ANKE

ANKE, a magnetic spectrometer and detection system at an internal target position of COSY, allows to separate and momentum analyze ejctiles 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. Currently, the experimental program at ANKE focuses on:

1. K^+- (and later K^--) meson production in the **nuclear medium**.

2. Investigation of the **light scalar resonances** $a_0/f_0(980)$.

3. Study of the proton induced **deuteron breakup** at high momentum transfer.

4. Measurement of neutral meson (π^0, η, ω, ...) production in **proton-neutron** collisions.

The detection systems of ANKE have been extended by a negative particle detector which is optimized for K^--meson detection. It has been used in a test beam time in spring 2002 during which the production of **ϕ-mesons** has been measured in pp interactions for the first time at COSY. Further technical developments for ANKE comprise:

a. An **atomic beam source** (ABS) which, together with a storage cell, can be used as a polarized internal target for double polarization experiments.

b. A **frozen pellet target** for investigation at highest luminosities, $\mathcal{L} > 10^{32}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$.

c. Target-near **solid state detectors** which will be installed inside the vacuum pipe of COSY for **spectator tagging**.

d. An **electromagnetic calorimeter** which will allow to measure photons from, e.g., decay of neutral mesons.

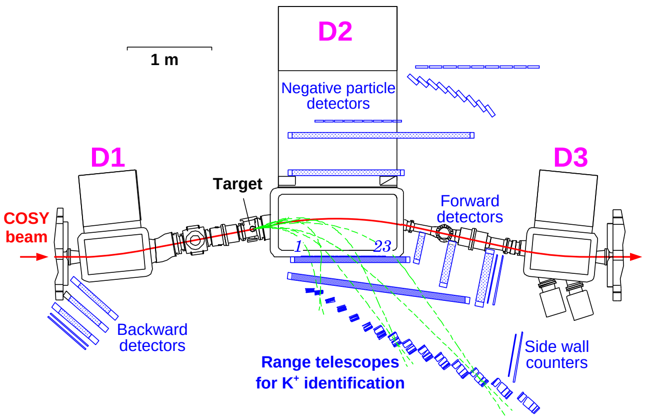

Fig. 1: Sketch of ANKE and the detection systems.

K^+-meson production in the nuclear medium

The design of ANKE and its detection systems have been optimized to measure the production of K^+-mesons with small cross sections in a huge background of other particles. As a first set of experiments, the production of K^+-mesons in pA ($A =$ C, Cu, Ag, Au) has been investigated by inclusive measurements of double differential K^+ spectra in the beam-energy range $T_p = 1.0\ldots2.3$ GeV. The data at the lowest beam energies, far below the free nucleon-nucleon threshold at 1.58 GeV, reveal a high degree of collectivity in the target nucleus. Based on simple kinematical arguments it can be shown that the intrinsic momenta of the nucleons participating in the reaction must be large (up to $\sim$ 550 MeV/c if the kaons are produced in a single collision between the beam proton and one nucleon). Alternatively, more than one nucleon at rest must take part in the reaction, i.e. the effective target mass must be up to $6m_N$. For a detailed understanding of the processes leading to subthreshold K^+ production microscopic model calculations are under way.

Another major result from the inclusive measurements is that the data on cross section ratios for K^+ production on different target nuclei allow to determine the nuclear K^+ potential (or the "in-medium mass") at normal nuclear density $\rho = \rho_0$. As an example, Fig. 2 shows the cross section ratio Au/C measured with ANKE in the momentum range $p_K \sim 150\ldots600$ MeV/c. For all beam energies between 1.5 and 2.3 GeV the

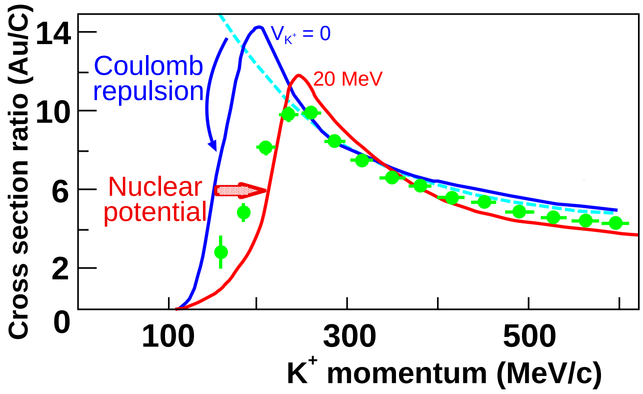

Fig. 2: Cross section ratio Au/C for proton-induced production of K^+ mesons measured at a beam energy of $T_p = 2.3$ GeV (green circles). The effect of the repulsive Coulomb and nuclear potentials is indicated by the lines which are the results of model calculations with a CBUU transport code (dashed - no potentials, dark blue - only Coulomb, red - nuclear potential for kaons, nucleons, and Λ hyperon taken into account).

ratios exibit similar shapes, rising with decreasing kaon momenta passing a maximum and falling down towards lower momenta. This peculiar shape could be explained by a combined effect of repulsive Coulomb and nuclear potentials which the K^+ "see" in the nuclear environment. This is illustrated in Fig. 2 by the lines representing the results of a model calculation. Without any potentials (light blue line) the amount of produced kaons would steadily rise towards lower momenta — due to stronger rescattering processes in the heavy Au nucleus which tend to slow down the kaons once they are produced. When a nuclear kaon potential of $V_K^0 = 20\,\mathrm{MeV}$ is used (and taking into account the absorption of the incident proton by including a baryon potential into the calculations) a reasonable agreement with the experiment is achieved, with a maximum close to the experimental value of $245 \pm 5\,\mathrm{MeV/c}$ (red line). More refined model calculations will permit us to achieve an improved description of the shapes of the measured spectra and to determine the nuclear K^+ potential with an accuracy of better than 3 MeV. It should be noted that studies of the nuclear potentials cruicially depend on the detection of *low momentum* kaons, which currently is only possible at ANKE.

The second phase of the experimental program on in-medium K^+-production has started in fall 2001 with a test measurement on (K^+p) and (K^+d) coincidences. For the first time, these data allow to draw direct conclusions about the K^+-production mechanisms. As an example, Fig. 3 shows the momentum spectra of deuterons produced in coincidence with kaons at a beam energy of 1.2 GeV. The upper spectrum, obtained in the full angular-momentum acceptance of ANKE, reveals a prominent peak at $p_d \sim 960$ MeV/c. This

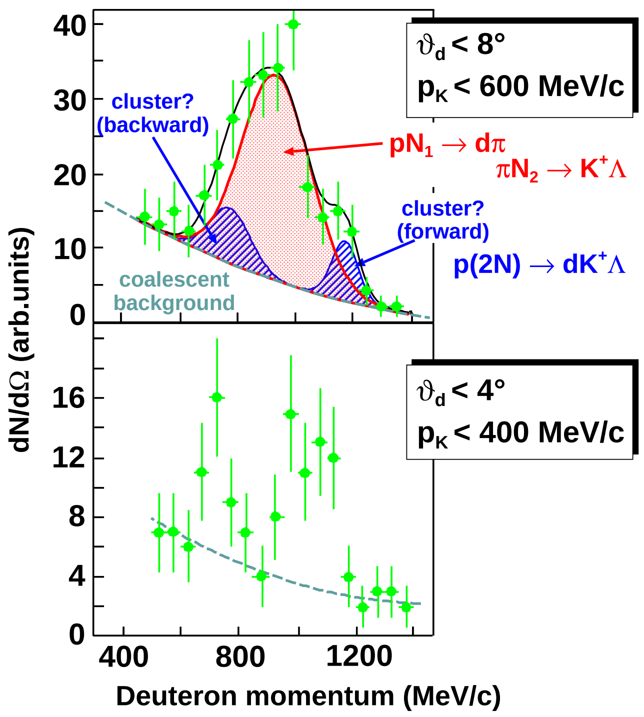

Fig. 3: Momentum spectrum of deuterons from the reaction $p(1.2\ \mathrm{GeV})\mathrm{C} \to (dK^+)X$ (green circles). The upper spectrum is obtained in the full ANKE angular-momentum acceptance, whereas the lower for restricted deuteron angles and kaon momenta. According to phase-space simulations, these cuts should suppress the events from two-step K^+ production. Two peaks remain which are possibly due to production of kaons on $(2N)$ clusters, $p(2N) \to (dK^+)\Lambda$.

agrees with model predictions for deuterons produced in the particular two-step mechanism $pN_1 \to d\pi$, $\pi N_2 \to K^+\Lambda$. Our data show that this process contributes to about 30% of the total kaon yield at this beam energy. A hint on more exotic processes comes from the observation that the deuteron peak has a width of about 350 MeV/c, thus significantly larger than the value of 200 – 250 MeV/c expected for the "normal" two-step process. It can be presumed that this is due to two smaller peaks at both sides of the central one, which can be attributed to the production of K^+-mesons on a two-nucleon cluster, i.e. $p(2N) \to (dK^+)\Lambda$. A corresponding fit to the data with three Gaussians is shown in the upper part of Fig. 3. According to phase-space simulations, the K^+ (deuterons) from the cluster mechanism should have smaller momenta (emission angles) than two-step kaons. Thus, after applying such conditions to the data one expects a strong reduction of the central $(pN_1 \to d\pi)$ peak, whereas events from the cluster mechanism should remain largely unaffected. This expectation is confirmed by the lower spectrum of Fig. 3 for restricted kaon momenta and deuteron angles. Thus the two peaks might be attributed to kaon production on (2N) cluster with forward and backward emission (in cms) of the deuteron. Further correlation measurements aiming at a better understanding of the different mechanisms have been approved by the COSY-PAC and are scheduled for summer 2003.

A proposal to study K^+K^--production in pA collisions is in preparation. These measurements will make use of the new detection system for negatively charged ejectiles (see below) which has been commissioned in 2002. Goal of this proposal is not only to study medium effects on the K^--meson but also to measure the target-mass dependence of ϕ-meson production. Several theoretical publication predict a significant increase of the ϕ-decay width in nuclear matter, due to a strong actractive K^- potential in nuclei (i.e. a significantly smaller "in-medium mass").

Study of light scalar resonances at ANKE

The lightest scalar resonances $a_0(980)$ and $f_0(980)$ are two well established states in the excited meson spectrum. However, their interpretation as conventional $q\bar{q}$ states is by no means undisputed. In spite of a variety of data on the production of the a_0/f_0 with electromagnetic and hadronic probes, their nature is still in doubt and the various scenarios about their structure allow to describe the data equally well. Thus, an experimental program using the ANKE spectrometer has been started aiming at complementary data from pp, pn, pd and dd interactions close to the $K\bar{K}$ threshold.

The a_0 has isospin 1 and three charge states -1, 0, $+1$, whereas the f_0 has isospin and charge 0. From a test of isospin relations in hadronic reactions, e.g. $pp \to da_0^+$ vs. $pn \to da_0^0$ or $pd \to {}^3Ha_0^+$ vs. $pd \to {}^3He\,a_0^0$, valuable information about the structure of the a_0 and f_0 and possibly about a_0-f_0 mixing can be expected. This isospin violating mixing may be significantly larger than in the case of π^0 and η mesons. In this context the reactions $dd \to {}^4He\,a_0^0/f_0$ are of special relevance, since only the isospin 0 state (f_0) can be produced directly due to isospin conservation. Thus the observation of the reaction $dd(\to {}^4He\ f_0 \to {}^4He\ a_0^0) \to {}^4He\ \pi^0\eta$ may be a direct indication of a_0-f_0 mixing.

First measurements of a_0^+ resonance production in the reaction $pp \to da_0^+$ have been performed in 2001 at $T_p = 2.65$ GeV ($Q = 46$ MeV excess energy above the $K\bar{K}$ threshold) and 2002 at $T_p = 2.83$ GeV ($Q = 103$ MeV). Both experiments aim at the simultaneous measurement of the two main decay channels $a_0^+ \to K^+\overline{K}^0$ and $\pi^+\eta$. The analysis of the reaction $p(2.65\,\mathrm{GeV})p \to dK^+\overline{K}^0$ has been finalized; the total cross seection for this reaction (see upper part of Fig. 4) as well as mass and angular distributions have been obtained.

It is a priori not clear which fraction of the observed $pp \to dK^+\overline{K}^0$ events can be ascribed to resonant $K\bar{K}$-production via the a_0^+. The lines in the upper part of Fig. 4 correspond to a model prediction for resonant (red solid) and non-resonant (blue dashed) $K\bar{K}$-production. According to this model, resonant production is dominant, however, the $\bar{K}d$ final-state interaction is not yet taken into account in this approach. The model also predicts that the non-resonant $K\bar{K}$-pairs are dominantly in a relative P-wave whereas kaons from a_0^+-decay must be in an S-wave.

The possible different angular-momentum configurations should be reflected in the shape of the invariant mass distribution of the $K\bar{K}$-pairs which is shown by the lines in the lower part of Fig. 4. Our data clearly favor dominance of S-wave $K\bar{K}$-production. On the other hand, the measured angular distributions (not shown here) cannot be explained by pure a_0^+-resonance production. This indicates that for a complete description of the data also the $\bar{K}d$ final-state interaction (mediated, e.g., by the $\Lambda(1405)$) has to be taken into account.

Observation of K^-- and ϕ-mesons

The ANKE spectrometer dipole D2 leaves room for the in-

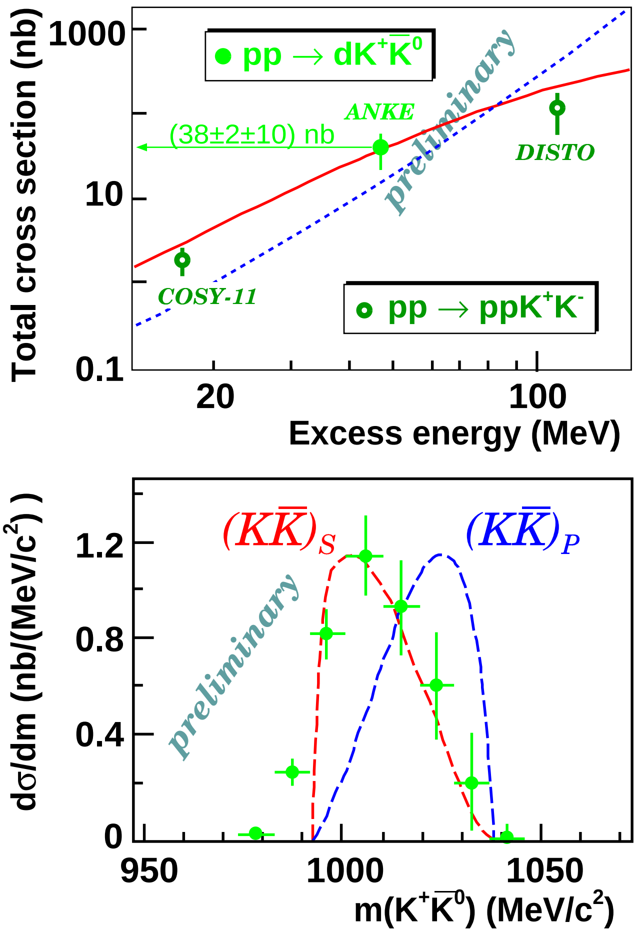

Fig. 4: Upper Total cross section for the reaction $pp \to dK^+\overline{K}^0$ from ANKE and model predictions for the resonant (i.e. via the chain $pp \to da_0^+ \to dK^+\overline{K}^0$, red line) and non-resonant contributions (blue). For comparison the cross sections for the reactions $pp \to ppK^+K^-$ from COSY-11 and DISTO are also shown. Lower: Invariant $K^+\overline{K}^0$ mass distribution. The lines show phase-space behavior for a relative S/P-wave of the $K^+\overline{K}^0$ pair (red/blue).

stallation of a detetection system for negatively charged ejectiles. The final setup of the detector elements — partially inside the return yoke of D2 (Fig. 1) — and the readout electronics has been finalized in summer 2002. The system can detect negatively charged pions and kaons. In combination with the positive detection system, reactions like ϕ-meson and K^+K^--pair production on elementary as well as on nuclear targets can be investigated.

The first experiment using these detectors foresees to measure the near-threshold ϕ-production cross section in pp collisions by detecting the K^+K^- decay mode. In spring 2002 a first week of beam time at an excess enery of $Q = 35$ MeV was taken. The data analysis still is in progress, as a first remarkable result we show in Fig. 5 the invariant K^+K^--mass spectrum with a clear peak around the ϕ mass. This is the first observation of ϕ-meson production in pp collision at COSY. The measurements will be continued in 2003 at different Q values.

The $pp \to pp\phi$ data from ANKE may lead to a better understanding of this reaction near threshold. In addition, they will provide — together with existing data for the reaction $pp \to pp\omega$ from SPES-III and TOF — the cross-section ra-

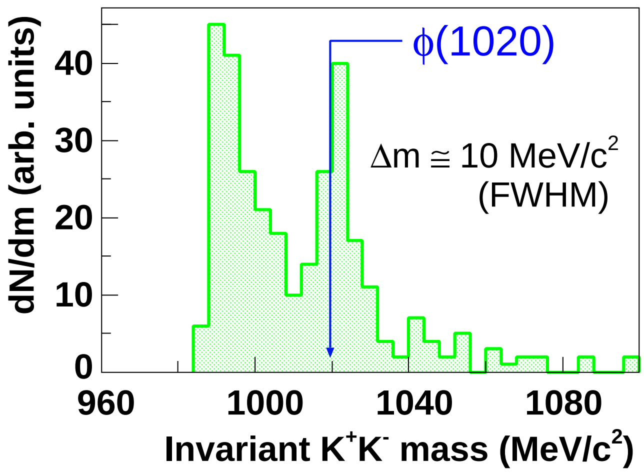

Fig. 5: Invariant K^+K^- mass distribution measured at ANKE for the reaction $p(2.7\,\text{GeV})p \to pp\phi$. The enhancement at lower masses is due to misidentified $K^+\pi^-$ events.

tio $R_{\phi/\omega} = \sigma_\phi/\sigma_\omega$. Under the assumption that the Okubo-Zweig-Iizuka (OZI) rule is fulfilled and using $\alpha_v = 3.7°$ as the deviation from the ideal SU(3) ω-ϕ mixing angle, one expects $R_{OZI} = \tan^2\alpha_v = 4.2\times10^{-3}$. A deviation from this value might be a hint on intrinsic strangeness in the proton or on the importance of higher-order rescattering processes leading to ϕ production.

The events shown in Fig. 5 were obtained by detecting only two coincident particles, i.e. the K^+K^--pair. This demonstrates the feasibility to measure at ANKE ϕ-meson production also in proton-nucleus reactions, without detection of a third coincident particle. A corresponding proposal is in preparation. Another already approved proposal aims at the investigation of the neutral scalar resonances a_0^0 and $f_0(980)$ in $pn \to dK^+K^-$ reactions. These data will also be used to study ϕ-meson production on the neutron, i.e. the reaction $pn \to d\phi$.

ω-meson production on the neutron and spectator counters

R. Schleichert, 1/2 page

Deuteron breakup

F. Rathmann, 1 page

The Polarized Internal Target (PIT)

Many few-nucleon interaction studies benefit significantly from experiments involving spin-degrees of freedom. While in a standard cross-section experiment, only a single observable is probed, additional observables become accessible, when either beam or target, or wherever possible, both are polarized. It should be emphasized that after closing of the Cooler operation at IUCF in 2002, COSY remains the only ring capable of storing polarized protons and deuterons on a worldwide scale. For state-of-the-art spin-physics experiments in the hadronic sector with polarized beams at COSY, a polarized internal target (PIT) is presently being developed for ANKE. Besides our development, only one other PIT is prepared in the electromagnetic sector for the physics programme of the BLAST facility at MIT-Bates. These two targets will allow for complementary studies using both polarized electromagnetic and hadronic probes in the future.

The polarized atomic beam source, which will feed the PIT, is depicted in Fig. 6. The source provides a beam intensities of $7.4 \cdot 10^{16}$ atoms/s in two hyperfine states of hydrogen, which constitutes a world record for this type of PIT. This success is largely based on the high performance of a new system of high-field permanent magnets, developed by us.

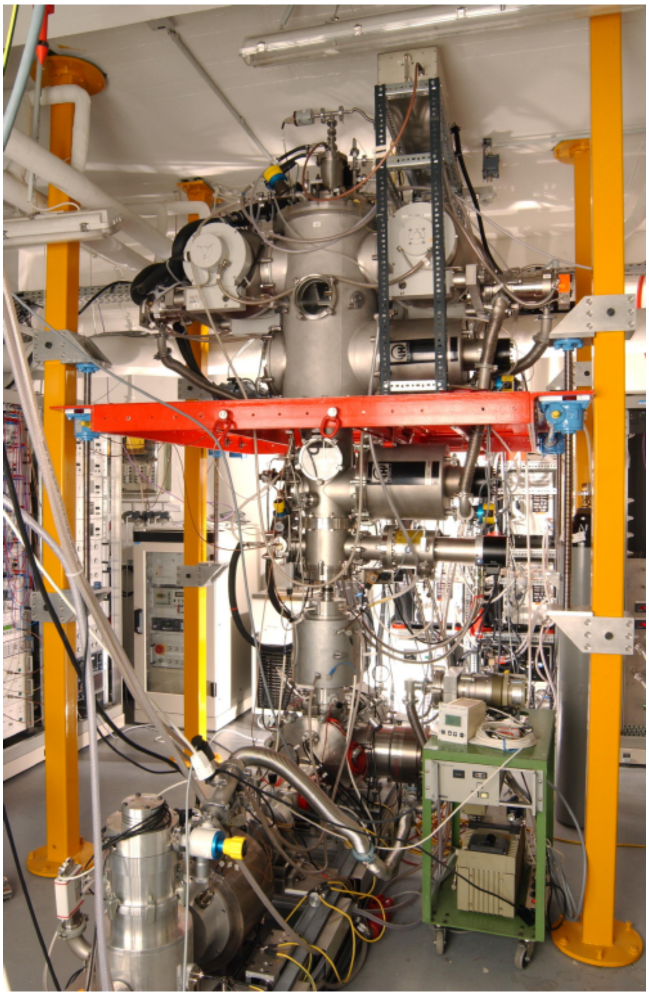

Fig. 6: The atomic beam source for the polarized internal target of ANKE (laboratory set-up). The polarized atoms are injected into an ionizer and electrostatically deflected onto the horizontal axis. The nuclear polarization of the atoms is subsequently analyzed by the Lamb-shift polarimeter.

The nuclear polarization of the PIT will be determined from a measurement of the polarization of atoms extracted from the storage cell, ionized and then injected into a Lamb-shift polarimeter. This polarimeter, developed at the University of Cologne, is also shown in Fig. 6. The measured population of magnetic substates ($m_I = \pm 1/2$) of an atomic hydrogen beam is shown in Fig. 7.

The detected asymmetry of the Lyman-α light after all correction yields a nuclear polarization of $P = 0.89$. Tests with prototype storage cells, aiming at the identification of cell dimensions suitable for the ANKE target, are underway. The implementation of the target at the internal spectrometer ANKE constitutes a major technological enterprise. Recently, a new large target chamber has been implemented at ANKE to accommodate storage cells in the future, a new set of small-aperture horizontal and vertical beam position monitors, and a system of target-near detectors. Among the

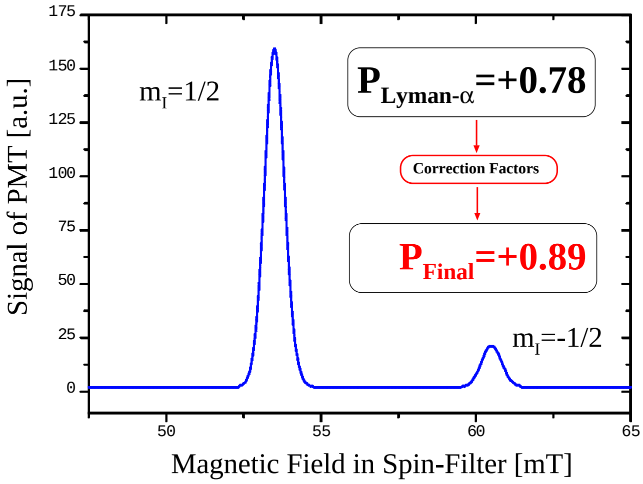

Fig. 7: Magnetic substate population of an atomic hydrogen beam and the resulting polarization values determined with the Lamb-shift polarimeter.

first experiments to be carried out with the new PIT at COSY is the measurement of the proton-induced deuteron breakup, which as a first step in the sequence of investigations has been studied in an unpolarized experiment.

But the need to provide higher luminosity for COSY prevails in particular for experiments involving polarized beams. Due to the limited target density available from e.g. a PIT, in order to reach luminosities beyond 10^{30} $cm^{-2}s^{-1}$ requires to provide similar numbers for polarized particles stored in COSY than currently available unpolarized.

Frozen pellet target

The ANKE frozen pellet target, see Fig. 8, will allow measurements at highest luminosities while the interaction zone is almost point like and the gas load on the ring vacuum is very small. According to the experience with a similar target at CELSIUS, luminosities of $\mathcal{L} > 10^{32}\,cm^{-2}s^{-1}$, e.g. comparable to solid-state strip targets, are expected.

In the ANKE target droplets of liquid hydrogen — and later also from other liquefiable gases — are produced from a continuous flux of liquid hydrogen which enters a triple-point chamber (TPC, containing hydrogen gas close to triple-point conditions) through a vibrating nozzle with a diameter of currently 40 μm. These droplets will freeze due to evaporation cooling when they leave the TPC into the accelerator vacuum through a thin tube of ~ 0.5 mm diameter and a few cm length. In contrast to the CELSIUS target the cryostat is cooled with liquid nitrogen and helium which should minimize distortions induced, e.g., by vibrating cold heads.

The target is currently being prepared in a test stand located in the COSY accelerator hall (Fig. 8). In 2002 the target cryostat and the hydrogen supply system have largely been modified, and a new TPC, offering larger observation windows for an optical diagnostic system, has been installed. During several test runs stable fluxes of hydrogen droplets have been obtained in the TPC, see Fig. 9. The production of frozen pellets has not been observed yet since the corresponding diagnostic tools — based on two video cameras and a laser system — still are in preparation. They will be available in spring 2003 when first test runs with pellet production are scheduled. During these tests nozzles with diameters down to 20 μm will be used.

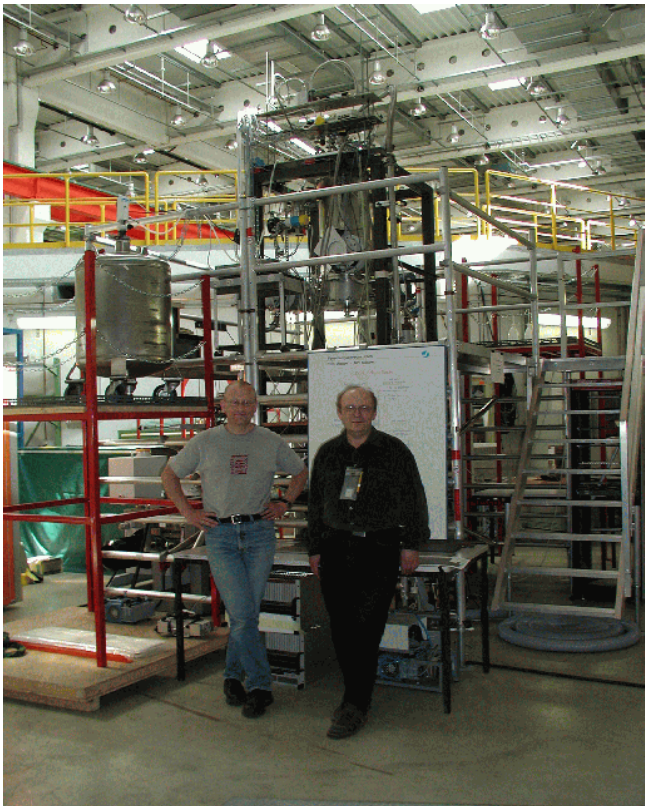

Fig. 8: Test set-up of the ANKE pellet target in the COSY hall.

Since the proposed experiments with the pellet target (e.g. investigation of neutral scalar mesons) also require neutral particle detection, it is planned to install the target at ANKE together with the photon detector.

Photon detector

The compact, large-acceptance electromagnetic calorimeter with a diameter of less than 80 cm has reached its final design phase. It will cover polar angles between 25° and 165° with full azimuthal acceptance and will be used to detect multi-photon final states (e.g. decay of neutral mesons) in coincidence with charged ejectiles in forward direction.

In the beginning of 2002 modules combining lead tungstate ($PbWO_4$) crystals and shielded Hamamatsu R5505 fine-mesh photomultipliers were successfully tested at the photon beam line of MAMI (University of Mainz). Linearity, time and energy resolution, gain and count-rate stability of this specific combination were found to be well suited for this application. Moreover, on-going crystal tests show that recent samples of $PbWO_4$ have an increased light output and, thus, an even better performance. While these investigations have been done using standard high-voltage dividers, the final modules will use active Cockroft-Walton bases. A set of these bases has been ordered from HVSys in Dubna, Russia, and will be tested finally beginning of 2003.

About 900 of these single modules have to be mounted in a sphere around the target point. In order to keep the flexibility to have different near-target installations (or to combine them) it is a strong requirement that all of them can be exchanged within one maintenance week of COSY. This can be achieved only with a modular design of the full setup. Therefore, it is planned to use quarter or half spheres made of carbon fibre as containers to allow a convenient and fast

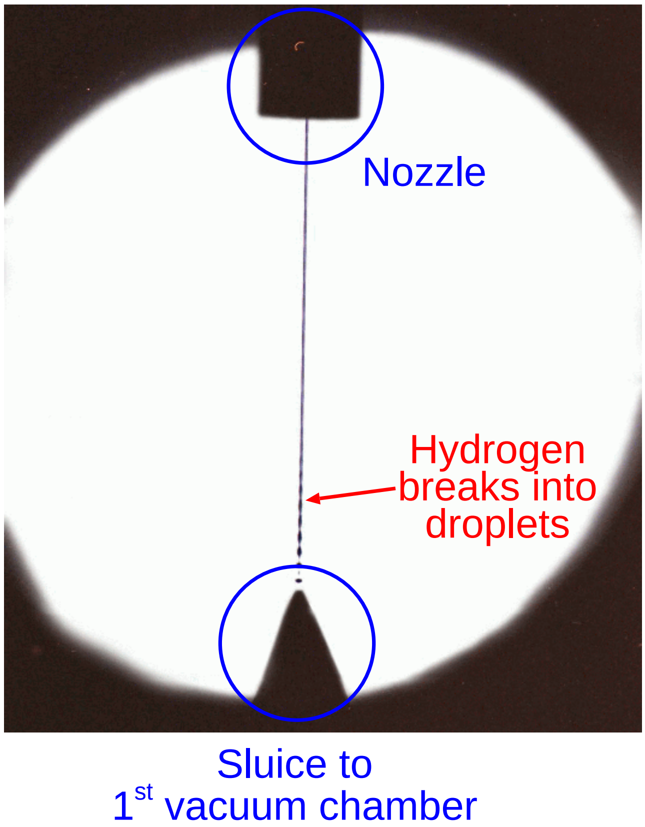

Fig. 9: Stable flux of liquid hydrogen droplets in the TPC. The nozzle diameter and frequency were 40 μm and 6 kHz, resulting in a droplet diameter of $\sim$ 80 μm.

assembling and disassembling of the whole detector. For this purpose discussions have started with the Zentralabteilung für Technologie (ZAT) of the FZJ and the Institut für Kunststoffverarbeitung (IKV), RWTH Aachen. It is intended to fix the final geometry within the second half of 2003.

In parallel, the newly developed read-out electronics for the TAPS spectrometer will be modified and adopted to the photon detector. Furthermore, the development of a veto detector (to be placed inside the crystal shell) will start at the Institute of Physics of the Jagiellonian University in Cracow. Within the current time schedule it is foreseen to have the full setup ready for installation at ANKE in the first half of 2006.

External activities: Measurements at PSI

Measurement of the hadronic ground-state shift ε_{1s} and broadening Γ_{1s} in pionic hydrogen gives access to fundamental parameters of the pion-nucleon interaction like the isoscalar and isovector s-wave scattering lengths and the pion-nucleon coupling constant. Ongoing improvement in Chiral Perturbation Theory — the low-energy approach of QCD — will allow calculations at the per cent level, which should be experimentally tested with comparable accuracy. The isovector scattering length is directly related to the hadronic broadening and constitutes one key point for the comparison of theory and experiment.

Hence, the main goal of the new pionic hydrogen experiment at the Paul-Scherrer-Institut (PSI) is to achieve finally an accuracy for Γ_{1s} of about 1%, which is an improvement of seven as compared to previous experiments. The technique is based on the cyclotron trap to produce a bright X-ray source for a focusing reflection-type crystal spectrometer. Bragg reflected X-rays are measured by a large-area two-dimensional position-sensitive detector set up with Charge-Coupled devices.

The essential part of the experimental program is to study the influence of non-radiative de-excitation processes during the atomic cascade, which compete with X-ray emission and occur in collisions with target molecules. At first, formation of molecular structures like [(πpp)p]ee could cause an energy shift of the X-ray lines, which falsifies the result for ε_{1s}. Secondly, when de-excitation energy is shared as kinetic energy between the collision partners (Coulomb de-excitation), a Doppler broadening of the X-ray lines occur. Consequently, the strategy of the experiment is to measure at various densities.

A first series of measurements has been completed in 2002, covering the pressure range from 3.5 bar to liquid. No density effect for ε_{1s} could be established. To study the line broadening due to Coulomb de-excitation, the three $\pi H(2p-1s)$ (2.4 keV), $\pi H(3p-1s)$ (2.9 keV) and $\pi H(4p-1s)$ (3.0 keV) transitions were studied at a target density equivalent to 10 bar (Fig. 10). An increase of the line width was found for the $2p-1s$ line compared to the $3p-1s$ transition, which is attributed to the higher energy release available for the acceleration of the pionic-hydrogen system. This result is corroborated by a reduced line width of the $4p-1s$ transition (see this report). At present, the data are being analysed. An improvement of both ε_{1s} and Γ_{1s} is expected by a factor of about 2.

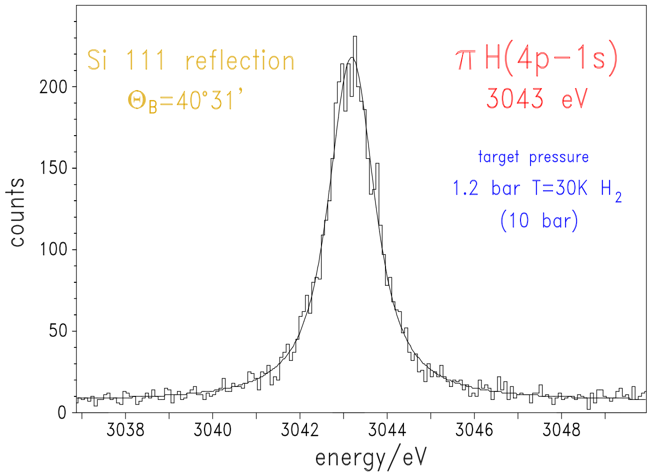

Fig. 10: $\pi H_{4p\rightarrow 1s}$ transition measured in 2002. 5400 events were taken over 2 weeks of beamtime with a peak-to-background ratio of 35 to 1.

A further improvement for Γ_{1s} requires a more precisely known correction for the Doppler broadening. This will be achieved by future studies of muonic hydrogen, where hadronic broadening cannot contribute to the line width. In preparation, an electron-cyclotron-resonance-ion-trap (ECRIT) has been set up at PSI to measure the crystal response with narrow X-ray lines emitted from electronic hydrogen- and helium-like light ions. A successful commissioning in 2002 resulted in a high rate for X-rays from helium-like Ar (see this report). Such high-statistics studies will replace the measurement of the crystal spectrometer response with the $\pi^{12}C(5g-4f)$ line used up to now, for which the statistics — and correspondingly the accuracy — are limited due to beam time considerations.

For the measurement of X-rays from light and medium Z exotic atoms, a high-rate capable detector system based on fully depleted CCDs as used in X-ray astronomy satellites has been build up. It has been tested successfully in 2002 (see this report). Because the measurable energy range extends to below 2 keV, it will be the ideal diagnosis tool for optimising beam-injection for the next step of the pionic hydrogen experiment.

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.