THE ANKE EXERIMENT

Overview

ANKE, a magnetic spectrometer and detection system at an internal target position of COSY, allows one to separate and momentum analyse ejectiles from the circulating COSY beam with forward emission angles around 0˚. Due to its large solid angle and wide momentum acceptance ANKE can be used for a variety of experimental studies. Outstanding results from ANKE in 2003 are:

1. First measurement of the K^+-production cross section in proton-neutron interactions,
2. Study of a_0^+-resonance production in *pp* reactions,
3. Measurement of ω and η-meson production in proton-neutron collisions,
4. Measurement of the proton-induced deuteron breakup

Further major technical developments for ANKE comprise:

a) The development of the atomic beam source for the polarized internal target has been finalized. This target will be used for double polarization experiments at ANKE.

b) The ANKE pellet target has produced droplets of frozen hydrogen and liquid nitrogen.

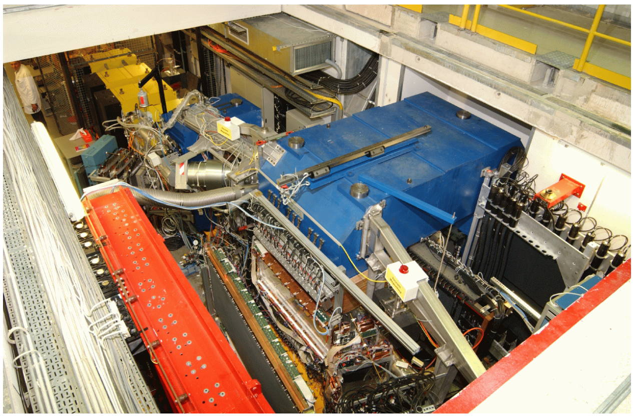

Fig.1: Photo of ANKE and the detection systems.

Strangeness Production in pp and pn interactions

The layout of ANKE, including detectors and the DAQ system, has been optimised and used to study K^+-spectra from proton-nucleus collisions at beam energies down to T_p = 1.0 GeV (p = 1.70 GeV/c), thus far below the free nucleon-nucleon threshold at T_{NN} = 1.58 GeV. This is a very challenging task because of the small K^+-production cross sections, *e.g.* 39 nb for *pC* collisions at 1.0 GeV. In subsequent measurements ANKE has been used to measure K^+-mesons in coincidence with protons and deuterons from $pn \rightarrow pK^+X$, $pp \rightarrow d\,K^+\,\overline{K}^0$, and $p^{12}C \rightarrow p/d\,K^+X$ reactions.

K^+-production in pn interactions

Data on the K^+-production cross section from *pn* interactions in the close-to-threshold regime are not available yet. This quantity is, for example, crucial for the theoretical description of proton-nucleus and nucleus-nucleus data since it has to be used as an input parameter for corresponding model calculations. Predictions for the ratio σ_n/σ_p still have large uncertainties, they range from one to six, depending on the underlying model assumptions.

K^+-production in proton-deuteron collisions has been measured with ANKE at two beam momenta, p = 2.60 and 2.81 GeV/c (see Fig. 2). Based on the assumption that the K^+-production cross section on the deuteron is governed by the sum of the elementary *pp* and the *pn* cross sections, *i.e.* $\sigma_D = \sigma_p + \sigma_n$, the experimental distributions have been simulated, treating the ratio σ_n/σ_p as a free parameter. Figure 2 shows the resulting momentum spectra for $\sigma_n = \sigma_p$, $2\sigma_p$, $3\sigma_p$ and $4\sigma_p$. The best agreement between data and calculations is obtained for $\sigma_n/\sigma_p \sim 3$ at 2.60 GeV/c and $\sigma_n/\sigma_p \sim 4$ at 2.81 GeV/c.

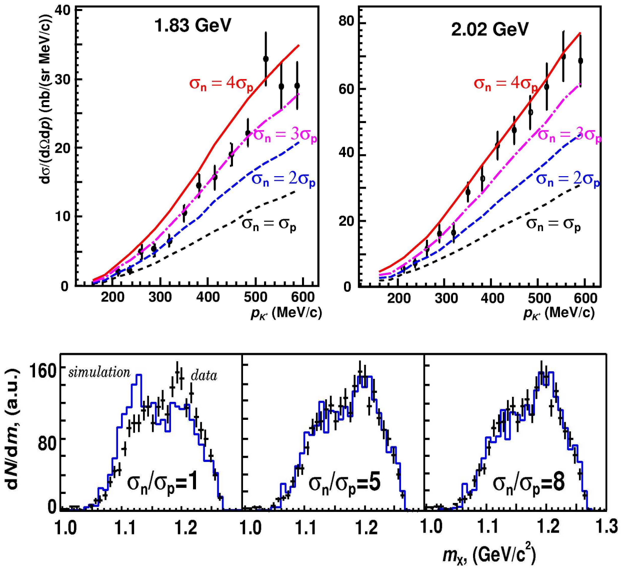

Fig. 2: Upper: Preliminary double differential $pD \rightarrow K^+X$ cross section at 2.60 and 2.81 GeV/c in comparison with model calculations using different ratios σ_n/σ_p (lines). Lower: Missing mass m_X for $pD \rightarrow K^+pX(p_{sp})$ events at p=2.81 GeV/c (preliminary) in comparison with model calculations.

The resulting large value of σ_n/σ_p from the inclusive spectra is supported by the analysis of missing-mass spectra from $pD \rightarrow K^+pX(p_{sp})$ events (where p_{sp} denotes the unobserved spectator proton) from the same beam time. The spectrum for 2.81 GeV/c is also shown in Fig. 2 and is compared with the result of the Monte-Carlo simulations, again for different ratios σ_n/σ_p. The best agreement between data and simulations is obtained for σ_n/σ_p ~(4–5).

Study of light scalar resonances

A primary goal of hadronic physics is to understand the structure of mesons and baryons, their production and decays, in terms of quarks and gluons. The non-perturbative character of the underlying theory – Quantum Chromo Dynamics (QCD)– hinders straightforward calculations. QCD can be treated explicitly in the low momentum-transfer regime using lattice techniques, which are, however, not yet in the position to make quantitative statements about the light scalar ($J^P = 0^+$) states. Alternatively, QCD inspired models, which use effective degrees of freedom, are to be used. The constituent quark model is one of the most successful in this respect. This approach treats the lightest scalar resonances $a_0/f_0(980)$ as conventional $q\bar{q}$ states. However, they have also been identified with $K\bar{K}$ molecules or compact qq-$\overline{qq}$ states. It has even been suggested that at masses below 1.0 GeV a full nonet of 4-quark states might exist. Such possible deviations from the minimal quark model have a parallel in the baryon sector, where the recently discovered Θ^+ state requires at least five quarks.

The existing data are insufficient to conclude on the structure of the light scalars and additional observables are urgently called for. In this context the charge-symmetry breaking (CSB) a_0-f_0 mixing plays an exceptional role since it is sensitive to the overlap of the two wave functions. It should be stressed that, although predicted to be large long ago, this mixing has not unambiguously been identified yet in corresponding experiments.

An experimental program has been started at COSY, which aims at exclusive data on a_0/f_0 production close to the $K\bar{K}$ threshold from *pp*, *pn*, *pd* and *dd* interactions - *i.e.* different isospin combinations in the initial state. The reactions $pp \to ppK^+K^-$ and $pd \to {}^3He\,K^+K^-$ have been measured at COSY-11 and MOMO, respectively, at excitation energies up to Q = 56 MeV above the $K\bar{K}$ threshold. However, mainly due to the lack of precise angular distributions, the contribution of the a_0/f_0 resonances to $K\bar{K}$ production remains unclear for these reactions.

During the first experiment which has been made at ANKE, the reaction $pp \to dK^+\bar{K}^0$ has been measured exclusively (by reconstructing the $\bar{K}^0$ from the measured dK^+ missing mass) at beam momenta of p = 3.46 and 3.65 GeV/c (Q = 46 and 103 MeV). These measurements crucially depend on the high luminosities achievable with internal targets, the large acceptance of ANKE for close-to-threshold reactions, and the excellent kaon identification with the ANKE detectors. The obtained differential spectra for the lower beam momentum are shown in Fig. 3.

The background of misidentified events in the spectra of Fig. 3 is less than 10%, which is crucial for the partial-wave analysis. This analysis reveals that the $K^+\bar{K}^0$ pairs are mainly (83%) produced in a relative *S*-wave (dashed line in Fig.3), which has been interpreted in terms of dominant a_0^+-resonance production.

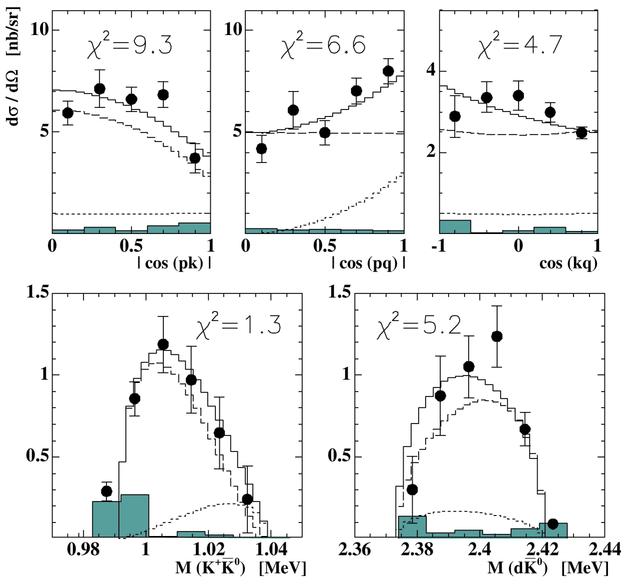

Fig. 3: ANKE data for the reaction $p(3.46\ \text{GeV/c}\}p \to dK^+\bar{K}^0$. The shaded areas correspond to the systematic uncertainties of the acceptance correction. The dashed (dotted) line corresponds to $K^+\bar{K}^0$-production in a relative *S*-(*P*-) wave and the solid line is the sum of both contributions.

Data on the reaction $pp \to d\pi^+X$ have been obtained at ANKE in parallel to the kaon data. In contrast to the latter, where the spectra are almost background free, the $\pi^+\eta$ signal is on top of a huge multi-pion background. This makes the analysis of this channel more demanding and at present even model dependent. A total cross section of $\sigma(pp \to d\pi^+\eta) \sim 4.6\ \mu b$ has been extracted from the data with a resonant contribution of $\sigma(pp \to da_0^+ \to d\pi^+\eta) \sim 1.1\ \mu b$. Together with the cross section for the $a_0^+ \to K^+\bar{K}^0$ channel this yields a branching ratio of B.R.($K\bar{K}/\pi\eta$) ~ ($0.029 \pm 0.005_{stat} \pm 0.02_{syst}$) which is in reasonable agreement with model calculations B.R.($K\bar{K}/\pi\eta$) ~ 0.04 for this beam momentum, thus confirming the interpretation of dominant resonant $K^+\bar{K}^0$ production via the a_0^+ .

The experimental results on a_0^+ production in *pp* interactions can also be regarded as a successful feasibility test for a longer experimental program with the final goal to determine the charge-symmetry breaking a_0-f_0 mixing amplitude. These measurements will require the use of a photon detector, which is not yet available at COSY. However, it is planned to relocate the WASA detector from its current location at CELSIUS/TSL to COSY in summer 2005, which will then make these experiments feasible.

Heavy hyperon production

Compared to the spectrum of nucleon resonances, the excitation spectrum of hyperons (Λ, Σ) is not well known. Of particular interest is the Λ(1405) where quark models have difficulties to explain its low mass, and which alternatively has been interpreted as a $\bar{K}N$ bound state. Precise data from hadronic interactions, in particular on the Λ(1405) mass distribution, are still lacking. The Σ(1480) is even less known, the Particle Data Group cites it as a "bump" with unknown quantum numbers.

The reaction $pp \rightarrow K^+pY$ has been measured with ANKE at maximum COSY momentum of 3.65 GeV/c. At this momentum six hyperons can be produced: Y = Λ(1116), Σ(1192), Σ(1385), Λ(1405), Σ(1480), and Λ(1520). They can be identified at ANKE by detecting events of the type $pp \rightarrow K^+p\pi^{\pm}X$, *i.e.* charged pions from the heavy hyperon decays (like $\Sigma(1480) \rightarrow \pi^{\pm}\Sigma^{\mp}$), in coincidence with K^+p pairs. Figure 4 shows the K^+p missing mass distribution for selected events with $m_X = m_\Sigma$.

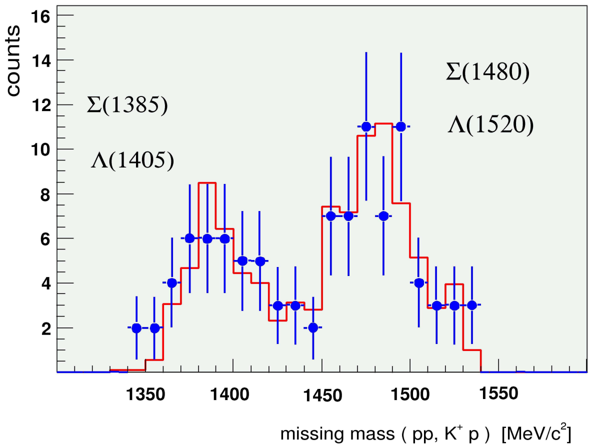

Fig. 4: Missing mass m_Y spectrum for the reaction $pp \rightarrow K^+pY$. The solid line shows the result of a Monte Carlo simulation with contributions of the indicated heavy hyperons.

Also shown in the Figure is the result of a Monte-Carlo simulation. Significant contributions of all four heavy hyperons are needed to reproduce the shape of the measured distribution. The best agreement between data and simulation is obtained for the Σ(1480) mass being equal to 1470 MeV.

Planned measurements of the Θ^+ pentaquark state

In Feb. 2004 a measurement will be performed at ANKE aiming at the detection of the recently discovered Θ^+ resonance with a mass of about 1540 MeV. It will be tested whether the Θ^+ can be detected in the reactions $pp \rightarrow K^0\, p\Lambda\pi^+$, $pp \rightarrow K^0\, p\Sigma^+$, and $pn \rightarrow K^0\, p\Lambda$ at maximum COSY energy.

Meson Production in pn and dd interactions

One advantage of meson production in nucleon–nucleon collisions is that, besides the spin of the particles, the isospin is an internal degree of freedom to be manipulated. A two-nucleon initial state can either be in an isotriplet configuration (T = 1 with T_3 = +1, 0, –1 for *pp*, *pn* or *nn* states, respectively) or in an isosinglet state ($T = T_3 = 0$ for *pn*). Variation of the initial-state isospin in $pN \rightarrow pNx$ reactions (where x denotes an isoscalar meson) may provide information about the production operator. In case of η production the observed ratio $R = \sigma_{tot}(pn \rightarrow pn\eta)/\sigma_{tot}(pp \rightarrow pp\eta) \sim 6.5$ is generally attributed to isovector dominance in model calculations based on meson exchanges. Data on the production of heavier isoscalar mesons (ω, ϕ) in *pn* interactions are not available yet.

At ANKE *pn* interactions can be studied using a deuterium cluster-jet target as an effective neutron target and detecting low momentum recoil protons (p_{sp}) in a silicon telescope placed inside the COSY vacuum close to the target. These recoil protons can be treated as "spectators" that influence the reaction only through their modification of the kinematics.

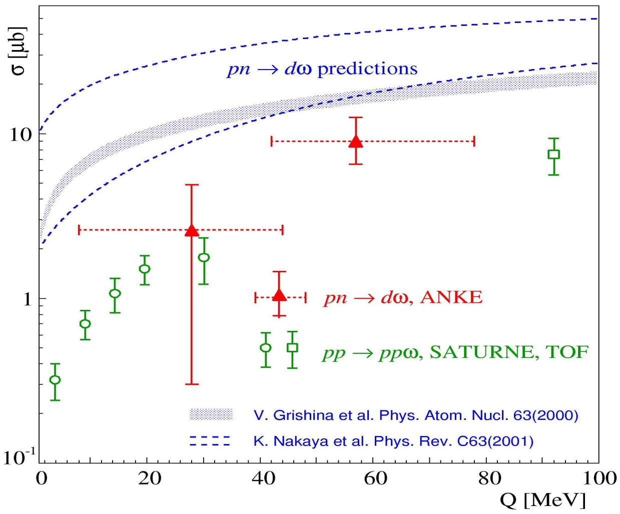

Fig. 5: Measured total cross section for ω-meson production in *pp* (green) and *pn* (red triangles, preliminary) interactions in comparison with model calculations (blue lines).

Figure 5 shows the measured $pn \rightarrow d\omega$ cross section from ANKE in comparison with *pp* data from literature and model calculations as a function of the excess energy Q. The fact that the *pn* cross sections – although lying above the corresponding *pp* data – are significantly smaller than the theoretical predictions, suggests that the reaction mechanism for ω production differs from that for the η, possibly implying a relatively larger contribution from isoscalar meson exchange.

Figure 6 shows the result of a first beam time on the reaction $pn \rightarrow d\eta$. The data have also been obtained with the spectator-tagging technique and a clear η signal has been observed for Q values in the range 0…45 MeV. The data analysis, in particular the extraction of absolute cross sections close to threshold, is still in progress.

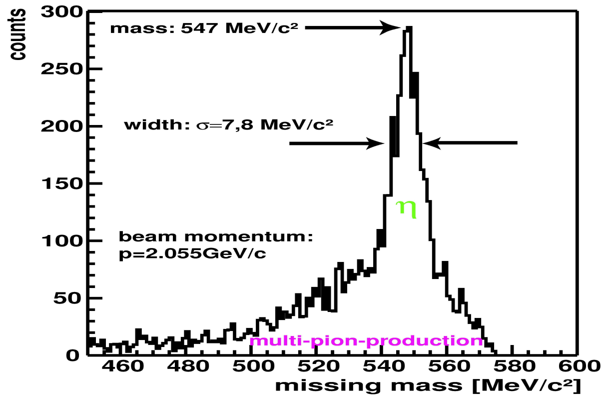

Fig. 6: Missing mass distribution for the $pD \to p_{sp}\ dX$ reaction.

The ANKE data on η production in *pn* interactions are not only interesting in view of production mechanisms, but one may also expect information about the low-energy η-nucleon interaction. The strength of this interaction has led to speculations on the existence of quasibound η-nuclear states, even in the two-nucleon system. Such a state should show up as a threshold enhancement of η-production in nuclear reactions. Therefore, the data analysis and future measurements of $pn \to d\eta$ should aim at cross sections with high *Q* resolution, in particular for excitation energies smaller than 10 MeV.

An enhancement of the threshold production amplitudes has also been reported for the $^3He\eta$ and $^4He\eta$ final states. However, the data from literature do not provide precise information on differential cross sections, in both cases it has to be assumed that close to threshold only *S*-waves contribute. For $dd \to {}^4He\eta$ only the total cross sections are available, and data for higher *Q* values are missing which could provide some information about the onset of *P*-waves. Measurements of the $dd \to {}^4He\eta$ reaction have been started at ANKE, total cross sections together with angular distributions will soon be available for $Q \leq 43$ MeV.

During a beam time in Feb. 2004, aiming at the study of $a_0/f_0(980)$ production in *pn* interactions, also data on the reaction $pn \to d\phi \to dK^+K^-$ will be taken. This will allow one to determine the ratio $R = \sigma_{tot}(pn \to d\phi)/\sigma_{tot}(pp \to pp\phi)$, using *pp* data from ANKE which currently are being analysed.

Deuteron-Breakup Studies

The deuteron breakup reaction $pd \to ppn$ at GeV beam energies and in kinematics similar to backward elastic scattering $pd \to dp$ provides a new tool to investigate the *pd* dynamics at high-momentum transfer. This process has been investigated at ANKE for beam energies T_p = 0.6…1.9 GeV and forward emission of fast proton pairs with small relative energy E_{pp} < 3 MeV. The results have been compared with calculations based on a theoretical model previously applied to the $pd \to dp$ process. Using the the Reid soft core (RSC) and Paris potentials, the model only reproduces the measured cross sections at the lowest energy (Fig. 7). Recently, it has been shown that the use of the Bonn potential in the framework of the same model yields a much better agreement for all beam energies.

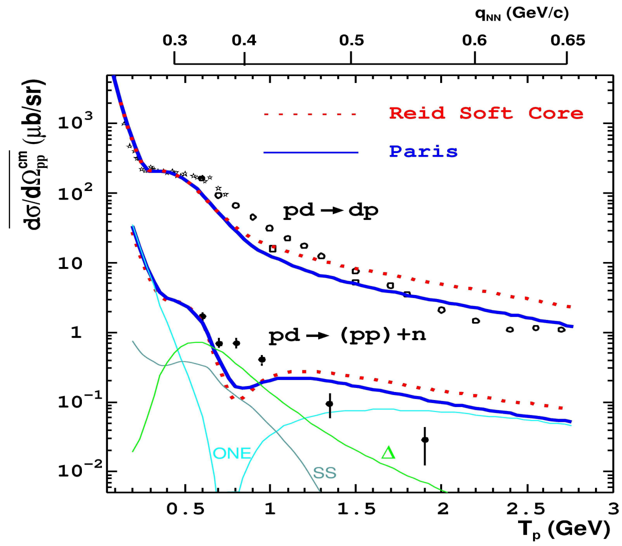

Fig. 7: Measured (•) and calculated (lines) cross sections for the breakup reaction $pd \to ppn$ and of $pd \to dp$ backward elastic scattering (o).

For further insight, additional data, in particular polarization measurements, are needed to provide a complete set of observables. A first measurement of the spin up/spin down asymmetry for the breakup process has been carried out, during which the EDDA detector has been used to obtain a reference value for the beam polarization. The analyzing power A_y^p predicted by our model is expected to follow an approximately linear function of the neutron emission angle in the range from 180° to 166°. The preliminary measured slope differs by about two standard deviations from the value predicted by the RSC potential.

For the few-nucleon interaction studies with polarized beams and targets at COSY a polarized gas target of internal storage cell type is currently being developed.

The Charge-Exchange Reaction $\vec{d}\,p \rightarrow (pp)n$

The complete description of the *NN* interaction requires precise data, in particular from double polarization experiments, for phase-shift analyses (PSA), from which the scattering amplitudes can be reconstructed. For the *pp* system such experiments have been carried out to beam energies of about 3.0 GeV, whereas much less information is available on spin observables in elastic *np* scattering, especially above 0.8 GeV. The PSA results for the isospin $I = 0$ *NN* system are poorly tested and measurements of any observable at small angles is highly desirable in order to improve the PSA solutions below 40° (c.m.s.). ANKE covers the angular range $\vartheta_{\text{c.m.s.}} \sim 0\ldots30°$.

Information on the spin-dependent *np* elastic amplitudes in backward direction (i.e. the Charge-Exchange (CE) region) can be obtained by measuring the CE breakup of polarised deuterons scattered on a hydrogen target.

The ANKE experimental program will first utilise unpolarised and tensor-polarised deuteron beams and an unpolarised hydrogen cluster target. The differential cross section will give the overall intensity of the spin-dependent parts of the CE process. The tensor-polarised deuteron beam allows one to separate the absolute values of three spin-dependent amplitudes. The use of transversely polarised deuterons impinging on a polarised hydrogen target and measuring the spin-correlation coefficient opens the possibility of obtaining the relative phases between the amplitudes. A first test measurement has been carried out with the polarised deuteron beam at an of energy $T_d = 1.2$ GeV. Its aim was to check the feasibility of the experiment and to develop polarimetry of the COSY deuteron beam with ANKE.

For the $\vec{d}\,p \rightarrow {}^3He\pi^0$ reaction the tensor analysing power T_{20} has been measured at SATURNE. These data can be used to determine the tensor polarisation of the deuteron beam. A preliminary result for the identification of this reaction is shown in Fig. 8.

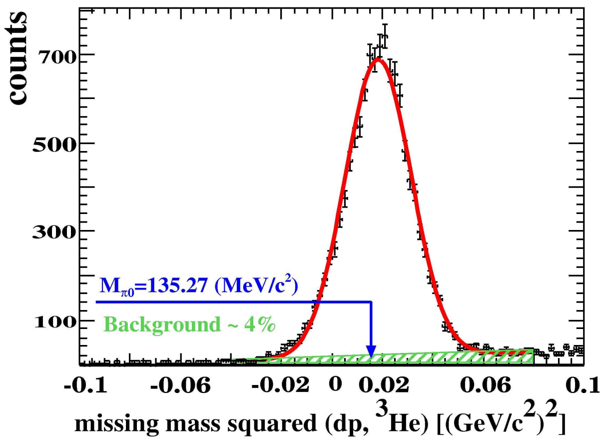

Fig. 8: Missing mass squared for the reaction $\vec{d}\,p \rightarrow {}^3He\,X$. The results of the peak fit are indicated.

The Polarized Internal Target (PIT) for ANKE

The development of the polarized atomic beam source (ABS) for ANKE has been finalized. Beam intensities of 7.8×10^{16} polarized hydrogen atoms per second in two hyperfine states have been reached, with polarizations of about 90%. In order to increase the target density for experiments at ANKE, the polarized beams from the ABS will be fed into a storage cell which will be located ~50 cm in front of the spectrometer dipole D2. Figure 9 shows the future location of the PIT at ANKE.

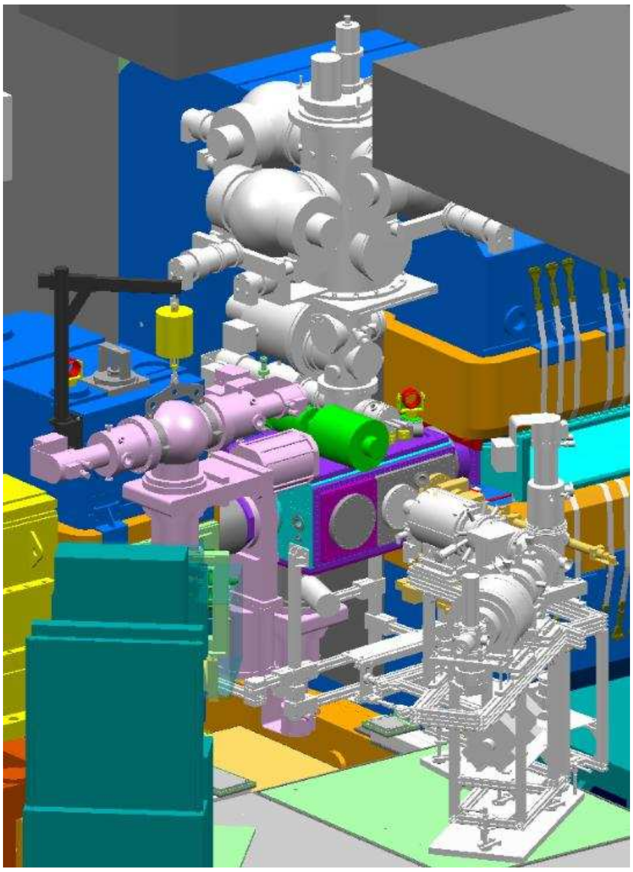

Fig. 9: Future position of the atomic beam source (vertical grey) and the Lamb-shift polarimeter at ANKE between the dipoles D1 and D2 (blue).

Installed at the PIT of the ANKE spectrometer, a Lamb-shift polarimeter (LSP) will be used to measure the nuclear polarization of the hydrogen or deuterium cell gas. A small fraction of the cell gas is deduced by a polarization-sample tube and fed into the LSP ionizer. Compared to the intensity of the directed beam from the ABS, the intensity of the incomming atoms drops by about 4 orders of magnitude. To study the feasibility of these measurements, a test setup of feeding, storage, and sample tubes was fed by the polarized H beam from the ABS. From the new ionizer the expected number of polarized protons (10^9 p/s ~ 0.1 nA) could be extracted. However, the background by unpolarized protons, stemming from residual gas, was higher than expected. Further measurements are underway.

The ANKE Frozen Pellet Target

Preparation of the pellet target for operation at an internal target position of COSY has made significant progress in 2003. Droplets of frozen hydrogen ("pellets") have been observed for the first time behind the exit sluice from the triple point chamber (TPC) and a continuous flow of liquid nitrogen droplets could be generated in the TPC and has been injected into the first vacuum chamber.

Figure 10 shows the flow of hydrogen pellets which could be generated during test runs of several days. The pellets have been produced from a liquid hydrogen jet with 60 μm diameter and a velocity of ~3 m/s. The frequency of the vibrating nozzle has been varied between 3–4 kHz.

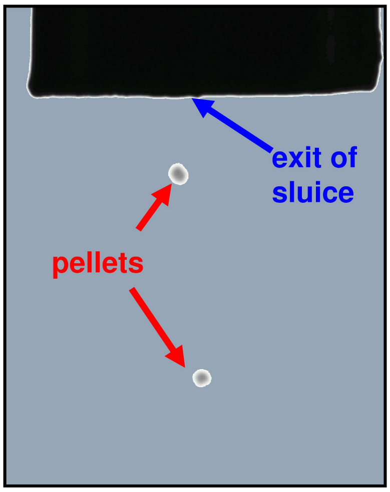

Fig. 10: Frozen hydrogen droplets leaving the triple-point chamber (TPC) of the ANKE pellet target into vacuum.

In another test run new metal nozzles with channels of 38 μm diameter have been used and, for the first time, nitrogen droplets have been observed in the TPC, see Fig. 11. For these tests the target was operated at nitrogen triple point conditions and a droplet generator frequency of 3 kHz. The temperature in the gas condenser was stabilized and controlled with the standard helium cooling system.

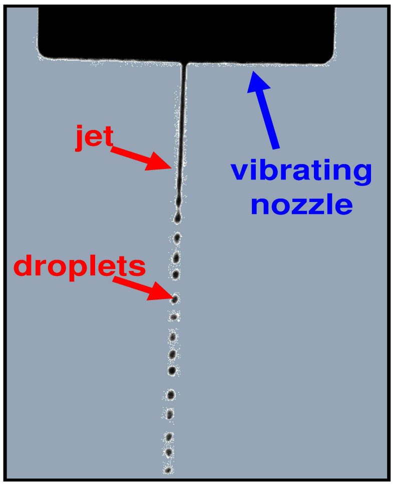

Fig. 11: Continuous flow of a liquid nitrogen jet in the TPC breaking into droplets by acoustic excitation.

Acknowledgements

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System development for COSY experiments is done in close cooperation with the Central Laboratory for Electronics (ZEL). The main goal is to improve the efficiency, flexibility and standardization including state of the art technologies.