Nucleon-Nucleon Final State Interactions in Single Pion Production

Proposal by the ANKE group for an experiment at the COSY accelerator.

Abstract

As part of the commissioning and calibration process of the ANKE spectrometer, it is proposed to perform angle and momentum measurements of pions emitted from the $pp \to \pi^+ d$ reaction in the forward direction. Combining these measurements with those of $NN \to \pi NN$, studied both inclusively and with two particles in coincidence, should give new information on the spin/isospin structure in pion production leading to low mass NN pairs.

1 Proposition & Perspective

It is proposed first to measure the angle and momentum of the pion, emitted in the two-body

$$pp \to \pi^+ d \tag{1}$$

reaction, in a small angular region around $0°$ as a function of beam energy in the range $300 \le T_p \le 800$ MeV. This experiment is required for the commissioning and calibration of different elements of the ANKE forward angle facility in a high count-rate experiment.

It is secondly proposed to study the two charged particles corresponding to the three-body reaction

$$pp \to \pi^+ pn\,, \tag{2}$$

at 450 and 550 MeV, by measuring well the pion variables and merely insisting that a proton be identified in coincidence. Especial emphasis will be placed on the region of low np excitation energy, i.e. the near-forward quasi-two-body reaction, where the normalization of the cross section can be achieved using the single-arm $pp \to \pi^+ d$ data, which are taken under very similar kinematic conditions. In this region the S-wave final state interaction (fsi) between the two nucleons is very strong, and it is this special choice of kinematics which distinguishes the experiment from many of the earlier ones. The data will allow us to deduce the ratio of the pion-production cross sections leading to spin-singlet and triplet final np pairs in the fsi peaks.

Similar physics information can be obtained by measuring well the proton and gating instead on the existence of the pion around 0°. Since the two analyses should give rise to identical cross sections, a comparison of the approaches will provide a deeper understanding of our apparatus.

Depending upon the experience gained with the present experiment, we intend to propose at some future date:

a) The measurement of both protons from the

$$pp \to pp\,\pi^o \tag{3}$$

reaction, again with priority being placed on the two protons lying in the S-wave fsi peak. The comparison of this and the $pp \to \pi^+ pn$ cross sections would yield an independent measurement of the singlet/triplet ratio in the final two-nucleon system.

b) The quasi-free production of π^- on the neutron in the deuteron,

$$pd \to \pi^- pp(p_s)\,, \tag{4}$$

where p_s is an unobserved low energy spectator proton. This is the third independent isospin cross section. The combined investigation of the three reactions 2–4 as functions of beam energy in the NN fsi region should show quantitatively the dominance of the Δ at $T_p = 600$ MeV together with the increasing importance of the N^*'s at 750 MeV. Investigations in the limited kinematic region proposed are the natural extension of work on the forward-angle $pp \to \pi^+ d$ reaction, which has been so influential in the understanding of pion production.

These experiments are well suited to the design characteristics of ANKE and could have future continuations through the use of polarised beam and target. One advantage of the ANKE geometry is that in the forward direction the initial spin correlations are automatically transferred to the final NN system.

A successful study of two-baryon systems at low excitation energy in pion production would raise the possibility of investigating low energy hyperon-nucleon interactions through the corresponding kaon-production reactions

$$\begin{array}{lll} pp \to K^+ p\,\Lambda & & \\ & \searrow & \\ & & p\pi^-\,, \end{array} \tag{5}$$

and similarly

$$pd \to K^+ d\,\Lambda\,. \tag{6}$$

The use of polarised beam and target in these, and the analogous Σ-production experiments, in addition to providing more information on the reaction mechanism, could also yield valuable constraints on the hyperon-nucleon (deuteron) spin-spin interactions.

The proposed studies will therefore

1. provide the necessary experience with and calibration of ANKE,
2. give valuable information on the spin/isospin structure in pion production leading to low mass NN pairs,
3. allow us to envisage continuations through the use of polarised particles and/or the detection of strange particles.

2 Physics Motivation

The ANKE spectrometer was conceived for the study of nuclear reactions where one or more charged particles are produced at medium energies close to 0°. The eventual use of polarised beams and targets is foreseen. This facility must be well tested and calibrated before being used for the accepted experiments on sub-threshold K^+ (COSY #18) and K^- production (COSY #21), both of which have low counting rates and high backgrounds.

The standard calibration reaction in our energy domain, of which we also wish to take advantage, is $pp \to \pi^+ d$. The cross section is high and its two-body kinematics gives rise to a secondary pion beam with a well defined momentum. The known values of the cross sections from the literature also provide a reliable normalization for the data [1].

Some of the cross sections for pion production leading to unbound nucleon-nucleon states are also large, in particular $pp \to \pi^+ pn$. Of especial interest are those parts of phase space where the two final nucleons emerge with low relative energy since they are then subject to a strong final state interaction (fsi). This is the natural generalisation of the $pp \to \pi^+ d$ experiment and the ANKE set-up is ideally suited for observing the resulting small opening angles associated with such reactions.

In several experiments only the π^+ from the $pp \to \pi^+ pn$ reaction was detected, as for example at 400 and 450 MeV [2], 420 and 500 MeV [3], 600 MeV [4], 800 MeV [5], and 1000 MeV [6]. However only the TRIUMF data, which were taken at low energies and large angles [2], allow a reasonably clean separation of the three-body reaction from that of the two-body deuteron peak.

Such data can be analysed [7] within the framework of microscopic reaction models based on one-pion-exchange taken in conjunction with the standard Watson formulation [8] for the np fsi, as was done for example in [9]. As can be seen from Fig. 1, such calculations can give a satisfactory description of the $pp \to \pi^+ pn$ experimental data providing that the spin-singlet np fraction is about one third of the total, essentially independent of energy in the 400 – 1000 MeV range. However these calculations have difficulty reproducing $pp \to pp\pi^\circ$ data, where the fsi region is pure spin-singlet . Moreover, they have not been calibrated on the known $pp \to \pi^+ d$ information.

A more robust approach is to use rather a simple fsi theory which depends

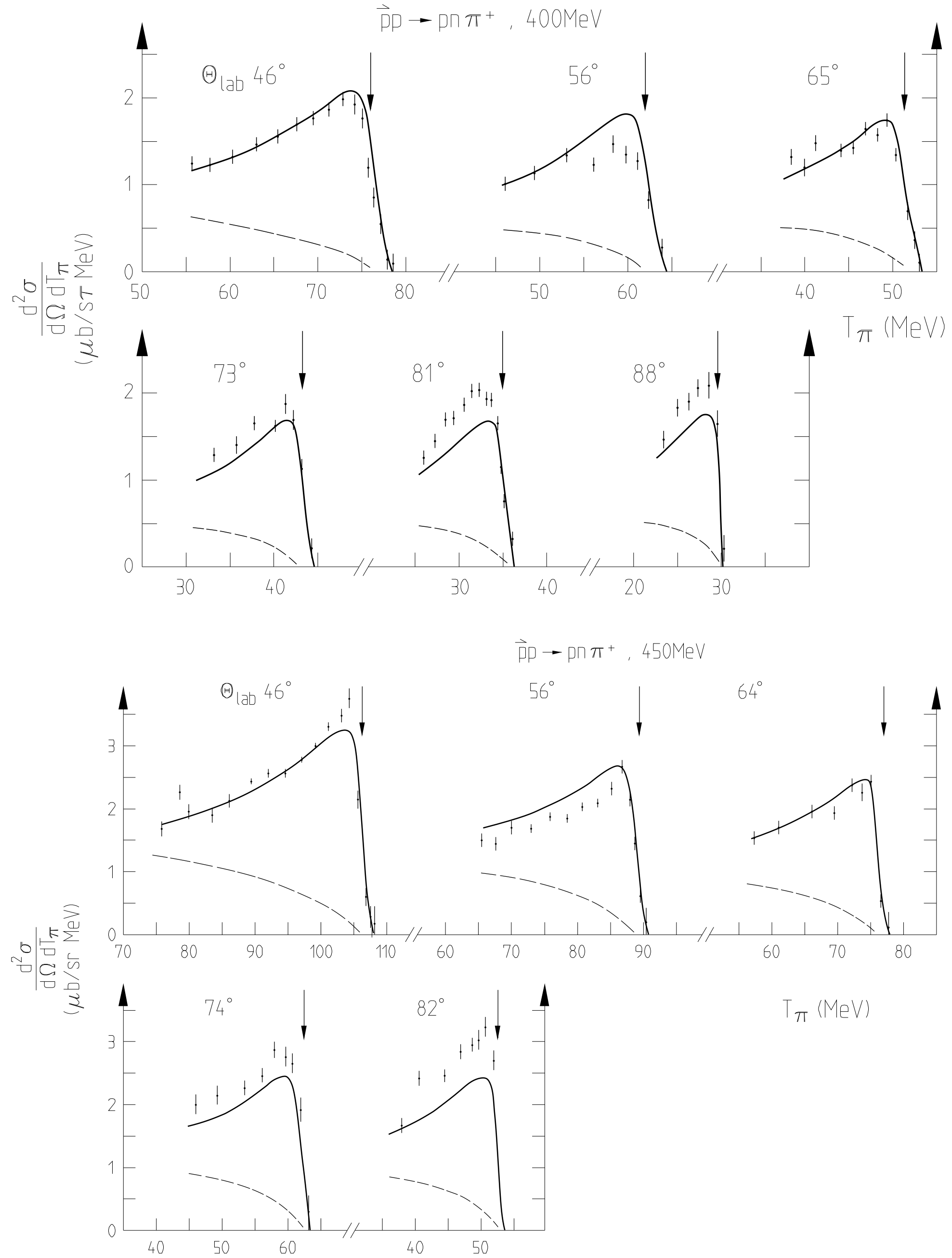

Figure 1: Laboratory differential cross sections for $pp \to \pi^+ pn$ as functions of pion energy and angle taken from [2]. The dashed curves are one-pion-exchange-model calculations, whereas the solid ones include a Watson fsi enhancement [7] with a fixed 33% singlet contribution. The arrows indicate the position of pions from the reaction $pp \to \pi^+ d$.

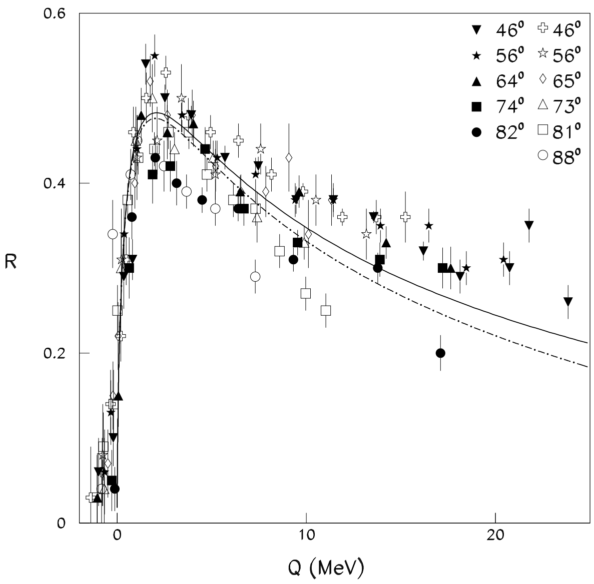

Figure 2: The ratio $R = 2\pi\epsilon \, \frac{\mathrm{d}^2\sigma}{\mathrm{d}\Omega_\pi \mathrm{d}Q}(pp \to \pi^+\{np\}) \Big/ \frac{\mathrm{d}\sigma}{\mathrm{d}\Omega_\pi}(pp \to \pi^+ d)$ of experimental cross sections, where Q is the np excitation energy and ϵ is the deuteron binding energy. The data are taken from [2] at 450 MeV (closed symbols) and 400 MeV (open symbols). Providing the interaction is of short range then the final S-wave triplet np state is expected to contribute to this ratio an amount [10] $R = \frac{p(\pi^+ pn)}{p(\pi^+ d)} \frac{\sqrt{x}}{1+x}$, where $x = Q/\epsilon$. The dashed curve corresponds to 400 MeV, the solid to 450 MeV, the difference being due to the variation of the ratio of the pion cm momenta p in the two reactions as a function of beam energy.

weakly upon the model assumptions [10]. This shows that the final np S-wave spin-triplet spectrum may be predicted quantitatively knowing the cross section for $pp \to \pi^+ d$. Shown in Fig. 2 is the ratio of cm cross sections as a function of Q, the np excitation energy. Due to kinematic effects, the data at the largest angles at the two energies are more affected by resolution problems in Q, leading to difficulties in isolating the two-body deuteron peak used for cross section normalization. The agreement of the 400 and 450 MeV data [2], for laboratory angles less than 80°, with the predictions of this approach shows that at low Q the fraction of final T=1, S=0 np pairs is 10% or less at these energies [2]. This figure is much less but more reliable than the results of microscopic calculations [7].

In experiments at higher energies the energy resolution is worse, but the application of the model to experimental data shows that the fraction of singlet final states is around $(20 \pm 5)\%$ at $T_p = 600$ MeV [4] and at 1000 MeV it has risen to about $(30 \pm 5)\%$ [6].

This steady increase in the importance of low mass spin-singlet np states with beam energy is confirmed through the study of the inverse reaction in pion absorption in ^{3}He [11]. The $\pi^- \,{}^3\text{He} \to np\,n_s$ reaction, where n_s is a low energy neutron spectator, corresponds to the capture on a low energy proton-proton pair in the nucleus, whereas $\pi^+ \,{}^3\text{He} \to pp\,p_s$ must be associated with an interaction on a neutron-proton pair. The latter cross section, which may be as much as a factor of 20 larger than the former, shows a typical Δ peak. The energy variation of the $\pi^-(pp) \to np$ reaction on the other hand is much wider, such that above the Δ region the T=1, S=0 absorption becomes significant, possibly reflecting the importance of N^* resonances.

It would clearly be far better if the energy variation of this important singlet/triplet ratio were deduced from clean $NN \to \pi NN$ measurements rather than absorption experiments in ^{3}He, where the presence of an extra nucleon clouds the interpretation. A systematic study of $pp \to \pi^+ pn$ as a function of energy in a single experiment would allow the determination of the evolution of the ratio for quasi-two-body production throughout the Δ and into the N^* region.

With excellent energy resolution ($\Delta Q < 0.3$ MeV), it would be possible to distinguish between the production of singlet and triplet fsi peaks by their different shapes, but our expected resolution in np excitation energy is typically 3 MeV (FWHM) at 550 MeV. Under such conditions, to isolate the three-body reaction from that of $pp \to \pi^+ d$, it would be of great advantage to detect the proton in coincidence. Several experiments have been published on the $p(p,\pi^+ p)n$ reaction in the COSY energy domain [9, 12], though none of them in the ANKE forward-angle geometry. In order to use the $pp \to \pi^+ d$ reaction for cross section normalization in the low Q region, our primary measurement would be on the pion, with a relatively loose gate on the proton solely to establish its presence. It is mainly for testing and calibration purposes that we will afterwards investigate the identical cross section by looking at the information on the angle and momentum of the proton and gating it by demanding the presence of a pion.

Apart from Coulomb corrections, which are important at very low values of

Q, the cross section for the production of $(I=1, S=0)$ np pairs in the S-wave fsi peak is related to that for pp pairs through isospin invariance,

$$\frac{d\sigma}{d\Omega_\pi dQ}(pp \to \{pn\}_{I=1}\pi^+) = \frac{d\sigma}{d\Omega_\pi dQ}(pp \to \{pp\}\pi^\circ)\,.$$

Since, as we have seen, such singlet production is small compared to the triplet at low beam energies, there are great advantages in measuring it directly rather than making a $pp \to \pi^+ pn/pp \to \pi^+ d$ subtraction using fsi theory. The identification of the fsi peaks in the $pp \to \pi^+ pn$ and $pp \to pp\pi^\circ$ reactions with good energy resolution involves very different experimental conditions and is subject to different systematic effects. An eventual study of both reactions would lead to useful tests of our understanding of the ANKE spectrometer. Moreover the combined results, taken in conjunction with those from $pp \to \pi^+ d$, would provide valuable cross-checks in any subsequent analysis.

There have been measurements of the two protons in the $pp \to pp\pi^\circ$ reaction [13], but most experiments in the COSY energy region have determined the angular and energy distribution of the π° by detecting the two decay photons with rather modest resolution [14, 15]. Though the major emphasis in the published works has been placed on total cross sections, the restricted energy information at 450 MeV [14] is consistent with a singlet/triplet ratio of about 5%, though this analysis is model dependent. The figure is however in accord with the 10% upper limit established through the fsi approach [10].

The calibration and normalization of the proton detection for a $pp \to pp\pi^\circ$ measurement will be carried out in the initial charged pion experiment. It should of course be noted that in the fsi peaks the two protons from the reaction will fall on the same part of the detection system as the one proton from the $pp \to \pi^+ pn$ production.

A third independent, but much more demanding, production cross section to consider for the future is that for

$$np \to \pi^- pp\,. \tag{7}$$

It is possible to deduce from this the cross section σ_{01}, corresponding to an initial $I=0$ NN pair leading to an $I=1$ pair, through the isospin relation

$$\sigma_{01} = 2\sigma(np \to pp\pi^-) - \sigma(pp \to pp\pi^\circ)\,.$$

From a comparison of np [16, 17] and pp [15] total cross section measurements, it is seen that σ_{01} is the smallest of the three isospin cross sections at medium energies. The neutron-induced data in the pp fsi region are of rather limited quality [18], though attempts have been made at 0° with the TRIUMF SASP spectrometer [19]. However this region has been investigated in some detail in an ingenious experiment at TRIUMF, where all three fast charged particles from quasi-free production in deuterium were measured, leaving only an unobserved spectator proton (p_s) [20]. By performing kinematic fits it is then possible to identify the $d(p,\pi^- pp)p_s$ reaction, and hence that for $pn \to \pi^- pp$, and also deduce better information on the pn cm energy than merely spreading the result over the whole Fermi motion. We only want to mention here that the $np \to \pi^- pp$ reaction has also been successfully studied for backward-going pions at much higher momenta ($p_\pi = 1.98$ GeV/c) with good resolution on the pp pair [21].

To complete the measurements of the NN fsi peaks in pion production, it is attractive to consider studying this reaction in the ANKE forward angle small-Q geometry. We realise however that the conditions for such an experiment can only be established once the experiments involving two-particle detection have given good results.

3 Experimental Programme

In the initial experiment we wish to measure with the ANKE system π^+ with momenta of a few hundred MeV/c produced by the $pp \to \pi^+ d$ reaction. This will then be extended to the study of pion-proton coincidences resulting from the $pp \to \pi^+ pn$ reaction.

3.1 The ANKE Setup

The design for the magnetic spectrometer ANKE, whose layout is shown in Fig. 3, comprises a main magnet D2 and a detection system which in 1997 will consist of TOF-start counters, multiwire proportional chambers (MWPC), stop telescopes placed close to the focal plane in the side direction and optimised for the detection of kaons with momenta below 600 MeV/c, and the side hodoscope designed principally for the observation of protons and deuterons in coincidence with kaons measured in the side detector. The first-level trigger signal is derived from the TOF spectra between one stop counter in the side telescopes and the relevant start counters (coincidence matrix).

3.2 Commissioning and Calibration with a Solid Target using the $pp \to \pi^+ d$ Reaction

Positive pions produced in the $pp \to \pi^+ d$ reaction in the forward direction are the best particles to be used in most of this commissioning because

- The two-body kinematics gives a secondary pion beam of known momentum which, for fixed beam energy, varies very slowly with angle close to $0°$ [$\Delta p/p \leq 0.15\%$ for $\theta_\pi^{\rm lab} \leq 2.5°$, rising to three times this for $\theta_\pi^{\rm lab} \leq 5°$],
- In the energy range $450 \leq T_p \leq 1000$ MeV the cross sections are well known with typical accuracies of $\pm 10\%$ [1],
- The cross sections vary slowly with pion laboratory angle near $0°$, typically only 1-2% per degree, and so an uncertainty of less than 10% is introduced by integrating over an angular cone with $\theta_\pi^{\rm lab} \leq 5°$,
- The cross sections are sufficiently high to give good count rates.

The principal technical goals are to commission and calibrate the complex ANKE system. Since during the proposed measurements the target, spectrometer magnet D2 and the detection system will be set up identically as for the

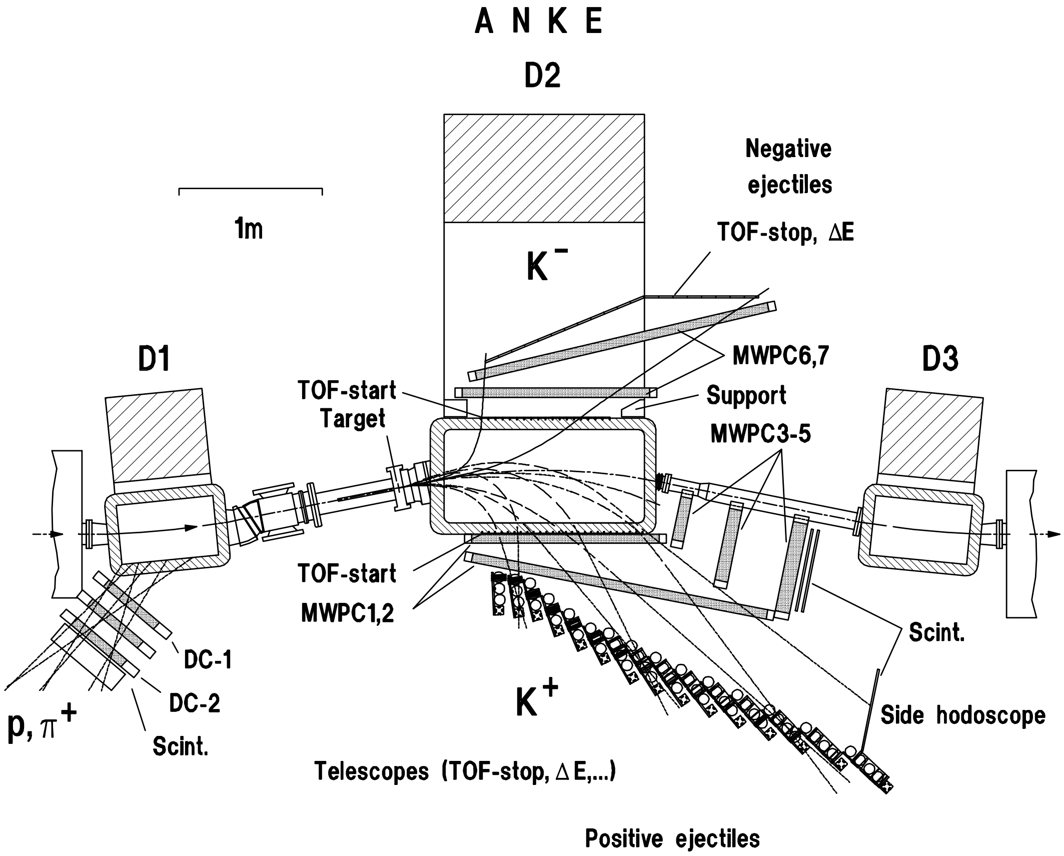

Figure 3: The ANKE detection system showing the TOF-start counters, the telescopes for K^+ detection and the side hodoscopes which will be in place for the 1997 run. The planned positions of the forward, backward and negative particle detectors are also indicated.

measurements on K^+ production, the information which shall be obtained from the calibration measurements will directly serve as a basis for the analysis of the data on kaon production. In particular the main goals of the calibration measurements are:

- To investigate the time resolution δt and study the tails of the time distribution far-off the peak maximum ($\pm 10\,\delta t$),
- To check ray-tracing with the help of the MWPC's,
- To measure the angular and momentum acceptances of the side telescopes,
- To establish the momentum resolution $\Delta p/p$ of the ANKE spectrometer,
- To investigate the normalization constants of the spectrometer and test appropriate monitors.

It is important to note that the peak of the two-body reaction is sufficiently large and clean to allow for these measurements the use of a solid CH_2 instead of a pure hydrogen target. This will not only simplify the experiment but also lead to higher luminosities. For a foil with a minimal thickness of 100 μg/cm^2, containing 10^{19} H/cm^2, and 10^9 protons circulating at 10^6 turns per second, the luminosity will be $10^{19} \times 10^6 \times 10^9 \times 0.01 = 10^{32}$ cm^{-2}s^{-1}, if 1% of each burst passes through the target.

In the region of the pion peak in $pp \to \pi^+ d$ reaction the background of π^+ coming from the carbon will be 20% or less, as is illustrated by the data at 450 MeV shown in Fig. 4. The continuum also varies smoothly with momentum and so it will be possible to accomplish most of the calibrations even without a carbon-background subtraction.

The TOF system will be precalibrated off beam with pulsed light sources and with radioactive sources. This calibration will be verified for some selected telescopes through the measurement of pions from the $pp \to \pi^+ d$ reaction. At medium energies, pions with laboratory angles less than about 10° will hit one of the telescopes in the side detectors, see Table 1. This telescope number is defined by the energy of the proton beam and the field strength in D2. Thus variation of the proton-beam energy allows to select a certain telescope. Examples of the pion trajectories at 300, 450, 700 and 1200 MeV are shown in Fig. 5. The count rates and background effects expected, in the momentum region of the

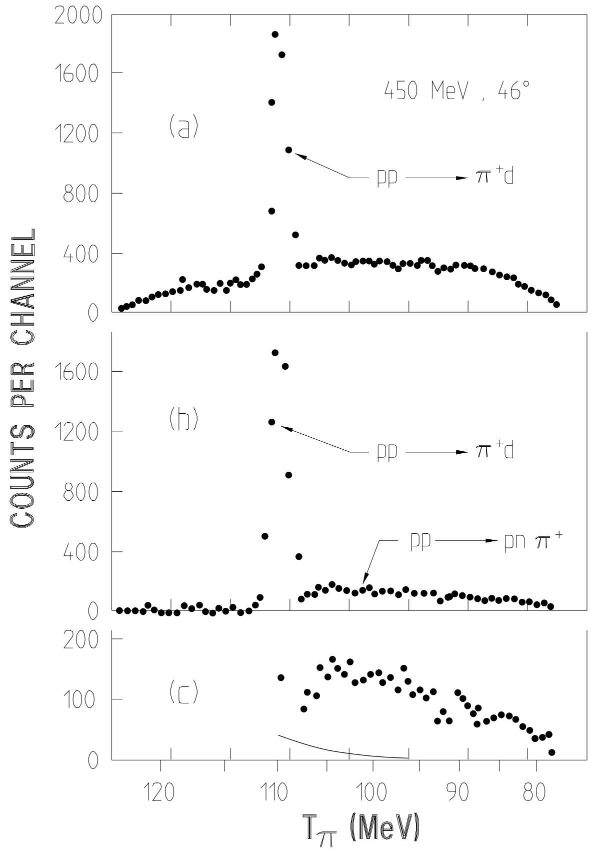

Figure 4: (Taken from [2]) (a) Pion spectrum from a CH_2 target recorded at 46° (lab) at $T_p = 450$ MeV. The continuum to the left of the $pp \to \pi^+ d$ peak arises from the carbon in the target; that to the right, from carbon and the $pp \to \pi^+ pn$ reaction. (b) Spectrum after subtraction of the tails on the peak response function and subtraction of the carbon background. (c) Low energy region of (b) on an expanded scale. The solid line shows the magnitude of the low energy tail subtracted.

$pp \to \pi^+ d$ peak, for a CH_2 target with a luminosity of 10^{32} cm^{-2}s^{-1} are also given in Table 1.

Table 1: Count rates and carbon background with a polyethylene target. For each beam energy the the pion momentum and the number of the telescope $(1 \ldots 15)$ or side hodoscope $(16 \ldots 21)$ which can be calibrated with the pion beam from the pp reaction is indicated. The field strength in dipole D2 is choosen such that in all cases the radius of curvature of the circulating COSY beam is 4.05 m as it will also be during the measurements on K^+ production.

T_p (MeV)	$\frac{N(H_2)}{N(C)}$	$N(H_2)$ (π^+/s)	p_π (MeV/c)	Field strength (T)	# of counter
300	1.0	90	97	0.665	4
400	6.4	1200	223	0.785	11
500	11.3	2500	319	0.897	14
600	12.5	3000	411	1.003	16
700	7.8	1800	501	1.105	17/18
800	4.3	1300	591	1.204	19/20

For a given energy, say 450 MeV, trajectory calculations indicate that the π^+ peak from the $pp \to \pi^+ d$ reaction should appear in telescope N^{o}12. Hence in telescope N^{o}13 there should only be a π^+ background from carbon, whereas in N^{o}11 there should be this plus pions from the three-body $pp \to \pi^+ pn$ reaction, as illustrated in Fig. 6. If the pion peak is well centred in telescope N^{o}12, then we expect the counts to be in the ratio $N_{11} : N_{12} : N_{13} \approx 0.25 : 1.0 : 0.15$.

The proposed measurements discussed in this section will allow to determine the properties of the spectrometer magnet D2 (angular and momentum acceptance) and to test the raytracing procedures. Furthermore, the TOF counters and the corresponding fast trigger can be calibrated. The full efficiency of the side telescopes for K^+ mesons will be tested in a later experiment using kaons produced with a much higher proton beam energy ($\approx$ 1500 MeV).

3.3 Study of the $pp \to \pi^+ pn$ Reaction

We are also interested in $pp \to \pi^+ pn$ events, and to study these an additional measurement with a carbon target will be necessary. Since the targets are thin ($\leq$ 1 mg/cm^2), the pion and proton energy losses are very small ($\Delta E/E \leq 10^{-5}$)

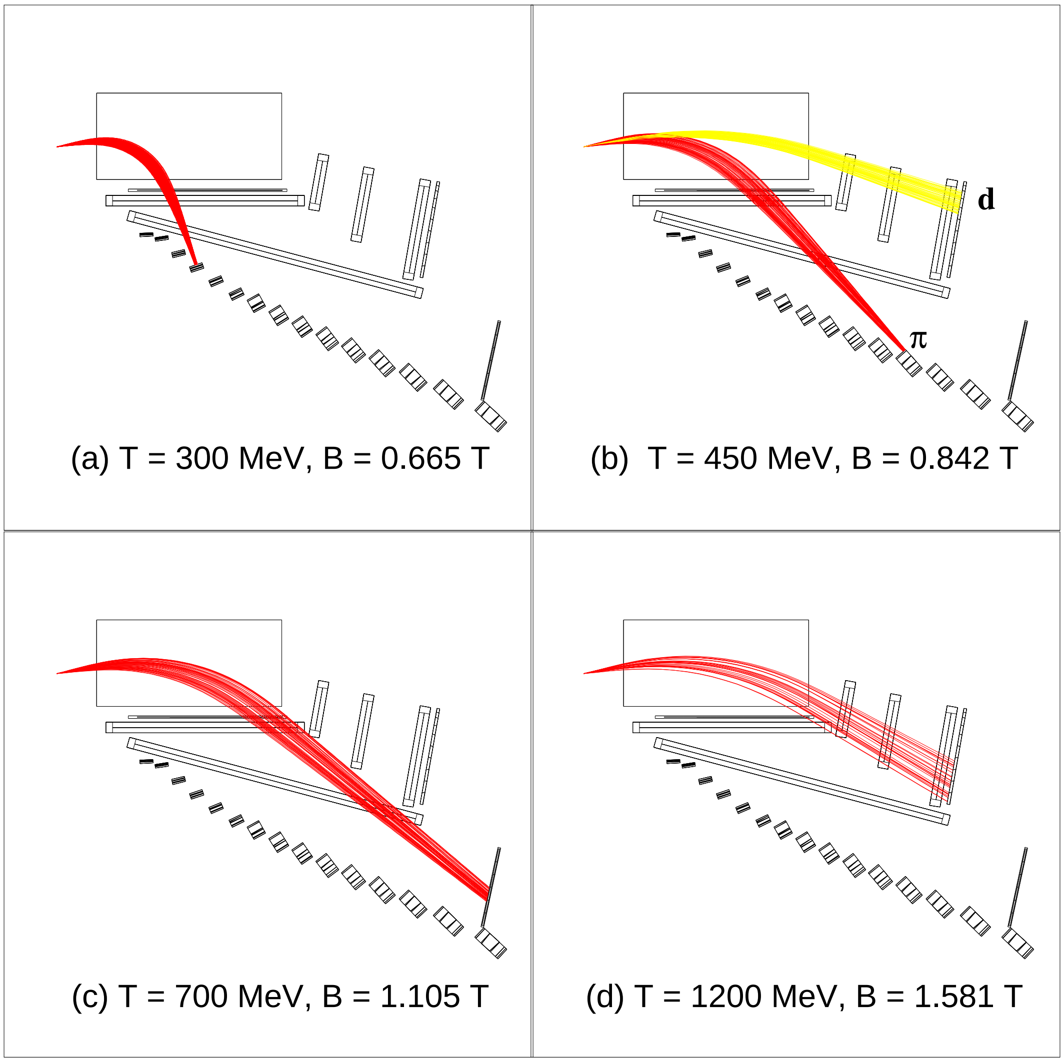

Figure 5: Pions from the $pp \to \pi^+ d$ reaction will fall on different elements of the ANKE detection system, depending upon the proton beam energy. This is illustrated at 300 MeV (a), 450 MeV (b), 700 MeV (c), and 1200 MeV (d). Additionally at 450 MeV the trajectories of coincident deuterons are shown hitting the forward detector. Note the absence of focussing in this case. These deuterons can be used for the commissioning of the forward detectors as soon as it will be available.

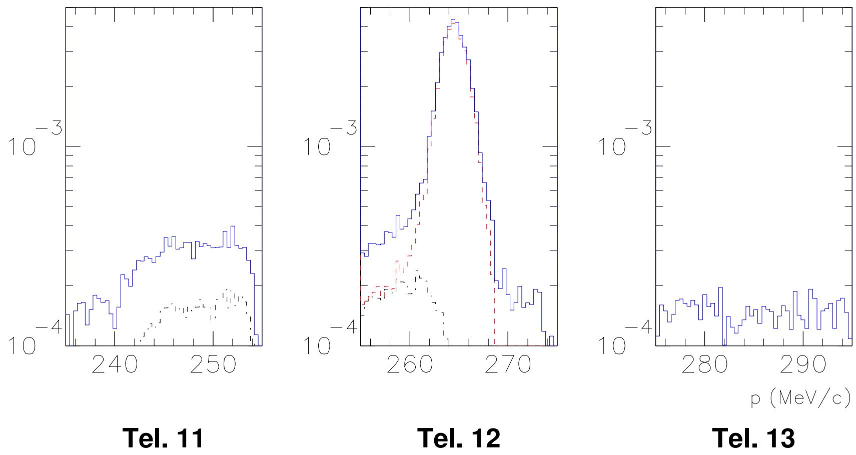

Figure 6: Simulated momentum spectra for pions produced in p(CH_2) collisions at 442 MeV for telescopes N^o 11–13 (solid line). The contributions from the $pp \to \pi^+ d$ (dashed line) and $pp \to \pi^+ pn$ (dashed-dotted line) reactions are indicated.

and so it is not necessary to make identical C and CH_2 targets. The pion spectra from the two targets, above the momentum corresponding to the free $pp \to \pi^+ d$ reaction on hydrogen (the left hand side of the pion peak in Fig. 4a) can be normalised relative to each other.

The CH_2/C subtraction will yield the pion spectra for the $pp \to \pi^+ d$ and $pp \to \pi^+ pn$ reactions consistently normalised, but with count rates for the three-body process in the fsi region about a factor of 10 – 20 less than the corresponding two-body rates. Due to the 1% momentum resolution, the fsi part of the pion spectrum coming from $pp \to \pi^+ pn$ will be smeared and partially hidden under the $pp \to \pi^+ d$ peak, as can be seen in the examples shown in Fig. 7.

One advantage of the ANKE spectrometer is the possibility of detecting all the charged particles escaping from the target region with angles less than about 10°, and in particular the protons from the $pp \to \pi^+ pn$ reaction in the fsi region. Such protons are forward-going with momenta p_p essentially one half of the momentum p_d of the deuterons from the $pp \to \pi^+ d$ reaction. If a proton in the momentum range

$$0.9\,\frac{p_d}{2} \leq p_p \leq 1.1\,\frac{p_d}{2}$$

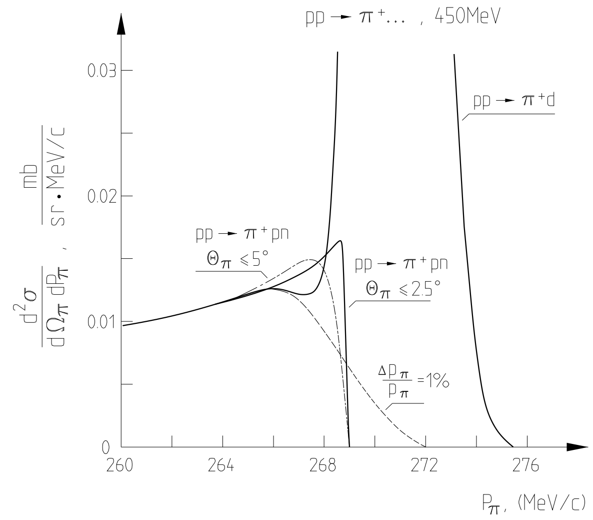

Figure 7: Expected pion spectrum in the $pp \longrightarrow \pi^+X$ reaction at 450 MeV showing the dominance of the deuteron peak at the high momentum edge of the spectrum. The influence of imposing different pion angular cuts is shown but these are largely washed out if the pion momentum resolution is 1% or more.

is demanded in coincidence with the pion, then the large two-body peak is eliminated from the pion spectrum, leaving the three-body part of the spectrum largely undisturbed because around 0° the geometric acceptance is essentially 100% for protons. As a consequence the normalization relative to the known $pp \longrightarrow \pi^+d$ cross section will be left intact and, as discussed in §2, this is vital for the estimation of the relative np singlet/triplet production rates.

On the other hand, if we look for the spectrum of protons in coincidence with near-forward-going pions, then we should see a rather narrow fsi peak of the type shown in Fig. 8 at a momentum defined by the quasi-two-body fsi kinematics. This should again be normalised to the $pp \longrightarrow \pi^+d$ cross section, though it does depend on the pion detection efficiency and and/or luminosity. Presenting the data in this way will give useful cross-checks on our system.

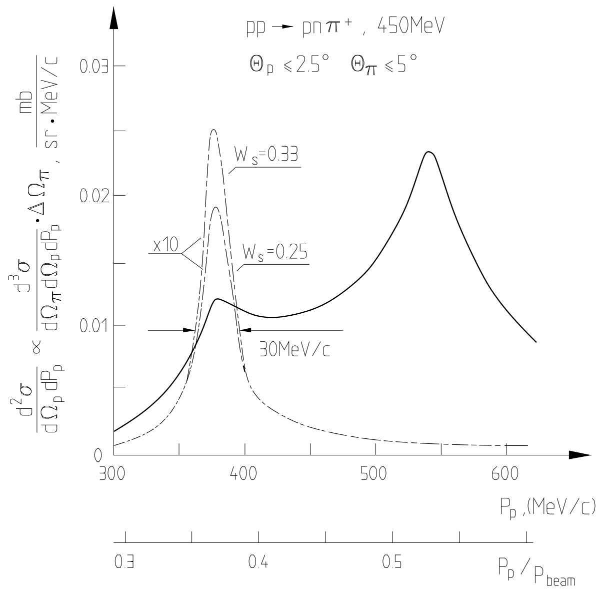

Figure 8: Predicted momentum spectrum of protons from the $pp \rightarrow \pi^+ pn$ reaction with the proton detected near the forward direction. Solid line corresponds to not requiring a pion coincidence. The dashed-dotted lines require a small angle pion in coincidence. The effect of different singlet/triplet ratios W_s is also shown.

4 Machine Requests

1) We request that machine development time be assigned immediately after the installation of ANKE to to ensuring that COSY functions well with ANKE with the beam passing through the target.

2) We request a total of 3 weeks beam time in the beam energy range $300 \leq T_p \leq 800$ MeV in 1997.

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