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Title: Development Of A Hydrogen And Deuterium Polarized Gas Target For Application In Storage Rings

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Overview:
The exploration of spin degrees of freedom in nuclear and high-energy interactions requires the use of spin-polarized projectiles and/or spin-polarized targets. During the last two decades, the use of external beams from cyclotrons has to a large extent been supplanted by use of circulating beams stored in storage rings. In these experiments, the circulating particles pass millions of times through targets internal to the ring. Thus the targets need to be very thin to avoid beam loss by scattering out of the acceptance aperture of the ring. . An overview of the recent history of polarized gas-target development is found in [1].

Our work has concentrated on the development and use of spin-polarized gas targets of pure atomic hydrogen and deuterium and applications in storage rings. Polarized atoms are produced by an “atomic-beam” source (ABS), in which a directed beam of H atoms travels in a high vacuum along the axis of six-pole magnets, which provide a strong inhomogeneous field which focuses one of the two electron spin states in the hydrogen-atom and rejects the opposite state. The H atoms are produced in a dissociator vessel, which breaks up molecules in hydrogen gas by a radio-frequency discharge. Typically, the polarized H-beam intensity is a few times 10^{16} hydrogen atoms/sec. The angular momentum of the polarized electron is transferred to the proton in the H-atom by oscillating electromagnetic fields (RF-transition units, see ref [1]).

Use of the atomic beam itself as a target for the circulating beam in a storage ring is possible in principle but quite inefficient because of the low probability of hitting atoms which are in rapid flight. We had shown earlier that the target thickness can be improved by a factor or 100 or more, by injecting the atomic beam into tubes of typically 20-50cm length and 1-2 cm diameter (“storage cell”). The protons or electrons in the storage ring pass along the axis of this tube, while the atomic beam is injected through a side-arm attached midway through the tube. The H atoms make a few hundred wall collisions as they diffuse through the tube before they exit through one of the openings. Potential problems with this technique are the loss of polarization in wall collisions, and loss of circulating beam as it travels through a long, narrow channel. We have shown that both problems can be overcome. The reaction products of the nuclear interactions in the call have to pass through the cell walls before reaching the detectors, so that thin walls are a requirement.

During the award period 03/01/1997-12/31/2007 we applied these techniques to a large series of experiments at three storage rings: the Indiana University Cooler facility, using stored proton beams between 100 and 400 MeV, the 2 GeV electron storage ring at DESY, and the RHIC collider at Brookhaven National Laboratory. All three were large collaborations where our primary contribution, besides participation in data acquisition and data analysis was to provide the target technology. The work resulted in 50 publications in refereed journals in addition to a large number of contributions at international conferences. The references given below are thus only a sample of the published record.

Experiments with 100-400 MeV Protons (IUCF-Indiana)
The Wisconsin atomic-beam source, installed at the proton storage ring facility (IUCF "Cooler") in Bloomington, IN, was used to inject polarized atoms into thin-walled cells surrounded by solid-state detectors. The polarized target protons were bombarded with a circulating beam of polarized protons, cooled by electron cooling. The target polarization (P=80%) could be reversed and directed at will in the x, y, or z-directions by energizing one of three sets of guide-field coils surrounding the target [2]. This made possible the first detailed, highly accurate absolute measurements of spin-correlation coefficients (Axx, Ayy, Azz, Axz) in pp elastic scattering as a function of angle and energy up to 400 MeV [3.4] resulting in much improved nucleon-nucleon phase shifts.
Studies of the spin-dependence in pp pion production near threshold is of particular interest because the results relate to the nature of the nucleon-nucleon force at short distance. Because of the very small reaction cross section (nano-barns) observations became practical only through the development of storage-cell targets combined with high intensity (2mA) of the stored proton beam. In our experiments [5,6] the pion was identified based on the missing-mass in collisions which observed recoil and forward proton in coincidence.
While the nucleon-nucleon (NN) force is well determined from measurements such as the ones mentioned above, the question arises whether in systems comprising three or more nucleons there are specific three-body forces acting beyond the pairwise forces between nucleons. Claims have been made of the existence of three-body forces, based on analyzing-power and spin-correlation observations in the scattering between nucleons and deuterons.
In order to provide more decisive data on the three-body system, we redesigned the RF transition units in the atomic-beam source to allow production of either a vector- or tensor-polarized deuterium target. Combined with the stored polarized proton beam, this allowed observation of an extensive set of spin-correlation parameters in p-d elastic scattering (i.e. spin 1/2 on spin 1) as a function of angle [7] [Comparison with theoretical prediction with or without three-body forces showed clearly that inclusion of three-body forces produces no overall improvement in the agreement between calculation and experiment. Thus at the moment there is no reliable evidence for the existence of three-body forces in nucleon-deuterium scattering.

Experiments with 2 GeV Electrons (DESY, Hamburg, Germany),

The HERMES experiment on the HERA accelerator at DESY investigates the quark-gluon structure of matter. The internal polarized gas target is a thin-walled Al storage cell, constructed as part of the DOE project at Wisconsin. The atomic-beam source which supplies the polarized atoms was constructed at the Max-Planck Institute in Heidelberg, in collaboration with Wisconsin (supported by the Humboldt Foundation) [8]. The target cell is cooled to 100K in order to increase the target density. Cooling to lower temperatures increases wall recombination and thus reduces the polarization. The target assembly, including a magnet producing a strong transverse magnetic field, was constructed at Wisconsin. A high degree of target polarization (90%) is achieved reproducibly during runs lasting several weeks.

The target polarimeter detects only hydrogen atoms, but recombination of atoms in collisions with the cell wall produce a contamination of the target gas by molecules of unknown polarization. The degree of contamination is measured but it is not known if in the recombination process the protons loose their polarization. Loss of polarization in recombination makes the largest contribution to the uncertainty in target polarization. To answer the question of polarization loss in recombination of H atoms on surfaces, we undertook a separate, elaborate experiment at the IUCF proton ring, in which we measured the target polarization under conditions where recombination was induced on a cooled copper surface. A supercoducting magnet supplied a magnetic guide field of variable strength [9]. The nuclear polarization of the molecules, relative to the polarization of the atoms before recombination, increased from near zero in a weak magnetic field to 0.42±0.02 in a 0.66 T field. A simple model of the relaxation accounts quantitatively for the observations.

The HERMES collaboration has studied various aspects relevant to the nucleon spin structure. During the present report period, HERMES results have been published in 32 papers in refereed journals in which the Wisconsin group (Haeberli and Wise) are co-authors.

Internal Polarized H-target at RHIC (BNL).

Half-way through the award period covered in this report, our principal activity shifted to work at the Brookhave Collider RHIC, where polarized protons are injected and accelerated in order to understand the spin structure of the proton. Colliding polarized protons at RHIC probes the proton with strongly interacting probes, complementing deep-inelastic lepton scattering such as the work at CERN and DESY. However, for RHIC-SPIN, polarized protons are accelerated to such high energies (presently 100 and 200 Gev) that no reactions of known polarization-analyzing power exist to measure the degree of beam polarization with adequate accuracy. The problem is exasperated in that for pp collider experiments, the beam polarization uncertainty enters twice, once for each beam. Thus the estimated 30% accuracy for p-C scattering in the Coulomb-nuclear interference region is inadequate.

The problem is solved by inserting a polarized atomic hydrogen target of accurately known proton polarization in the ring [10]. Earlier experiments at Fermi Lab have shown that there is a non-zero but poorly known analyzing power at small angles (Coulomb-nuclear interference). If the polarization of the target in the ring is known, the analyzing power can be measured by scattering an unpolarized beam and observing the left-right asymmetry of the scattered protons. The known analyzing power in turn is used to measure the unknown beam polarization. In practice, both experiments are combined into a set of measurements with polarized beam and polarized target, where both polarizations are reversed periodically. Besides yielding results for the pp analyzing power as a function of scattering angle (i.e. momentum transfer), the experiment in addition yields values for the pp spin correlation coefficient.

While simple in principle, the problem is to produce a polarized hydrogen target of sufficient density and high, accurately known degree of polarization. For RHIC, the use of the storage cell technique to enhance the target thickness, described above, was considered impractical because the cell limits the ring acceptance and the very low-energy recoils to be detected would loose all or most of their energy in the call wall. We thus accepted the challenge to design a new atomic-beam source of the highest achievable intensity, whose free jet would be traversed by the RHIC beam. The polarized jet would be traversing the RHIC beam from above and after passing through the interaction region the degree of polarization of the hydrogen atoms was to be measured by a suitable atomic polarimeter.

The completed polarized jet consists of a dissociator and an arrangement of high-gradient sixpole magnets with radio-frequency spin-flip transitions, followed by a target chamber with surface-barrier detectors to detect recoil protons. This is followed by a polarimeter to measure the absolute atomic-beam polarization [11]. The overall length of the differentially-pumped system is 3.5 m. The source delivers reproducibly $1.2\text{x}10^{17}$ polarized H-atoms/sec into a 9 mm diameter 28 cm after the last spin-separation magnet. This intensity, the highest intensity achieved anywhere, was the results of an extensive design study undertaken at Wisconsin. The optimization calculations [12] considered a large number of parameters: dissociator temperature, distribution of sixpole diameters, tapers, lengths and spacing, as well as intensity loss by gas scattering. The actually measured intensity somewhat exceeds the design value of $0.9\text{x}10^{17}$ by 30% for reasons which are not entirely understood.

The RHIC polarized H-jet target has been used routinely for proton spin experiments since 2004. The peak analyzing power at 100 GeV Is (4.7±0.2)%, in excellent agreement with calculations based on Coulomb-nuclear interference [13}.

Our recent work addressed the question of systematic errors in the determination of target polarization as well as future experiments with a polarized deuteron target.

The atomic-beam polarimeter shows that the H-atom polarization to very high and is determined to very high accuracy, namely (95.8±0.1)%. However, the accuracy is limited by contamination of the jet with hydrogen molecules resulting primarily from recombination of atoms on various surfaces. Work of the HERMES collaboration has shown contamination of several percent. To address this problem, we developed a device to measure the H_2 fraction in the jet target directly. An electron beam of 600 eV energy is passed at normal incidence through the atomic beam and the resulting ions are extracted and momentum analyzed by a deflection magnet. The mass scan clearly shows the expected small peaks in the mass spectrum corresponding to H_2 and H_2O. The corresponding reductions of the H polarization are (2.3 ±0.7)% and (0.15±0.03)% respectively, where the errors arise primarily from uncertainties in the relative ion-collection efficiencies. The final result for the total proton target polarization is P = (93.4 ±0.7)%.

Other recent work addressed the question how the RHIC polarized-target experiments could be extended to vector- and tensor-polarized deuterium targets. We reached the conclusion, that the most effective way was the construction of an addition radio-frequency transition unit for deuterons, to be inserted in the available drift space between to two groups of sixpole magnets. Changing the gas in the dissociator from hydrogen to deuterium produces no problem.

Consequently, a strong-field 3-5 deuterium transition was constructed and tested at Wisconsin and shipped to BNL. Installation in the present atomic-beam source allows the deuteron vector polarization to be changed between +1/2 and –1 and the tensor polarization to be changed between –1/2 and +1.

Summary:
The goals of the proposed project were met or exceeded. The awards have permitted to Wisconsin group to contribute to fundamental new experiments at the IUCF proton storage, at the DESY-HERA 2 GeV electron ring and at the Brookhaven collider RHIC in a very cost-effective way.

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