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POLARIZED FEW-NUCLEON TARGETS: NEW DEVELOPMENTS

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Abstract

We discuss recent improvements in producing polarized few-nucleon targets for nuclear and particle physics experiments. The emphasis is on progress with polarized gas targets intended for experiments at electron and proton storage rings.

1. Introduction

The cross sections for the scattering of leptons or hadrons from few-nucleon targets depend on the incoherent sum of the squares of (spin-dependent) amplitudes. In contrast to the cross sections, spin dependent observables probe both the magnitudes and relative phases of the basic amplitudes. Measurements of cross sections have thus frequently been useful in supporting theoretical models, whereas measurements of spin observables involving either polarized beams, or polarized targets, or both, have often been instrumental in burying some of the models, or in restricting the range of their applicability. As examples we mention: i) the observation of large spin effects with high energy protons in high-$p_\perp$ pp collisions [1], which is in contradiction to simple expectations of perturbative QCD; ii) the measurement of the spin structure function of the proton [2] which has led to the 'spin crisis', i.e. the realization that a large fraction of the proton spin may not be carried by the constituent quarks; iii) measurements of complete spin observables in elastic proton scattering from nuclei at intermediate energies (see e.g. ref 3) have exposed the inadequacy of conventional nonrelativistic scattering theories [4] and stimulated developments of density-dependent nucleon-nucleon interactions [5] and of relativistic impulse approximation calculations based on the Dirac equation [6].

In the following we give a brief introductory survey of the physics and technology of producing polarized targets. We limit the discussion to the light targets ^{1}H, ^{2}H and ^{3}He which are of greatest interest for intermediate and high energy physics. The principles involved are emphasized, with little mention of technical details. For more thorough discussions we refer the reader to recent conferences on polarization phenomena [7,8] and to the original literature.

2. General Considerations

2.1 Reaction Rates and Asymmetries

A critical consideration in any experiment is the optimization of the reaction rate

$$Y = \mathcal{L}\frac{d\sigma}{d\Omega}\Delta\Omega \; s^{-1}$$

where $d\sigma/d\Omega$ is the cross section of interest and $\Delta\Omega$ the detector solid angle. The luminosity

$$\mathcal{L} = F n_{targ} \; cm^{-2}s^{-1}$$

is a product of the beam flux F (number of beam particles per sec) and the areal density of the target n_{targ} (number/cm^2). Limits on n_{targ} may be imposed by target technology, but also, in the case of electron and proton storage rings, by requirements of accelerator operation. Targets in storage rings have to be very thin (typically $\leq 10^{-15}$ atoms cm^{-2}) to guarantee a sufficiently long lifetime of the stored beam. For fixed target experiments with hadronic beams luminosities $\mathcal{L} \approx 10^{28}$ cm^{-2}s^{-1} may be sufficient. In a recent experiment [9] this value was realized with a secondary pion beam of 5×10^6 /s and a polarized target of $n_{targ} = 2 \times 10^{21}$ ^{3}He atoms/cm^2. This can be contrasted with the projected luminosity of the HERMES experiment [10], $\mathcal{L} \approx 4 \times 10^{31}$ cm^{-2}s^{-1}, with a 30 GeV electron beam flux $F \approx 4 \times 10^{17}$ e$^-$s^{-1} and $n_{targ} \approx 10^{14}$ H or D atoms/cm^2.

The reaction yield in experiments with a pure, polarized target is

$$Y \uparrow \propto \sigma(1 + P_{targ}A)$$

where σ is the (unpolarized) differential cross section, and P_{targ} is the target polarization. A, the asymmetry of interest, can be obtained from the ratio of normalized yields,

$$R_o = \frac{Y\uparrow - Y\downarrow}{Y\uparrow + Y\downarrow} = P_{targ}A \; .$$

If the target contains, in addition to the fraction f_A of polarized atoms, a fraction (1 - f_A) of unpolarized material, the ratio $R = fR_o$ is attenuated by a 'dilution factor' f, i.e.

$$f = \frac{f_A\sigma}{(1 - f_A)\sigma_o + f_A\sigma}$$

where σ_o is the average cross section for the unpolarized atoms. Assuming the asymmetry A of interest to be small, the relative error in A is obtained from

$$\left(\frac{\delta A}{A}\right)^2 = \frac{1}{f^2 R_o^2 (Y\uparrow + Y\downarrow)} + \left(\frac{\delta P_{targ}}{P_{targ}}\right)^2 + \left(\frac{\delta f}{f}\right)^2$$

From this expression it is evident that P_{targ} and f should be determined as well as possible. A 'figure-of-merit' for the target, J_{targ}, can then be defined, which is inversely proportional to the running time required to achieve a chosen accuracy δA, i.e.

$$J_{targ} = n_{targ} P_{targ}^2 f^2.$$

For internal, window-less gas targets, which consist of a polarizing cell and a transfer line to a storage cell [11] with openings for the beam, an appropriate definition of the 'figure-of-merit' of the target is

$$J_{targ} = N\epsilon\, T_c^{-\frac{1}{2}} P_{targ}^2 f^2 \,.$$

Here N is the feed intensity into the polarizing cell, ϵ is the injection efficiency into the storage cell, and T_c the temperature of the storage cell. The density of gas atoms in the storage cell is proportional to $N\epsilon$, and inversely proportional to C, the combined gas conductance of the openings of the cell. For typical storage cell tube diameters compatible with beam requirements in the storage ring a thickness of $n_{targ} \approx 10^{14}$ cm^{-2} requires a feed intensity of the order of $I \approx 10^{17}$ /s. Cooling the cell increases the target thickness since the gas conductance decreases in proportion to the velocity of the atoms in the cell.

2.2 Principles of Nuclear Polarization

Although there exist a wide variety of polarized targets, several common features are shared by all the various methods used. The initial step always involves producing *atomic polarization* in the sample. Because the electron magnetic moment exceeds that of the nucleus by a large factor this is much easier than polarizing the nuclear spin directly. At low temperatures ($< 1K$) and high magnetic fields ($> 2T$) the statistical Boltzmann factor, $e^{-\mu_J B/kT}$, strongly favors population of the atomic substate m_J with the lowest magnetic energy. If an atomic beam in a Stern-Gerlach setup traverses a sextupole magnet with field gradient dB/dz the magnetic force perpendicular to the beam separates spatially the different magnetic substates of the atomic spin J because in strong fields m_J is a good quantum number. Another powerful method of producing atomic polarization is optical pumping [12], using circularly polarized photons from a laser. The repeated resonant absorption of $|\Delta m_J| = 1$ photons can result in nearly complete polarization of the atomic ground state.

In the next important step the *hyperfine interaction* between atomic spin J and nuclear spin I is exploited to transfer atomic polarization to the nucleus. For example, unwanted nuclear substates can be removed by microwave irradiation. In the Stern-Gerlach atomic beam source RF frequencies in weak fields can be tuned to transitions between two specific hyperfine states characterized by total spin F and substate m_F. The strong fields of the sextupole can then select those substates with a specific m_J and the wanted nuclear polarization m_I. Atomic polarization can also be transferred from one species to the nucleus of another species via the Fermi contact hyperfine interaction operating during collisions in the gas phase. This method is used in spin-exchange optical pumping.

The maximum value of the nuclear polarization depends on the *spin relaxation* processes in the sample. If we denote the polarization rate by γ_{pol} and the spin relaxation rate by $\Gamma_{rel} = T_1^{-1}$ the time-dependence of the nuclear polarization is

$$P_{targ}(t) = \frac{\gamma_{pol}}{\gamma_{pol} + \Gamma_{rel}} e^{-(\gamma_{pol} + \Gamma_{rel})t}.$$

The asymptotic value of P_{targ} is thus critically dependent on achieving long spin relaxation times T_1. Spin-relaxation mechanisms are caused by fluctuating magnetic fields at the cell surface associated with i) Fermi contact interaction with conduction s-band electrons in a metal [13]; ii) dipole-dipole interaction of diffusing spins [14]; iii) spin-orbit interactions. Careful sample preparation to eliminate harmful impurities is generally crucial. For gaseous targets it is necessary to coat the metallic walls of storage cells with a suitable substance, e.g. drifilm, or, at low temperatures, liquid N_2. The upper limit for T_1 in gases is caused by the dipole-dipole interaction of colliding polarized gas atoms which may become important especially at high pressures. For ^{3}He at 10 atm observed values for T_1 of $\approx$50 hours [15] are compatible with this relaxation mechanism becoming dominant. A special problem arises in electron storage rings where the beam bunches cause a significant time-dependent magnetic field around which the nuclear spin can precess. This problem can be overcome by applying a sufficiently strong magnetic holding field in the direction of the nuclear polarization.

The final step is a measurement of the absolute value of the nuclear polarization in the target. For double-cell arrangements where the polarization in the pumping cell may differ from that in the storage cell, and at storage rings where there may be significant beam-target interactions, the measurement should ideally sample atoms from the beam region only. If the target contains a sufficient number of atoms ($> 10^{18}$) the polarization can be measured and reversed by adiabatic-fast-passage NMR (AFP) [15,16]. The method can be calibrated by measuring, at the same RF frequency, signals from protons in a room-temperature H_2O sample in a cell of identical dimensions. In atomic beam setups the hyperfine states from a sample of the target gas can be analyzed by a

combination of deflections in the inhomogeneous fields of a sextupole magnet and by inducing RF transitions. The method of polarization analysis is essentially the same as that of producing the polarization. To separate atoms from recombined molecules the atomic beam can be chopped and analyzed in a quadrupole mass spectrometer [17]. In special cases a reaction asymmetry, which had been determined previously using an unpolarized target, can be used to measure the polarization of nuclei in the beam. For example, the target-related asymmetry of the ^{3}He(p,π^+)^{4}He reaction has been measured [18] to deduce accurate absolute polarizations of the TRIUMF ^{3}He target.

3. Polarized Targets of Hydrogen and Deuterium

3.1 Dynamic Nuclear Polarization at Low Temperatures

Most of our present knowledge of spin-dependent amplitudes involving polarized nucleons has come from solid targets polarized at low temperature and large magnetic fields by the method of dynamic nuclear polarization (DNP). If paramagnetic ions with spin S are embedded in a solid crystal containing nuclei (H or D) of spin I the dipole-dipole Hamiltonian is

$$\mathcal{H} = g\beta\vec{S}\cdot\vec{H} - g_n\beta\vec{I}\cdot\vec{H} - \frac{gg_n\beta^2}{r^3}\vec{I}\cdot\vec{S} - \frac{3(\vec{I}\cdot\vec{r})(\vec{S}\cdot\vec{r})}{r^2}$$

where r is the distance between the I and S dipoles. Irradiation with a strong RF field (ν = 28 GHz/T) to saturate one of two forbidden flip-flop transitions ($\Delta M_S = +1$, $|\Delta m_I| = 1$, e.g. I_-S_+) gives rise to nuclear orientation because the electron spin relaxation of a paramagnetic impurity is very short (rate T_{1e}^{-1}), while the nuclear polarization is largely decoupled from the electron spin and transported away slowly by spin diffusion (rate T_{1n}^{-1}). Because of the short paramagnetic relaxation and the weak coupling to the nuclear spin the method works even when the nuclei greatly outnumber the electronic spins. The nuclear polarization can be reversed by changing the RF frequency to saturate the other forbidden transition (e.g. I_+S_+). For Kramers ions such as Nd^{3+}, and at low temperatures, a model [19] predicts, generally in good agreement with experiment,

$$T_{1e} = AH^5\, coth(h\beta H/2kT)$$

and

$$T_{1n}^{-1} = T_{1e}^{-1}\frac{3\beta^2}{10Hr^6}sech^2(g\beta H/2kT)$$

At large H/T the last factor becomes extremely small

$$T_{1n}^{-1}(H,T) \propto H^3\, e^{-g\beta H/2kT},$$

Table 1. Materials used for DNP
From: W. Weyer, Helv. Phys. Acta 59 (1986) 728

material	polarized nucleons (%)	doping method	paramagnetic impurity	maximum polarization
$C_4\ H_9\ OH$	13.5	chemical	porphyrexide	0.80
$C_8\ H_{11}\ OH$	13.6	chemical	chromium V	0.95
$C_3\ H_6\ (OH)_2$	10.8	chemical	chromium V	0.98
$N\ H_3$	17.6	irradiation	NH_2	0.96
$C_3\ D_9\ OD$	23.8	chemical	chromium V	0.35
$C_3\ D_6\ (OD)_2$	0.30	irradiation	ND_2	0.49

suggesting the utility of semipermanent, 'frozen spin' targets (T_{1n} of several weeks is possible). Density matrix methods and the concepts of spin temperatures for the spin reservoir of the electronic system with a temperature separate from the Zeeman reservoir of nuclear spins have been developed [20] to describe cases where the electron spin resonance (ESR) linewidth $\delta\nu_e$ is comparable to the nuclear frequency ν_n.

High polarizations were first obtained by Schmugge and Jeffries [21] in lanthanum magnesium nitrate doped with a few % of Nd^{3+}. Currently used apparatus consists typically of a large magnet (2-5 tesla), a $^3He/^4He$ dilution refrigerator, a microwave generator (50-140 GHz, 1 Watt), and an NMR system for detecting the nuclear polarization. In addition to this hardware one has to develop electronic spin systems in materials of high H (or D) content with narrow ESR linewidth and high radiation damage resistance. A list of currently used materials is given in Table 1.

The NH_3 target of Crabb *et al* [22] uses a ^4He refrigerator of 1 Watt cooling power and a 5 T magnet, ν_e = 140 GHz and T = 1K to obtain rapidly ($\approx$ 30 mins.) high proton polarizations of $\approx$0.96. This target can accomodate high proton beam fluxes to study asymmetries in high-$p_\perp$ pp scattering [1]. The experiment detects both protons in a two-arm coincidence experiment, with negligible quasielastic background from knockout protons from N_2 and He. Thus the low dilution factor $f_A = 0.176$ is unimportant. This is in contrast to attempts by the SMC collaboration (NA47 at CERN) to measure the spin-dependent structure function of the neutron in a singles experiment using a butanol DNP target [23]. High statistical accuracy will be required to offset the unfavorable product ($fP_{targ} \approx 0.1$).

3.2 Ultracold Hydrogen Jet

At sufficiently low temperatures (< 0.5 K) and high fields (5-7 T) electron-

spin polarized atomic hydrogen can be trapped in magnetic storage bottles with densities in excess of 10^{18} atoms/cm^3 [24]. Because of the high degree of electron polarization ($\mu_e H \gg kT$) two hydrogen atoms with aligned spin cannot recombine to form a molecule. Niinikoski [25] and Kleppner [26] proposed to form a high-density polarized hydrogen beam by ESR pumping of transitions to the upper hyperfine states. The flipped atoms, now on a potential hill, accelerate out of the field to form an intense, low-velocity beam with a narrow velocity distribution. If the four energy states of H are labelled a-d in order of increasing energy the a and b states are trapped and the b and d states are expelled. At a field of 5 T the two allowed single-photon transitions have a frequency of 140 GHz and a frequency difference of 1240 MHz, equal to the hyperfine splitting. The nuclear and electron polarized atoms c (or d) diffuse into the field gradient region and, if they survive molecular recombination, are ejected as an atomic beam with a velocity of ≈200 m/s.

Two such setups are at present under development for the NEPTUN/NEPTUN-A high-$p_\perp$ pp scattering experiment at the 400 GeV UNK accelerator, one at the University of Michigan [27], and one at Dubna [28]. The apparatus consists of RF dissociator, continuous-flow dilution refrigerator, and a superconducting magnet producing an 8 T axial field. Wall coatings of teflon and ^{4}He are used to prevent recombination of atomic H. Microwaves are injected from one side of the bore of the magnet and the ejected atomic beam exits on the opposite side. A sextupole magnet is then used to focus the atomic beam. With a prototype jet the Michigan group has achieved an intensity of $N = 10^{16}$ atoms/s corresponding to a target thickness of $\approx 10^{12}$ atoms/s. The design aim for NEPTUNA is a target thickness of 10^{14} atoms/s.

3.3 Atomic Beam Source H and D Gas Targets

The classic Stern-Gerlach atomic beam source (ABS) for producing polarized protons and deuterium consists of dissociator, sextupole magnet for the selection of one electronic m_J state, RF transition in a weak field (one frequency for H, two for D, see Breit-Rabi diagrams), followed by another sextupole magnet which selects only the wanted hyperfine component. The resulting polarization, measured with an atomic-beam sampling polarimeter (see e.g. ref. 17), is high, but the intensity has been limited to typically $N \approx 3 \times 10^{16}$ atoms/s. At high flow rates powerful two-stage differential pumping, wall coatings, and careful optimization of the sextupole fields are necessary. A target of this kind has been operated at the VEPP-4 electron storage ring at Novosibirsk [29] giving a target thickness of $\approx 2 \times 10^{11}$ atoms/cm^2.

Following a suggestion of Haeberli [11] the target density can be increased by two orders of magnitude when the atomic beam is fed into a cooled storage cell. This technique has been applied recently at VEPP-3 [30] to measure the tensor

analyzing power T_{20} in $\vec{D}(\vec{e},e)$ scattering at 2 GeV. It is actively developed for experiments with antiprotons at LEAR (FILTEX), with 30 GeV electrons at HERA (HERMES), with 200-500 MeV protons at IUCF, and with the electron stretcher rings at NIKHEF and Bates. Impressive progress has been made recently by a Heidelberg-Marburg-München collaboration using the MPI Heidelberg test storage ring [31]. By careful optimization of the hydrogen ABS a record intensity of 8×10^{16} H atoms/s in two substates has been achieved. This flux was injected into a T-shaped storage cell of 11 mm diam and 250 mm length. The walls were teflon-coated to inhibit recombination and depolarization. Target thickness and polarization were deduced from elastic scattering of 27 MeV α particles from the storage ring using a coincidence setup. At an optimum working temperature of 80 K, and with two hydrogen substates, $P_{targ} = 0.45$ was measured compared to a maximum value of 0.5. The experiment showed that at least 90% of the initial polarization is conserved, although the atoms undergo about 500 wall collisions before leaving the cell. From these results one can expect that for the HERMES target in the HERA electron ring, with two substates in a strong axial decoupling field, areal densities of $n_{targ} = 1 \times 10^{14}$ H or D atoms/cm^2 and polarizations of 0.8-0.9 can be obtained.

3.4 Laser-Driven H and D Gas Targets

Higher polarized proton and deuterium intensities than those of ABS sources can in principle be achieved if spin exchange optical pumping is employed. Such a target is being developed for $\vec{D}(\vec{e},e)$ experiments at Novosibirsk by the group of R. Holt *et al* at the Argonne National Laboratory [32]. Deuterium gas is dissociated by an RF discharge and fed into an optical pumping glass cell which contains K vapor. A circularly polarized beam of 770.1 nm photons ($\sigma^{\pm}$, $\Delta m_J = \mp 1$) from a Titanium doped sapphire (Ti^{3+}:Al_2O_3) laser is used to optically pump the $P_{1/2} \rightarrow P_{3/2}$ D1 line of K. The atomic spin is transferred to the deuterium atom by spin-exchange collisions. The polarization of the deuterium atom, P_e, depends on the spin exchange rate, γ_{SE}, and on the combined spin relaxation rates for deuterium, Γ_{rel}, i.e.

$$P_e = P_K \frac{\gamma_{SE}}{\gamma_{SE} + \Gamma_{rel}}.$$

After obtaining polarized D atoms one has to induce RF hyperfine transitions in a medium magnetic field to produce nuclear polarization. Monte Carlo calculations suggest that values close to $P_{zz} = P_K$ and $P_{zz} = -P_K$ should be achievable for σ^+ and σ^- optical pumping, respectively. Deuterium atoms of large nuclear polarization will then be introduced into a cooled storage cell to increase the target density.

The major obstacle for producing high intensities consists in the fact that, at low magnetic fields, P_K is large only at K densities $[K] \ll 10^{12}$ cm^{-3} thus limiting

the spin exchange rate to values $\gamma_{SE} \leq \Gamma_{rel}$. At the high K concentrations necessary to increase γ_{SE} sufficiently P_K is substantially reduced by 'radiation trapping', i.e. the re-absorption of fluorescent photons ($\pi, \Delta m_J = 0$) de-exciting the $P_{3/2}$ excited state of K. At high magnetic fields radiation trapping is known to occur [33] at higher alkali densities ($\approx 10^{13}$ cm^{-3}) because the nuclear Zeeman splitting increases the energy spacing between the σ and π transitions. This has been demonstrated recently [34] using a 0.22 T field. Optical pumping of K at a density $[K] = 1.2 \times 10^{12}$ cm^{-3} occurred in a drifilm-coated pyrex cell at a deuterium flow rate of 1.7×10^{17} s^{-1}. The spin exchange rate $\gamma_{SE} \sim 1700$ s^{-1} was a factor six higher than could be achieved at low fields. The atomic polarization of the deuterium atoms was measured in a polarimeter consisting of a sextupole magnet followed by a compression tube detector. The molecular D_2 fraction was measured with a quadrupole mass spectrometer. From these data an atomic polarization of D of 0.73±0.03 was obtained. With increased laser power and improvements in the wall coatings of the dissociator an even higher figure-of-merit is anticipated. With further, in principle straightforward, developments of this method areal target densities of $10^{14} - 10^{15}$ atoms/cm^2 should be possible.

4. Polarized Targets of ^{3}He

The interest in polarized ^{3}He arises because nuclear structure models predict [35] that the two protons are mainly in a spatially symmetric S state, with the unpaired neutron carrying about 90% of the ^{3}He spin. Quasielastic and deep inelastic scattering of polarized electrons from polarized ^{3}He can thus provide information on electromagnetic form factors and on the internal spin structure of the neutron.

Forcible nuclear orientation methods using low temepratures and high magnetic fields have achieved high polarizations in solid ^{3}He [36]. The large magnetic fields and low heat capacity of the solid make these targets of limited use for applications in nuclear and particle physics. The only practical methods employ laser optical pumping of gaseous ^{3}He.

4.1 Metastability-Exchange Optical Pumping of ^{3}He

This method was developed three decades ago by Colegrove, Schearer and Walters [37]. Because of the high photon energy of 21 eV to reach the first excited state of He direct optical pumping is not feasible. Instead an indirect approach is chosen in which metastable helium atoms are polarized, and the polarization is transferred to the ground state atoms by metastability exchange collisions. Metastable 2 $^3S_1$ atoms are efficiently produced at $\sim$ 1 Torr of pure

helium in an electrode-less RF discharge. The metastables (density $[He^*] \approx 10^{10}/cm^3$) are optically pumped using the $2\ ^3S_1 \rightarrow 2\ ^3P_1$ transition at 1083 nm. With present arc-lamp-pumped Nd:LMA (neodymium-doped magnesium hexaluminate) lasers high output power ($\approx$ 5 Watts) and several longitudinal modes within the Doppler width of the He gas can be obtained [38]. The resultant electronic polarization is partially transferred to the nuclei by the hyperfine interaction. In a metastablity exchange collison the incoming metastable atom transfers its atomic excitation to the incoming ground state atom, leaving the outgoing ground state atom with the partially polarized nucleus. The reaction constant for this transfer is extremely large, $\gamma \approx 10^{-11}$ cm^3/s. A typical time constant for obtaining a steady-state value for the polarization is 1 min. For a laser power of 0.4 Watt the spin transfer rate is very large, about 2.5×10^{18}/s. The circular polarization of the 668 nm $3\ ^1D_2 \rightarrow 2\ ^1P_1$ light emitted from the discharge can be used as a relative polarization monitor [39]. This method has recently been re-calibrated [40] using AFP [15,16].

Since optical pumping by metastability exchange is efficient only at low pressure two methods are being used to increase the density of ^{3}He. The first of these was pioneered by J. Daniels *et al* [41] who used a Hg-Toepler pump to mechanically compress the ^{3}He gas. The difficulties consist in keeping the gas clean of impurities and avoiding any material such as stainless steel that could contribute to the spin relaxation rate. A group at Mainz [42] has achieved a pressure of 685 Torr in a volume of 120 cm^3 at a steady-state polarization of 0.3.

The second method of increasing the pressure involves coupling of the low-pressure pumping cell to a cooled storage cell [43]. Using this target at Bates, asymmetries in quasi-elastic scattering of polarized electrons from polarized ^{3}He were measured at $Q^2 = -0.2$ (GeV/c)^2 [44]. Two reaction geometries were used to determine asymmetries $A_{T'} \propto G_M^2$ and $A_{TL'} \propto G_M G_E$. The statistical accuracy was insufficient to judge the validity of the PWIA analysis [45] or to extract useful information on the neutron electric form factor G_E. Recently an improved version of this target has been constructed and tested [46] by an MIT/Madison/IUCF/Caltech collaboration using a 45 MeV proton beam from the IUCF cooler. During proton beam-on, the target was operated at a polarization of 0.40, flow rate of 1.2×10^{17}/s, and target thickness of 1.2×10^{14}/cmn^2. The storage cell dimensions were $16 \times 14 \times 400$ mm^2. This performance meets already the design goals for the ^{3}He part of the HERMES experiment [10].

4.2 Spin-Exchange Optical Pumping of ^{3}He

This method was discovered, also some three decades ago, by Bouchiat, Carver and Varnum [47], and developed further by Gamblin and Carver [48]. Alkali atoms, usually Rb at a density $[Rb] \approx 4 \times 10^{14}/cm^3$, are optically pumped via the 794.8 nm $5s\ ^2S_{1/2} \rightarrow 5p\ ^2P_{1/2}$ D1 transition. To avoid radiation trapping

at these high alkali densities a small amount of nitrogen (100 Torr) is present [49] to ensure radiation-less de-excitation of the $5p\ ^2P_{1/2}$ excited state of Rb. Absorption lineshapes, pressure shifts, and pressure broadening for ^{3}He pressures between 3-12 atm have been measured by Larson *et al* [15]. The atomic polarization is transferred to ^{3}He during He-Rb collisions via the contact hyperfine interaction. Because of the extremely small velocity-averaged spin exchange cross section, $< \sigma_{SE} v > \approx 6 \times 10^{-20}$ cm^3/s [15] pump-up times $\gamma_{SE}^{-1} \sim 10$ hours are encountered. To achieve relaxation times $T_1 \gg \gamma_{SE}^{-1}$ the cells have to be made of alumino-silicate glass (Corning 1720), and great care has to be taken to exclude impurities from the cell and the gas. Values of T_1 of 200 hours at 3 atm, and 50 hours at 10 atm, have been observed.

The advent of (Ti^{3+}:Al_2O_3) lasers of at least 4 Watt at 800 nm, and the development at TRIUMF of a cryogenic technique to boost the ^{3}He pressure to $\sim$ 10 atm [15] has greatly improved the figure-of-merit of this type of target. Present TRIUMF targets have a volume of 35-60 cm^3, and a density of (2-3)$\times 10^{20}$/cm^3. Using a laser power of 7-10 Watts, a steady-state polarization of typically 0.6-0.7, measured by AFP [15,16] or by the ^{3}He(p,π^+) reaction [18], can be maintained routinely over periods of many weeks. The target has the disadvantage of presenting $\sim$ 0.15 mm thick glass walls to the beam. The backgrounds from these 'hot spots' have been eliminated using tracking chambers which allow vertex reconstruction to the target. The N_2 impurity in the target (3.5 % atomic fraction, 15 % nucleonic fraction) has not significantly degraded the precision of the experiments carried out so far.

Because of the large figure-of-merit of the spin-exchange target a number of physics results have been obtained:

- parity and time-reversal violation studies [50] in resonance neutron absorption.
- measurements of quasi-elastic electron scattering to determine the neutron electric form factor at Bates has given results [51] similar to those of ref. 44.
- spin-distributions of nucleons in ^{3}He were probed for the first time by ^{3}He(p,2p) and (p,pn) knockout reactions at E_p = 220 and 290 MeV [52].
- a complete set of parity-allowed spin correlation parameters A_{ooij} at E_p = 200 and 500 MeV probes six complex spin-dependent amplitudes for elastic scattering of polarized protons [3,53]. For this purpose an adiabatic spin rotator has been built which allows the ^{3}He spin to be oriented in any direction in space. Low polarization losses per spin reversal of $\leq 10^{-5}$ imply a reduction of systematic errors by increasing the frequency of target spin flips.

- asymmetries in elastic pion scattering at $E_{\pi\pm} = 100$ MeV were found [9] to be extremely large at some angles, in agreement with an elaborate reaction model [54].

A large target of the spin-exchange type is at present being constructed for E142, an experiment to measure the spin structure function of the neutron using 23 GeV longitudinally polarized electrons at SLAC Endstation A. The target, a double-cell arrangement joined by a capillary, consists of a hot pumping cell containing the Rb, and a room-temperature target cell of 100 cm^3 volume. The areal density of the target is projected to be 8×10^{21} ^{3}He atoms/cm^2.

References

1. D.G. Crabb *et al*, Phys. Rev Lett. 65 (1990) 3241.
2. J. Ashman *et al*, Nucl. Phys. B328 (1989) 1.
3. O. Häusser, Colloq. de. Phys. 51 (1990) C6-99.
4. A.K. Kerman, H. McManus and R.M. Thaler, Ann. Phys. 8 (1959) 551.
5. L. Rikus and H.V. Geramb, Nucl. Phys. A426 1984) 496.
6. D. P. Murdock and C. J. Horowitz, Phys. Rev. C35 (1987) 1442.
7. PARIS90, Conf. Proc., Editions Frontieres, (Gif-sur-Yvette, 1990), J. Phys. (Paris), Colloq. 51, (1990).
8. *High Energy Spin Physics*, Bonn 1990, ed. by K.-H. Althoff, and W. Meyer, (Springer Verlag, Berlin, 1991).
9. B. Larson *et al*, Phys. Rev. Lett. 67 (1992) 3356.
10. The HERMES Collaboration, DESY PRC 90/01, (1990).
11. W. Haeberli, in *Nuclear Physics with Stored Cooled Beams*, AIP Conf. Proc. No. 128, (AIP, NY 1984), p. 251.
12. W. Happer, Rev. Mod. Phys. 14 (1972) 169.
13. K. Wassmuth and D. Fick, Phys. Rev. Lett. 59 (1987) 3007.
14. A. Abragam, *Principles of Nuclear Magnetism*, (Oxford University Press, Oxford, 1961).
15. B. Larson *et al*, Phys. Rev. A44 (1991) 2'08.
16. T.E. Chupp and K. Coulter, Phys. Rev. Lett. 55 (1985) 1074.
17. H.-G. Gaul, *High Energy Spin Physics*, Bonn 1990, (Springer Verlag, Berlin, 1991), p. 204.
18. O. Häusser, *Spin and Isospin in Nuclear Reactions*, Proc. Telluride Conf., ed. by S.W. Wissink (Plenum, New York, 1991) p.
19. T.J. Schmugge and C.D. Jeffries, Phys. Rev. 138 (1965) A1785.
20. A. Abragam and M. Goldman, Repts. Prog. Phys. 41 (1978) 397.

21. T.J. Schmugge and C.D. Jeffries, Phys. Rev. Lett. 9 (1962) 269.
22. D.G. Crabb *et al*, Phys. Rev. Lett. 64 (1990) 2627.
23. L. Klostermann, these proceedings.
24. H.F. Hess *et al*, Phys. Rev. Lett. 51 (1983) 483.
25. T.O. Niinikoski, Proc. Int. Symp. on *Spin Physics with Polarized Beams and Targets*, 1980, (Basel and Stuttgart, 1981),p. 91.
26. D. Kleppner and T.J. Greytag, Proc. Int. Conf. on *High Energy Spin Physics*, AIP Conf. Proc. 95 (1983) 546.
27. R.S. Raymond and T. Roser, in *High Energy Spin Physics*, Bonn 1990, ed. by K.-H. Althoff and W. Meyer, (Springer Verlag, Berlin, 1991) p. 156.
28. V.P. Ershov *et al*, in *High Energy Spin Physics*, Bonn 1990, ed. by K.-H. Althoff and W. Meyer, (Springer Verlag, Berlin, 1991) p. 160.
29. D.K. Toporkov *et al*, VIIIth Int. Symp. High Energy Spin Physics, Minneapolis, Particles and Fields Series 37, Vol. II (1989) 1286.
30. R. Gilman *et al*, Phys. Rev. Lett. 65 (1990) 1733.
31. E. Steffens, private communication.
32. L. Young *et al*, Nucl. Phys. A497 (1989) 529c.
33. D. Tupa and L.W. Anderson, Phys. Rev. A36 (1987) 2142.
34. K.P. Coulter *et al*, preprint (1992).
35. J.L. Friar *et al*, Phys. Rev. C42 (1990) 2310.
36. R.T. Johnson *et al*, J. Low. Temp. Phys. 10 (1973) 35.
37. F.D. Colegrove, L.D. Schearer, and G.K. Walters, Phys. Rev. 132 (1963) 2561.
38. C.G. Aminoff *et al*, J. Lum. 50 (1991) 21.
39. M. Pavlovic et F. Laloë, J. Phys. (Paris) 31 (1970) 173.
40. W.B. Lorenzon *et al*, Caltech preprint.
41. R.S. Timsit, J.M. Daniels, E.F. Dennig, A.K.C. Kiang, and A.D. May, Can. J. Phys. 49 (1971) 508.
42. W. Heil *et al*, in *High Energy Spin Physics*, Bonn 1990, ed. by K.-H. Althoff and W. Meyer, (Springer Verlag, Berlin, 1991) p. 178.
43. R.G. Milner, R.D. McKeown, and C.E. Woodward, Nucl. Instr. and Methods A274 (1988) 56.
44. C.E. Woodward *et al*, Phys. Rev. Lett. 65 (1990) 698.
45. B. Blankleider and R.M. Woloshyn, Phys. Rev. C29 (1984) 538.
46. R.G. Milner, private communication.
47. M.A. Bouchiat, T.R. Carver and C.M. Varnum, Phys. Rev. Lett. 5 (1960) 373.
48. R.L. Gamblin and T.R. Carver, Phys. Rev. 138 (1965) 964.

49. T.E. Chupp *et al*, Phys. Rev. C36 (1987) 2244.
50. K.P. Coulter, PhD Thesis, Princeton University (1989).
51. A.K. Thompson *et al*, Phys. Rev. Lett., in press.
52. A. Rahav *et al*, Phys. Lett. B275 (1992) 259; E.J. Brash *et al*, to be published.
53. E.J. Brash *et al*, to be published.
54. C. Bennhold, B.K. Jennings, L. Tiator and S.S. Kamalov, TRIUMF preprint.