Review of Polarized Internal Gas Targets

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Experiments utilizing polarized internal gas targets are discussed. Since a few years these targets are used at electron and proton machines and considerable progress has been made in operating them on a routinely basis. This paper will focus on experimental aspects, such as the design and construction of storage cells and different methods employed for polarimetry.

1 Introduction

Storage cells to enhance the target thickness provided by a source of polarized atoms have already been conceived some thirty years ago [1]. However, application of this technique to nuclear and particle physics became possible only through the advent of storage rings. The stored beam passes through the *internal* target about a million times per second and thus compensates for the low target thickness. In order to obtain higher target thicknesses compared to a free beam of polarized atoms, the dwell time of an atom in the vicinity of the stored beam must be increased. For that purpose an open ended T-shaped storage cell is inserted into the ring through which the stored beam passes and into which the atomic beam is injected. Thereby the luminosity can be raised by about two orders of magnitude. Nowadays, internal targets with densities around 10^{14} atoms/cm^2 and nuclear vector or tensor polarization close to the theoretical maximum are operated routinely at a various storage rings.

2 A Bit of History

The suggestion by Haeberli [1] to use a storage cell to enhance the available target thickness produced by an atomic beam source in 1966 was motivated by the successful application of a storage container in hydrogen maser applications [2]. The proof of principle of this approach was carried out by the Wisconsin Group in 1980 using a 12 MeV beam of α-particles incident on a proton target [3]. The atomic beam entered the storage vessel through a 10 cm long tube of 10 mm diameter. The storage volume (0.26 l) was coated with Teflon to avoid depolarization. The measured polarization after background subtraction was found to be compatible with the polarization of a free beam, thus essentially no depolarization occurred during an average of 900 wall collisions inside the vessel. The improvement in target thickness was a factor of six over that of a free beam.

In 1985 the FILTEX group proposed an internal polarized hydrogen target for LEAR at CERN [4]. The objective was to polarize a stored beam of antiprotons by spin-dependent attenuation in the polarized gas target (Spin-Filter-Method) and to subsequently carry out $\bar{p}p$-interaction studies. The goal was to achieve a target density of 10^{14} atoms/cm^2 in one substate.

Since 1988 an internal polarized deuterium target is operated at the electron storage ring VEPP-3 in Novosibirsk to measure the tensor analyzing power T_{20} in $e\vec{d}$-scattering [5, 6]. Substantial progress in atomic beam intensity could be achieved recently through the development of superconducting sextupole magnets [7].

In 1992, the FILTEX target was tested at the Heidelberg Test Storage Ring [8, 9, 10, 11]. A target thickness close to 10^{14} atoms/cm^2 in two substates was achieved, with a nuclear polarization of 0.8 for one substate. More details pertaining to the FILTEX test experiment are presented in Sec. 4.2.1.

In 1992, an optically pumped polarized $^3\vec{\mathrm{He}}$ target [12, 13] was installed at IUCF to study spin-dependent $\vec{p}^3\vec{\mathrm{He}}$-reactions [14]. This experiment represents the first measurement with a polarized beam incident on a polarized target internal to a storage ring. A target thickness of $1.5 \cdot 10^{14}$ atoms/cm^2 was reported [12]. Later, in 1995, the target was installed at the HERMES experiment at HERA/DESY to study the spin-structure of nucleons by deep inelastic scattering [15].

In 1996, the modified source for polarized hydrogen and deuterium atoms, developed initially for the FILTEX experiment, was installed at HERMES [15]. The storage cell setup of the HERMES experiment is discussed in more detail in Sec. 4.2.3.

Since 1994 the PINTEX collaboration at IUCF [16] is operating a polarized hydrogen and deuterium gas target [17, 18]. A few aspects of this facility [19] are discussed in Sec. 4.2.4.

Studies in $e\vec{d}$-reactions, similar to the ones performed at VEPP-3, have been carried out at NIKHEF, using an unpolarized electron beam incident on a tensor polarized internal deuterium gas target [20, 21, 22]. An ion-extraction system is employed to determine the target polarization (Sec. 5.2).

Among the currently operating polarized internal target experiments, the EDDA experiment at COSY is the only one that utilizes a free atomic jet [23, 24, 25]. Recently, the group has performed first tests with a storage cell, which will be dealt with in Sec. 4.2.5.

A new type of polarized hydrogen and deuterium source based on spin-exchange optical pumping has recently been installed in the IUCF cooler. First results in $\vec{p}\vec{d}$ elastic scattering have been obtained [26]. Details on the storage cell used in this experiment are given in Sec. 4.2.6.

There are two new facilities presently being prepared for nuclear physics experiments employing polarized internal gas targets. The Bates Large Acceptance Spectrometer Toroid (BLAST) experiment [27] will utilize the slightly modified polarized target used at NIKHEF for studies in polarized ed reactions. At COSY a polarized internal target is being developed to study the $\vec{p}\vec{d}$-breakup reaction in a collinear kinematic with the magnetic spectrometer ANKE [28, 29].

3 Polarized Internal Targets for Storage Rings

The interaction zone produced by a target source if no storage cell is used is given by the volume of overlap between stored and atomic beam, typically of the order of a cm^3. Target sources for this type of setup are optimized for maximum volume density inside the interaction zone, which increases with decreasing atomic velocity. When a storage cell is used, the target source is instead optimized for maximum intensity into the acceptance of the feed tube of the cell. In this case the interaction region is extended with cell dimensions typically ranging from 25 to 60 cm in length with diameters of 10 to 30 mm and cylindrical, elliptical, squared or rectangular cross sections.

The main advantages of polarized gas targets over solid targets are: *i)* high isotopical purity, *ii)* possibility of rapid spin reversal up to 100 Hz in $\vec{H}$ or $\vec{D}$ targets, *iii)* low background, since no container walls intercept the particle beam, and *iv)* no radiation damage, because the target gas is replenished every few ms. Polarized gas targets combined with beams internal to storage rings are therefore ideally suited for high precision experiments.

4 Storage Cells for polarized internal Targets

The main objective in the development of storage cells for polarized internal targets was the identification of suitable wall coating materials that inhibit depolarization of atoms stored inside the cell that are compatible with the ultra-high vacuum requirements of a storage ring.

4.1 Cell Coating

Early studies of wall depolarization in storage cells were performed by Price and Haeberli. These measurements were carried out with an apparatus described in Ref. [30]. A 50 keV beam of D^+ ions from a duoplasmatron source passes through a storage cell. Polarized $\vec{\mathrm{H}}^0$ atoms from an atomic beam source are injected into the cell through a feed tube. A weak magnetic guide field of 5 mT is applied over the cell. Inside the cell the electron pick-up reaction $D^+(50\,\mathrm{keV}) + \vec{\mathrm{H}}^0 \rightarrow \vec{\mathrm{D}}^0(50\,\mathrm{keV}) + H^+$ takes place. In a weak magnetic guide field electrons and protons of hydrogen atoms in a state $|m_j = 1/2, m_I = 1/2\rangle$ carry the same polarization. The electron pickup reaction in the cell transfers the initial polarization of the electrons through hyperfine interaction to the deuterium atom, which acquires a nuclear tensor polarization. The neutral $\vec{\mathrm{D}}^0$ atoms impinge on a tritiated foil located in a strong field of 30 mT. From the neutron asymmetry of the $^3\mathrm{H}(\vec{d}, n)^4\mathrm{He}$ reaction the tensor polarization of the deuterons is deduced. Using this method as a polarimeter the depolarization behaviour of various wall coating materials was investigated. Among the various materials investigated, Teflon stands out for its low depolarization and good vacuum compatibility.

4.2 Design and Construction of Storage Cells

The design of a storage cell must be well adapted to the experimental requirements of an internal target facility, taking into account properties of the stored beam, e.g. beam dimension, detector acceptance, possible background reactions from the cell walls, etc. Recently these design constraints for polarized internal targets have been reviewed by Meyer [31].

4.2.1 FILTEX

A boundary condition initially imposed during the measurements by the TSR machine group was to allow for injection of the beam without the storage cell acting as acceptance limiter. Therefore a storage cell that could be opened and closed like a clam-shell, shown in Fig. 1, was developed [8].

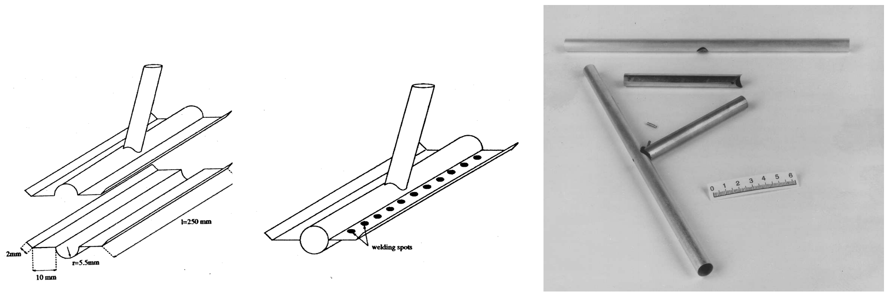

Fig. 1. Storage cells used during the FILTEX test experiment at TSR: Clam-shell cell (left), spot-welded clam-shell (center), and cell made from cylindrical tubing (right).

Only after the beam had been injected and cooled was the cell closed. The upstream end of the cell was attached to a cold head, thereby the cell center could be cooled to temperatures between 50-300 K. The longitudinal fins left and right of the cell were used to increase the heat conductivity. The rather low polarization observed for the clam-shell cell ($\approx 50\%$ of the theoretical maximum) was probably caused by exposure of atoms to the badly-coated fins of the cell. Spot-welding the two half cells together [8] (center in Fig. 1) substantially increased the polarization, once the TSR machine group was confident enough to give this approach a try. Eventually, for the FILTEX test experiment, closed cells manufactured from cylindrical aluminum tubes were used (Fig. 1). All cells were of the same dimensions, 250 mm length with a diameter of 11 mm and a wall thickness of 0.2 mm. The first two cell types (clam-shell, spot-welded clam-shell) were coated with Teflon FEP 120, while the final cells had Teflon TPFE 3170 coatings. Results of the polarization measurements will be presented in Sec. 5.1.1. All cells were also equipped with a small capillary near the cell center to allow for injection of unpolarized gas for background studies.

4.2.2 ^{3}He-Target at IUCF

The effects of depolarization in wall collisions in polarized ^{3}He gas targets are greatly inhibited due to the absence of hyperfine interaction. In that sense polarized ^{3}He atoms can be called *robust*. For this reason, the storage cells used for the experiments with $^3\vec{\mathrm{He}}$ at IUCF [14] remained uncoated. Aluminized mylar sheets of 1.7 μm thickness were attached to a support frame consisting of 0.2 mm thick aluminum pieces to form a 400 mm long cell of rectangular cross section ($h = 16.6$ mm, $w = 13.1$ mm), shown in Fig. 2. The experimental setup did not include any provision to cool the cell. The authors report a target thickness of $1.5 \cdot 10^{14}$ atoms/cm^2. If restrictions due to deadtime had not been encountered, an order of magnitude higher target thickness would have been possible.

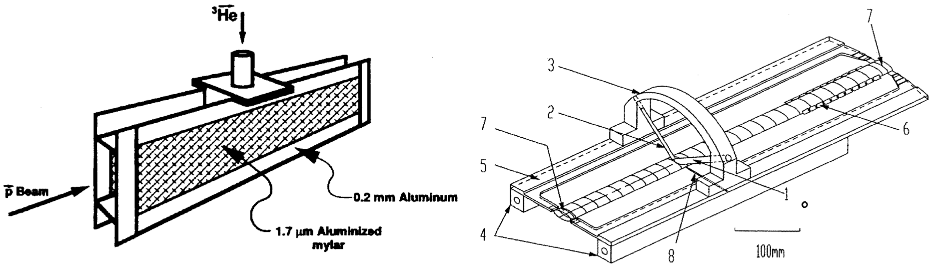

Fig. 2. Storage cells used for the $\vec{p}\,^3\vec{\mathrm{He}}$ studies at IUCF [14] (left) and the storage cell for HERMES [32] (right): 1) H/D feed tube, 2) sample tube, 3) support arch, 4) cooling rails, 5) support plates, 6) cell extension, 7) end support 8) unpolarized feed tube.

4.2.3 HERMES

The storage cell for HERMES at HERA/DESY (Fig. 2) is adapted to the beam distribution by an elliptical cross section ($w = 30$ mm, $h = 10$ mm). The cell walls consist of 75 μm thick aluminum, coated by drifilm to prevent depolarization [33]. The target cell can be cooled to temperatures between 35-260 K by cold helium gas that passes through cooling rails alongside of the target cell. A thin layer of ice is formed inside the cell, which has been found to effectively suppress both depolarization and recombination. This effect was first observed at Heidelberg during the development of the HERMES target polarimeter by Braun [34]. The strong magnetic holding field of the HERMES target must be rather uniform in order to prevent depolarization of target atoms by induced hyperfine transitions that are caused by the periodic time structure of the HERA positron beam [35]. Some aspects of the HERMES target polarimeter are discussed in Sec. 5.3.

4.2.4 PINTEX

For a measurement of low energy recoil particles thin cell walls are required. A storage cell design that complies with this requirement is the PINTEX cell, shown in Fig. 3. Storage cells of this type were used for measurements of polarization observables in *pp*-elastic scattering at IUCF [36]. Thin sheets of Teflon foil of $\approx$

450 μg/cm^2 thickness, stretched over fins, form a quadratic channel of about 1 cm^2 cross section [18, 37].

The storage cells used for the pion production experiments [38] were made from aluminum foil, coated by Teflon TPFE 3170 and similar in design to the cells used by the FILTEX group (see right side of Fig. 1), but employing significantly thinner cell walls of only 25 μm.

Another cell design employed by the PINTEX group is used for measurements of the nuclear polarization of molecular hydrogen formed by recombination inside the cell, where a valve and a Cu-recombiner box are attached to the cell center. Thereby the atomic-to-molecular fraction inside the cell can be varied. Details about this experiment that requires a strong longitudinal holding field can be found in Ref. [39].

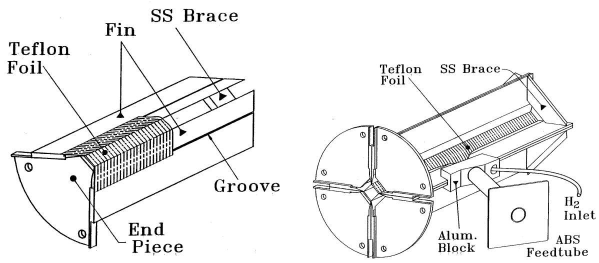

Fig. 3. Storage cell used by PINTEX for measurements of polarization observables in *pp*-elastic scattering [36]. One quadrant is depicted on the left, while the fully assembled cell is shown on the right. (Figures from ref. [18].)

4.2.5 EDDA

First tests with a storage cell inside the COSY machine at Jülich have been performed by the EDDA collaboration [40, 23]. Although the EDDA detector was not designed to accommodate an extended target, employing a storage cell at EDDA would still enhance the target thickness by about a factor ten [40]. In this factor the significant reduction in beam intensity because of acceptance limitations due to the cell during injection ($\approx$50%) has not been taken into account. It should be noted that for the time-reversal-invariance experiment [24] the full target thickness contributes and an enhancement factor of about 60 applies. The test cell of EDDA (Fig. 4) consists of a 300 mm long cell corpus (h = 12 mm, w = 29 mm) of 0.2 mm thick aluminum coated by Teflon PTFE 3170 that can be cooled down to 80-100K. Polarized atoms are injected into the cell through a conical 10 cm long feed tube (entrance/exit diameter 20/12 mm, Fig. 4) that is not rigidly attached to the cell, in order to remove the cell from the beam position without breaking of vacuum.

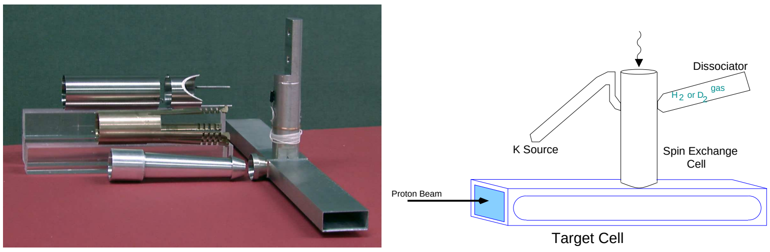

Fig. 4. Storage cell used by EDDA at COSY (left) with cell body and mechanical fixture to hold the conical entrance tube in place [40]. Storage cell used at the optically pumped spin-exchange target at IUCF [41] (right).

4.2.6 Laser-driven Spin-Exchange Target

The storage cell of the first internal target experiment utilizing a laser driven spin-exchange source presently installed at IUCF [41, 26] is shown in Fig. 4. The spin exchange cell is directly attached to the storage cell. Depolarization is inhibited by drifilm coating. In order to prevent condensation of potassium vapour on the cell walls, the temperature of the cell is raised to about 180 °C. The 400 mm long cell of wall thickness 3.2 mm (h = 19.1 mm, w = 38.1 mm) has thin windows of 0.3 mm thickness on the left and right to reduce multiple scattering. With a flow of about 10^{18} polarized atoms/s a target thickness around $4 \cdot 10^{14}$ cm^{-2} with vector polarization $P_z = 0.25$ for both hydrogen and deuterium targets is reported [41].

5 Polarimetry of Internal Gas Targets

Various methods have been applied to the problem of measuring the nuclear polarization of an internal gas target: *i)* Polarimetry through a known reaction, *ii)* extraction of ions formed inside the storage cell and subsequent polarization analysis, and *iii)* polarization analysis of an extracted sample of neutral atoms from the cell. These three methods will be discussed in more detail in this section.

There have also been two optical methods applied to determine the polarization of an internal gas target, both of which at this stage are suitable as a polarization monitor only, and not well adapted for a precise absolute determination of the target polarization. The Balmer-Polarimeter measures the circular polarization of light from hydrogen atoms excited to $n = 3$ states by electron impact [42]. The initial electron polarization of the ground state atoms is partially transfered into angular momentum of the excited state. The emitted Balmer-light is therefore circularly polarized and a measurement of the initial electron polarization is possible. The method is restricted to polarized targets operated in a weak guide field, where to a good approximation electron and nuclear polarization of hydrogen atoms are the same. For the $^3\vec{\mathrm{He}}$ target at HERMES an optical monitor was developed that measures the circular polarization of photons emitted in the $4^1D \to 2^1P$ transition [43].

It should be noted that a known (calibrated) reaction does not distinguish atoms from molecules inside the cell, nor from any other contaminant in the cell. This method is therefore the first choice wherever feasible, because the target is sampled in the same way as in the experiment under consideration. Other methods determine the nuclear polarization of atoms, and, with additional instrumentation also the atomic to molecular fraction in the cell. Recently, the magnitude of target polarization carried by the molecules was studied. A first measurement carried out at NIKHEF suggested a non-vanishing nuclear polarization of recombined deuterium molecules inside a storage cell $P_{\mathrm{molecule}}(D_2^{\mathrm{rec}})/P_{\mathrm{atom}}(D) = 0.81 \pm 0.32$ [44]. A more precise experiment, carried out by the PINTEX group at IUCF with hydrogen, reports $P_{\mathrm{molecule}}(H_2^{\mathrm{rec}})/P_{\mathrm{atom}}(H) = 0.42 \pm 0.02$ [39] in a 0.66 T magnetic field.

5.1 Known Reactions

Suitable for the determination of the nuclear polarization is any calibrated reaction that enables one to deduce the polarization of the target. Two examples are discussed below.

5.1.1 Example 1: 27 MeV αp scattering

Analyzing power and cross section for 27 MeV α particles incident on a proton target are well known [45]. Employing the detector system shown in Fig. 5, polarization and density of the FILTEX polarized hydrogen target could be measured at the Heidelberg Test Storage Ring [8]. The target was operated in a weak vertical magnetic guide field. Two measurements, separated in time by about four weeks during which high proton currents were stored, revealed that the polarization of the target is very stable (Fig. 5). It was concluded that no damage to the wall coating occurred. The target was operated at a temperature of 125 K where the figure of merit is highest.

5.1.2 Example 2: *pp* elastic scattering

The PINTEX detector system at IUCF [19], is designed specifically for experiments involving both polarized beams and polarized targets. It enables a very precise determination of target and beam polarization through the detection of *pp* elastic scattering. A precise analyzing power measurement in *pp* elastic scattering [46] provides the basis of a polarization calibration. It is of great importance that this calibrated polarization can be exported to serve as a standard at other energies [47]. Through the analysis of elastic *pp* events, it was possible to measure the target polarization along the cell axis, as shown in Fig. 6. It was also possible to deduce the effective reversal time (7 ± 1 ms), e.g. the time it takes to completely reverse or reorient the target polarization. High stability and high polarization characterize the longterm behaviour of the target, as illustrated in Fig. 6. Typical target thicknesses of $2 \cdot 10^{13}$ atoms/cm^2 with atomic beam intensities injected into the feed

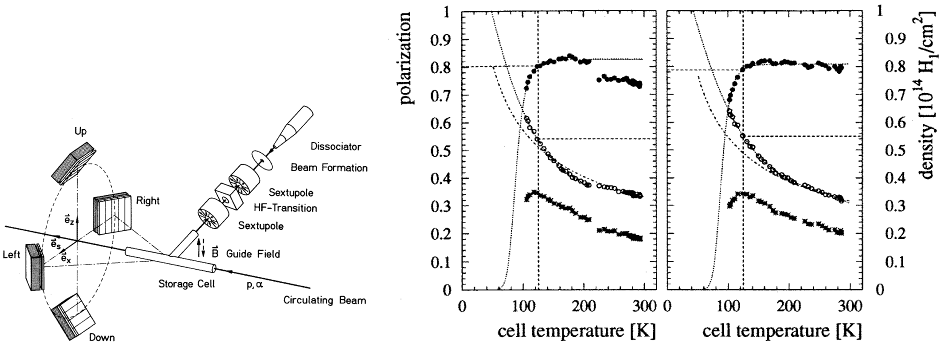

Fig. 5. Polarized internal target setup of the FILTEX test experiment [8] (left). Four sets of scintillation counters are used to detect scattered α-particles. Polarization P ($\bullet$), density d_t ($\circ$) and figure of merit $P^2 \cdot d_t$ ($\star$) of the target as a function of the central cell temperature (right) for two measurements separated by four weeks.

tube of the storage cell of about $3.6 \cdot 10^{16}$ atoms/s are obtained, which correspond to luminosities of about $5 \cdot 10^{28}$ $\mathrm{cm^{-2}s^{-1}}$ [36].

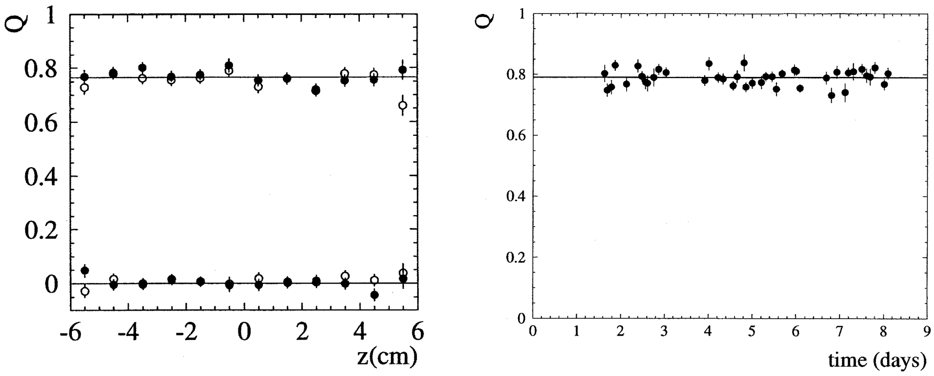

Fig. 6. Target polarization as a function of the longitudinal position in the storage cell (left) and as a function of time during a run (right). (Figures from ref. [48].)

5.2 Ion-Extraction

A first experiment of this kind made use of a low-energy electron beam to ionize the target atoms, which were extracted, accelerated to 70 keV, and directed on a tritiated foil for polarization determination by the $^3\mathrm{H}(\vec{d},n)^4\mathrm{He}$ reaction [49], as discussed in Sec. 4.1. The method can be directly applied to storage cell targets internal to storage rings, because enough atoms are ionized by the orbiting particles. This method is particularly useful in applications, where a strong longitudinal holding field is applied over the target through which the ions are focussed. At the internal target at NIKHEF [20, 50, 51] this method was experimentally realized [52]. The ion-extraction system of the NIKHEF storage cell target, employing a spherical deflector is shown in Fig. 7.

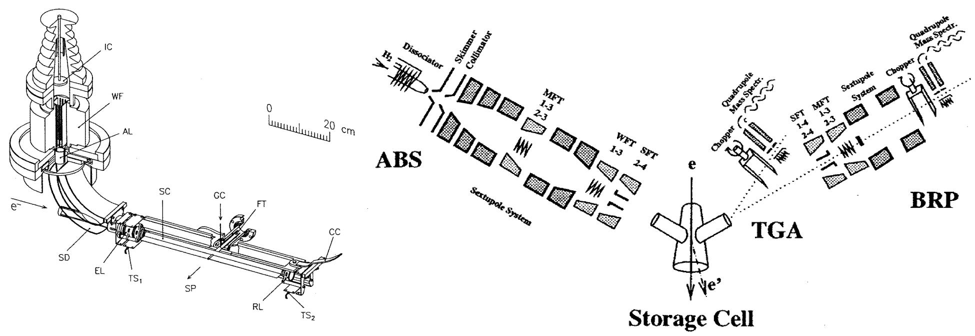

Fig. 7. Left: Storage cell and ion-extraction system used by the NIKEF group. Figure from ref. [51]. SC: storage cell, FT: feed tube, SP: sample port, RL: repeller lens, EL: extraction lens, SD: spherical deflector, WF: Wien-filter. Right: The HERMES target. The storage cell is fed by an atomic beam source (left). The composition of the target gas is measured via a target gas analyzer (TGA). The polarization of the target gas is measured by the Breit-Rabi Polarimeter (BRP). (Figure from ref. [53].)

One drawback of the experimental setup described above is that it is not directly applicable to polarized hydrogen targets, because of a lack of suitable low energy reactions to analyze the polarization of protons. The $^6\mathrm{Li}(\vec{\mathrm{p}},^3\mathrm{He})^4\mathrm{He}$ reaction, mentioned in ref. [49], requires energies of at least 260 keV, where the analyzing power becomes sufficiently large. A more promising method for both hydrogen and deuterium gas targets might be the combination of an ion-extraction system and a Lamb-shift polarimeter [54]. Such a polarimeter system is presently being developed by Schieck and collaborators at the University of Cologne for the polarized internal gas target of ANKE at COSY [55].

5.3 Extraction of a Sample of Polarized Atoms

The polarimeter of the HERMES target determines the nuclear polarization of a small fraction of the target gas ($\approx 3\%$) that is extracted by a sample tube (Fig. 2). A polarization analysis is performed through a measurement of hyperfine state occupation numbers in a Breit-Rabi Polarimeter [34]. The polarimeter (Fig. 7) consists of a set of strong and weak-field transition units and a sextupole magnet system. A chopper is used to suppress background. A separate target gas analyzer measures the atomic to molecular fraction of the target gas. Small systematic errors of 0.01 for the nuclear polarization of the extracted beam sample are reported [53].

6 Conclusions and Outlook

Much experience has been gained in operating polarized internal targets in the environment of electron and ion storage rings. An impressive body of information on systematic effects arising from interactions of beam and target, such as unwanted reactions with the walls of the storage cell, radiation damage of the wall coating, longterm behaviour etc. has been obtained. The physics results cover a wide range of topics from deep inelastic polarized lepton-nucleon scattering to measurements of spin correlation parameters and analyzing powers in elastic and inelastic proton-proton collisions. Atomic physics experiments are underway to investigate polarization effects in recombined hydrogen and deuterium molecules. The experiments benefit from the high purity of the target material and the high degree of polarization. Fast polarization reversal and the alignment along different axes eliminates systematic asymmetries to a high degree. Furthermore, the low target thickness turns out to be actually a benefit, because lifetime and high momentum resolution of the stored beam are hardly altered by the target. Polarized targets internal to a storage ring can thus be regarded as an ideal tool for high precision experiments. They have just begun to open a new door to hadronic interaction studies and one is inclined to predict they will continue to play a major role in years to come.

However, the need for higher target thickness prevails, particularly for electro-nuclear experiments. Most experiments could digest a factor ten higher target densities from sources of polarized H and D atoms used to feed storage cell targets. New developments in this field address a new dissociator based on a surface wave plasma discharge [56] and studies of a carrier jet system [57]. Higher fluxes of polarized atoms may be achieved through the development of new high field sextupole magnet systems. Considering the currently achievable fluxes from sources of polarized atoms, a substantial increase of the luminosity may also come from reduced transverse dimensions of the employed storage cells.

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