The basic design is shown in Fig. 4 but, for the proposed experiment, only the Forward Detector (FD) of ANKE will be used to measure the two outgoing protons[1]. The FD includes a scintillation hodoscope, wire chambers and Čerenkov counters, though the latter will also not be used here. The performance of the FD is described in detail in Refs. [12, 13].

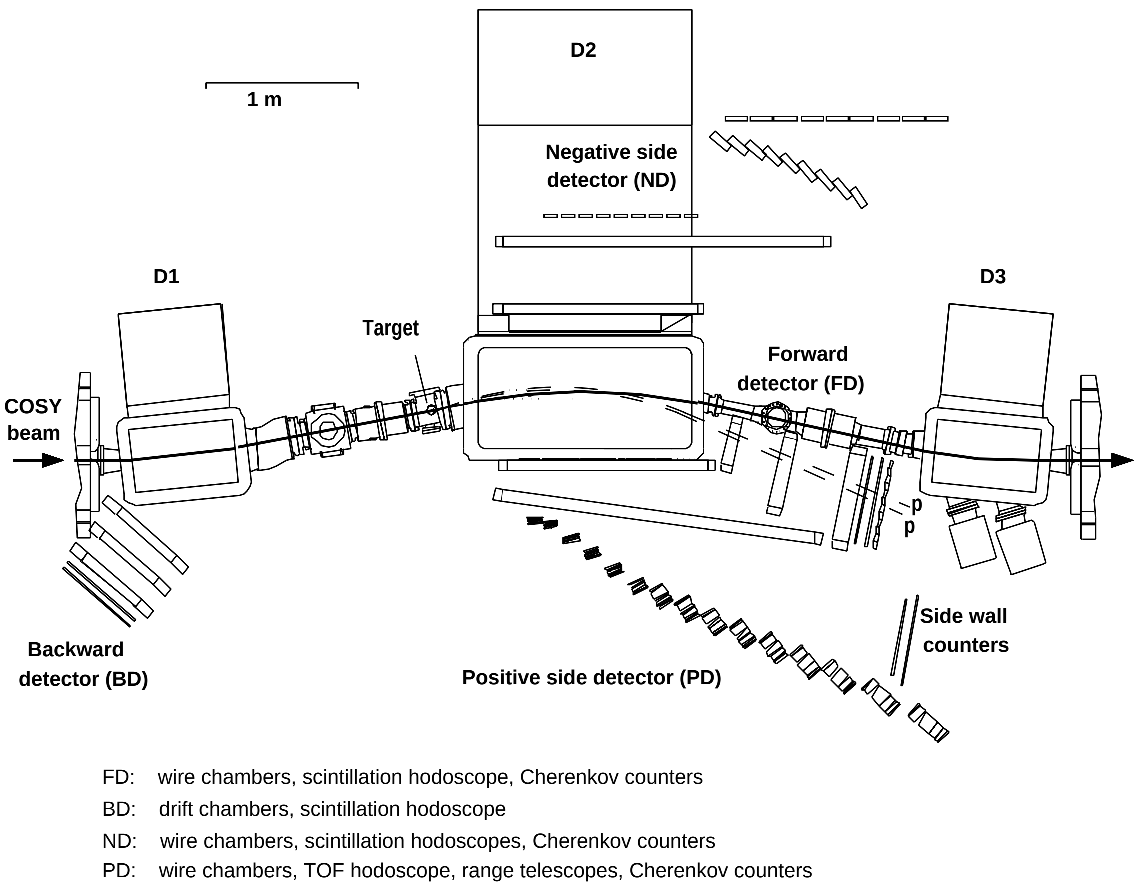


Figure 4: Schematic diagram of the ANKE experimental set–up.

The FD scintillation hodoscope, consisting of two planes of vertically oriented counters, provides timing and ionisation–loss information and is also used for trigger purposes. Its wire chamber system includes three tracking stations, each with X–, Y– and V–coordinate planes, which are used for the geometrical event reconstruction and measurement of the particle momenta *via* the track deflection in the magnetic field.

[1]The option of using the Positive Side Detector system is also being considered for the lower energies.

No modifications of the present detection system are needed for the proposed measurements since the FD performance proved to be completely adequate for the study the unpolarised $pp \to \{pp\}_s\pi^0$ reaction at 800 MeV [9]. The main characteristics of the FD that are relevant for this experiment are: resolution on the time difference between the arrival of the two protons $\sigma(\Delta t) < 0.5$ ns, momentum resolution $\sigma_p/p \approx 1\%$, resolution on relative energy of the two protons $\sigma(E_{pp}) = 0.2$–0.3 MeV for E_{pp} in the range 0–3 MeV.

The measurements will be done in a single polarised mode using a polarised proton beam and unpolarised hydrogen cluster jet target [14]. Once the polarised internal target [15] is commissioned at ANKE, double polarised studies of the $pp \to \{pp\}_s\pi^0$ and $pd \to p_{\rm sp}\{pp\}_s\pi^-$ reactions will become possible, allowing the measurements of spin–correlation observables.

3.2 Acceptance

The FD acceptance for various reactions is shown in Figs. 5 and 6 for proton beam energies of 800 MeV (experimental) and 500 MeV (simulated). These show the projection of the laboratory polar production angle onto a horizontal plane *versus* momentum. The curves correspond to kinematical loci for the reactions $pp \to \{pp\}_s\pi^0$, $pp \to pp$, and $pp \to d\pi^+$.

The horizontal acceptance at 800 MeV shown in Fig. 5 corresponds to a cms angular range of $\theta_{pp}^{\rm cm} < 15.4^\circ$ with respect to the incident beam direction. It changes slowly with beam energy within the 500–1000 MeV range whereas at 350 MeV it increases up to $\sim 90^\circ$. The vertical acceptance is $\pm 3.5^\circ$ so that the azimuthal acceptance of the FD depends upon the polar angle. For this reason, events for the data analysis will be selected, like it was done in [9], from the range of azimuthal angles where this dependence is rather smooth and does not lead to large uncertainties.

3.3 Trigger

A simple trigger requiring the coincidences of signals in two matching counters of the two hodoscope planes can be used, as was done in [9]. For that measurement the trigger rate was not very high and the dead–time of the data acquisition system reasonably small. If the experimental conditions are favourable and a high luminosity is achieved, this simple trigger may result in a significant dead–time. In this case the more selective trigger [16], which has already been used at ANKE, requiring the detection of two particles in the FD (independent of event topology) can be applied, thus decreasing the dead–time.

3.4 Previous measurements at ANKE with unpolarised beam

The unpolarised $pp \to \{pp\}_s\pi^0$ reaction has already been studied very successfully with ANKE at $T_p = 800$ MeV [9]. After selection of events with two tracks in the Forward Detector, a two–dimensional scatter plot of the momenta of two particles has been produced, as shown in Fig. 7. One can see islands corresponding to $pp \to d\pi^+$

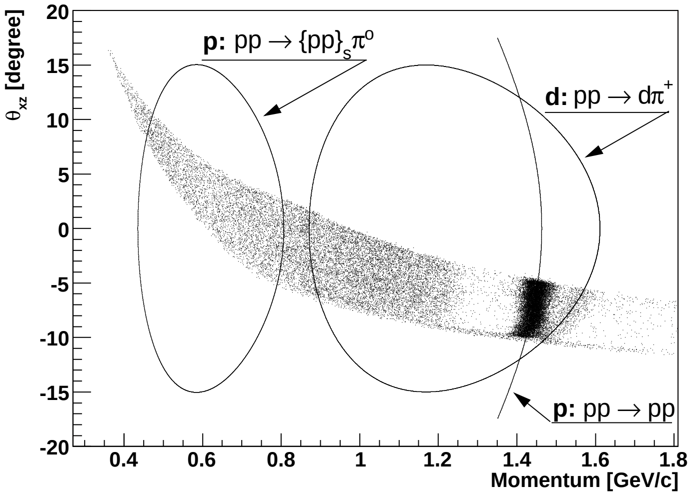


Figure 5: Experimental acceptance of the ANKE Forward Detector at the proton beam energy T_p=800 MeV in horizontal angle *versus* momentum. The curves show kinematical loci for protons and deuterons from the $pp \to \{pp\}_s\pi^0$ $pp \to pp$ and $pp \to d\pi^+$ reactions. Here, $\{pp\}_s$ denotes a forward proton pair with zero excitation energy.

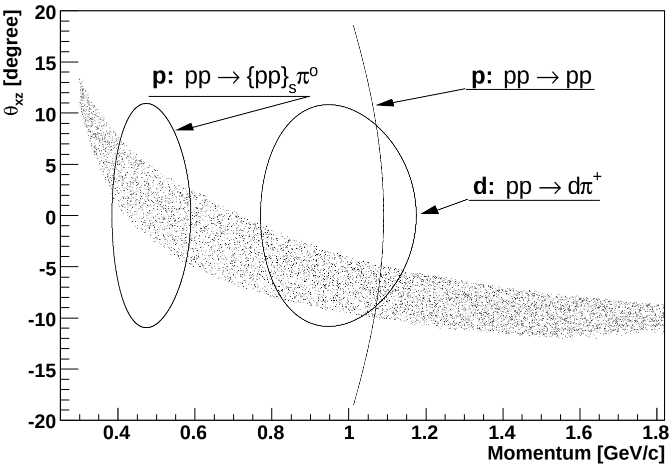


Figure 6: Simulated acceptance at $T_p = 500$ MeV. Notations are as in Fig. 5.

and bands from $pp \to pn\pi^+$ and $pp \to pp\pi^0$. Events from the latter reaction are well separated from other processes. The most serious background could arise from the $pp \to d\pi^+$ reaction, but this can be effectively suppressed by selection criteria on timing because of the large shift in the time difference between d and π^+ compared with that for two protons.

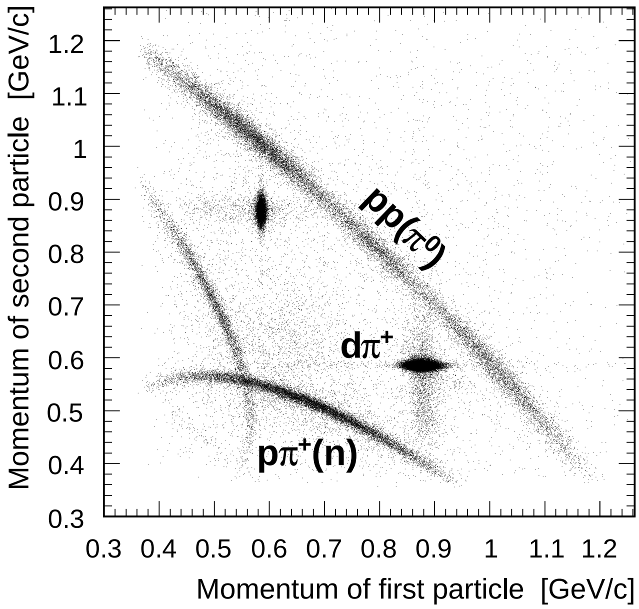


Figure 7: Scatter plot of the magnitudes of the momenta of two charged particles in the FD produced by proton–proton collisions at 800 MeV.

The missing–mass–squared distributions thus obtained are shown in Fig. 8 separately for events where two protons hit different or the same hodoscope counter. In the latter case it is, of course, impossible to apply any selection based on the time difference. In both panels a very clean π^0 peak is seen centered, within the experimental precision, at the $m_{\pi^0}^2$ position. The background is small and slowly varying and two-pion production can be clearly excluded. In total more than 5400 events of the $pp \to \{pp\}_s\pi^0$ process were identified.

In order to extract the differential cross section, the value of the integrated luminosity is needed. This was determined by measuring elastic pp scattering in parallel with other reactions and then comparing the resulting yield with that deduced from the SAID data base [17]. The measured $pp \to \{pp\}_s\pi^0$ differential cross section is shown as a function of $\cos^2\theta_\pi^{\mathrm{cm}}$ in Fig. 9.

Other results of the data analysis presented in Ref. [9] include distributions of the events over E_{pp}, which were found to be consistent with the pp final–state interaction parameterised in the Migdal–Watson approximation [18]. The angular distribution of the pp system in its rest frame was found to be consistent with isotropy, as expected for a ${}^1S_0$ state.

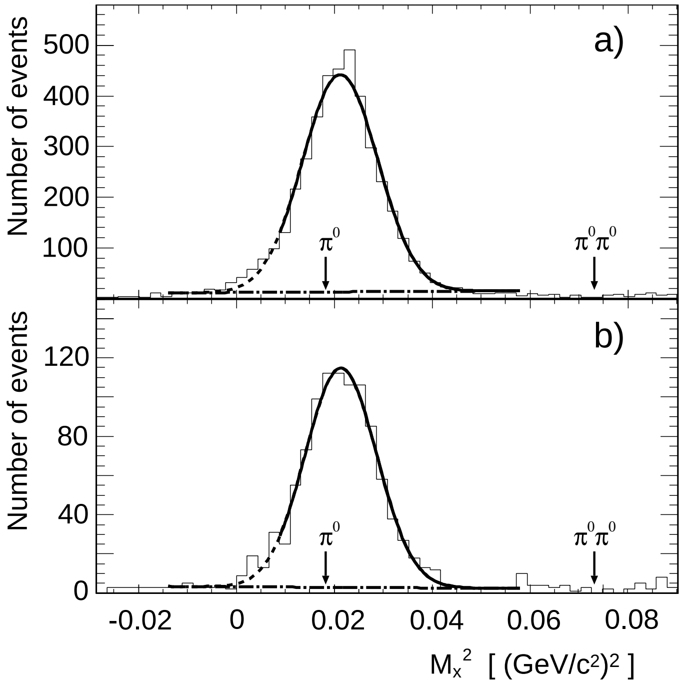


Figure 8: Distributions in the square of the missing mass for candidates for the $pp \to ppX$ reaction with excitation energy $E_{pp} < 3\,\text{MeV}$ when protons (a) hit different counters, and (b) the same counter. The reaction yield, obtained from fitting the data with a sum of Gaussian distribution and a constant background, is 4425 and 1008 π^0 events for cases (a) and (b), respectively.

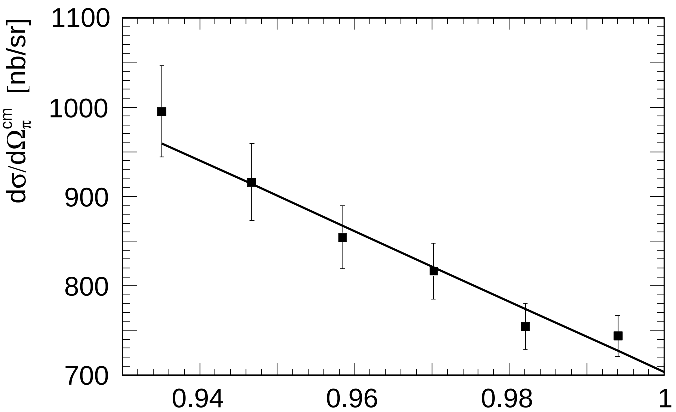


Figure 9: The measured $pp \to \{pp\}_s\pi^0$ differential cross section as a function of $\cos^2\theta_\pi^{\text{cm}}$ with the results of a straight–line fit.

In summary, the results presented in Ref. [9] confirm that the ANKE spectrometer is capable of detecting the $pp \to \{pp\}_s\pi^0$ reaction quite efficiently. The procedure of data analysis results in a clear identification of the process and allows the extraction of various distributions that can be compared with theoretical models.

3.5 Measurements with polarised beam

The procedure of measuring the proton analysing power has been developed and successfully applied earlier at ANKE in the experiment on the deuteron breakup reaction, $pd \to \{pp\}_s n$, with high momentum transfer at a proton beam energy of 500 and 800 MeV [19]. It is crucial to note that this process has a much smaller cross section than that of $pp \to \{pp\}_s\pi^0$.

The spin–dependent yield of the reaction is

$$Y_{\uparrow(\downarrow)}(\theta,\phi) = Y_0(\theta)\left[1 + P_{\uparrow(\downarrow)}A_y(\theta)\cos\phi\right], \tag{3.4}$$

where Y_0 denotes the spin-averaged yield, $P_{\uparrow(\downarrow)}$ is the beam polarisation oriented along the vertical y axis, and the polar and azimuthal angles, (θ,ϕ), are defined by the di–proton momentum in the cm system.

Due to absence of left–right symmetry in the ANKE spectrometer, a vector analysing power cannot be measured through the left–right count–rate difference. In order to measure A_y, data have to be taken with both directions of the beam polarisation. The analysing power is then obtained from

$$A_y(\theta) = \frac{\epsilon(\theta)}{P}\frac{1}{\langle\cos\phi\rangle}, \tag{3.5}$$

where $P = (P_\uparrow + P_\downarrow)/2$ and $\epsilon(\theta)$ is given by

$$\epsilon(\theta) = \frac{N_\uparrow(\theta) - N_\downarrow(\theta)}{N_\uparrow(\theta) + N_\downarrow(\theta)}. \tag{3.6}$$

Here $N_\uparrow$ and $N_\downarrow$ are the numbers of events obtained for opposite directions of the beam polarisation and weighted by the relative luminosities for the corresponding beam polarisation orientation.

The beam polarisation P can be found by simultaneous detection of processes for which the analysing powers are known. In the beam energy range of interest, $350 \leq T_p \leq 950$ MeV, the most suitable reactions for the ANKE conditions are elastic pp scattering and the $pp \to d\pi^+$ reaction. Values of the corresponding cross sections and analysing powers are available from the SAID data base [17].

If there are conditions where the SAID data are less precise, the polarisation export technique [20] could be applied. This method, already successfully used at ANKE [19], consists in arranging the accelerator cycle with alternate energy flat tops. Flat–top–*1* and flat–top–*3* are set for an energy where there is a reliable calibration process. The intermediate flat–top–*2* is set for the energy where the calibration data are less precise or missing. Provided that there is no depolarisation during the crossing of the resonances, the beam polarisation will be preserved for all flat tops. The polarisation at the intermediate energy can then be obtained from the data collected at flat–top–*1* and –*3*.

4 Beam time request

Based on arguments presented in Section 2, we plan to measure the differential cross section and the associated analysing power of the $pp \to \{pp\}_s\pi^0$ reaction at the proton beam energies $T_p = 350$, 500, 600, 700, 800 and 950 MeV. The highest energy point has been chosen in order to have a link with the data on the deuteron breakup reaction $pd \to \{pp\}_s n$ measured at this energy at ANKE [21].

To estimate the beam time required, we take the luminosity value L resulting from the number of stored polarised protons in the ring 6×10^9 and the hydrogen cluster target thickness $3 \times 10^{14}\,\mathrm{cm}^{-2}$. This gives $L \approx 2 \times 10^{30}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$. The beam polarisation is assumed to be $P = 0.5$. We then use theoretical estimations of the differential cross sections [6] and analysing power A_y [7]. To establish the angular dependence, sufficient statistics have to be accumulated in at least 5-6 bins within the accessible $\theta_{pp}^{\mathrm{cm}}$ angular acceptance. Taking into account the known detector acceptance and efficiency, the planning of the beam requirements for different energies looks as follows:

Beam energy (MeV)	Beam time (days)
350	3
500	4
600	2
700	2
800	1.5
950	1.5
Total	14

Such exposition would allow to measure A_y in each angular bin with an absolute precision of $\sigma(A_y) = 0.06 - 0.08$ on average.

In order to fulfill the planned measurements, the total request of this Proposal is **TWO weeks** of beam time with a polarised proton beam of energies from 350 to 950 MeV.

In summary, the experiment proposed here can provide completely new data on the energy dependence of the cross section and analysing power for the single pion production process in pp collisions in an energy range below, through, and above that of the Δ excitation. The selection of the $^1S_0$ di–proton final state greatly simplifies the amplitude analysis. At low energies the proposal is part of our stated long–term programme [2] to provide data of relevance for ChPT studies. At higher energies it is expected that our results will contribute to the study of reaction dynamics at medium energies and, in particular, to the role of the P–wave Δ–nucleon interaction.

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