SPIN STRUCTURE FUNCTIONS OF THE NEUTRON FROM SLAC EXPERIMENTS E142 AND E154

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A discussion is given of E142 and E154, which were experiments at SLAC to measure the spin structure functions of the neutron by scattering polarized electrons from a spin-exchange polarized ^{3}He target. Also discussed is the ongoing impact of the data, together with some questions that deserve further investigation. Finally, the importance of the development of spin-exchange techniques is covered, both with regard to spin-structure studies as well as with regard to applications in medical imaging.

1. Introduction

E142[1,2] and E154[3,4,5] are experiments that took place at SLAC in 1992 and 1995 respectively. In both cases the experiments collected data on the spin structure functions of the neutron by studying the scattering of polarized electrons from a polarized ^{3}He target. Given the time that has passed since these experiments took place, and the thorough manner with which related subject material was covered at the QCD workshop, it is challenging to identify the best and most relevant focus for this paper. There are, however, several points of lasting value. The first concerns the precision of the data. When E142 was published, it represented a significant step forward in precision studies of the spin structure of the nucleon. Furthermore, the data from E154 still stand as some of the most precise data in existence on polarized deep inelastic scattering. Another valuable lesson from these experiments is the central role played by experimental innovation. The high luminosities that were made possible by polarized ^{3}He targets were central to the great success of these two SLAC experiments. It is important to remember that at the time E142 was proposed polarized ^{3}He targets, such as they existed at the time, were one to two orders of magnitude smaller in size. Another lesson of considerable importance to our community is that the advances in target technology had implications that went well beyond

the study of spin structure. The techniques for producing large quantities of polarized ^{3}He developed for E142 were important to the development of a new technique for magnetic resonance imaging (MRI) using polarized noble gases. Lastly, it is important to look at the limitations of E142 and E154, and the questions that still remain. Even with the many studies of nucleon spin structure both at SLAC and elsewhere, there are still regimes in which the experimental data are rather sketchy, particularly at low Bjorken x. Using the current generation of accelerators, there are kinematic regions that are accessible in which further study might sharpen our understanding of nucleon spin structure.

2. The proton spin crisis in 1987

In 1988, the European Muon Collaboration (EMC) published their results on the spin structure function g_1^p of the proton[6,7]. The EMC results, together with the results from the earlier pioneering SLAC experiments E80[8] and E130[9], determined that the integral of g_1^p

$$\Gamma_1^p = \int_0^1 g_1^p(x)dx = 0.114 \pm 0.012(stat.) \pm 0.026(syst.) \quad ,$$

a result that was in strong disagreement with the Ellis-Jaffe (EJ) Sum Rule[10]:

$$\Gamma_1^p = \int_0^1 g_1^p(x)dx = 0.189 \pm 0.005 \quad .$$

(Here I quote the value of the EJ Sum rule as given in EMC's publication [a].) The EJ sum rule explicitly assumes that the fraction of spin carried by strange quarks is zero. The EMC results indicated otherwise. Within the quark-parton model, a determination of Γ_1^p together with the Bjorken Sum Rule[12], the assumption of SU(3) flavor symmetry, and results from hyperon decay allows a flavor decomposition of the spin of the proton. EMC's results indicated that the total spin carried by quarks was consistent with zero, and that the polarization of the strange sea was large and negative.

The EMC results challenged the accepted, if not ill-motivated, notion that the majority of the spin of the nucleon is carried by the quarks. A definitive test of the Bjorken sum rule took on great importance, requiring

[a] A more modern value for the EJ Sum Rule, evolved to a Q^2 of $5\,\mathrm{GeV}^2$, corrected to order α_S^3, and using updated values for the SU(3) couplings F and D would be $\Gamma_1^p = 0.163 \pm 0.004$[11].

data on the spin structure of the neutron. In their long paper[7], the EMC collaboration emphasized

> "... it is of crucial importance to measure the asymmetries from a target containing polarised neutrons ..."

SLAC E142 was proposed to answer that need, and to do so in a timely way with high statistics.

3. SLAC E142

E142 was designed to provide a high luminosity study of the spin structure of the neutron at a time when virtually no data on the neutron existed. Polarized electrons were scattered from a polarized ^{3}He target at energies of 19.4 GeV, 22.7 GeV, and 25.5 GeV. Whereas the the SLAC machine was capable of energies up to around 50 GeV, End Station A, where the experiment was performed, was only instrumented to handle roughly half the full machine energy. Two spectrometers were used at 4.5° and 7.0°. The average Q^2 of the data was $2\,\mathrm{GeV}^2$, and data were taken at values of Bjorken x as low as 0.03. Average beam currents were in the range of $1-4\,\mu$A, with an average polarization of 0.38 ± 0.02. The target polarization was 0.36 ± 0.02

Approximately 300 million events were used in determining g_1^n from E142. This is in contrast with just over one million events in the case of EMC. In terms of a figure of merit, however, the advantage was less pronounced. Both the target and beam polarizations were about a factor of two higher in EMC, and the dilution factor was about 60% better. Also EMC had the clear advantage that their lowest x bin was 0.015 versus 0.030 for E142. A comparison of data from the two experiments is shown in Fig. 1, together with the first deuteron results that came from SMC[13].

Critical to the success of E142 was the construction of a suitable polarized ^{3}He target. The target was based on the technique of spin-exchange optical pumping[14,15], a two-step process in which 1) rubidium atoms are polarized by optical pumping, and 2) spin is transferred from the Rb valence electrons to the nuclei of ^{3}He atoms by the hyperfine interaction during collisions. At the time it was proposed, it appeared that a polarized ^{3}He target could be built with a luminosity approaching $10^{36}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. Achieving such a luminosity, however, meant scaling of the volume of polarized gas by a large amount over anything that had been done previously. It was not clear to what extent unanticipated problems would be encountered.

Spin-exchange optical pumping typically takes place in a sealed glass

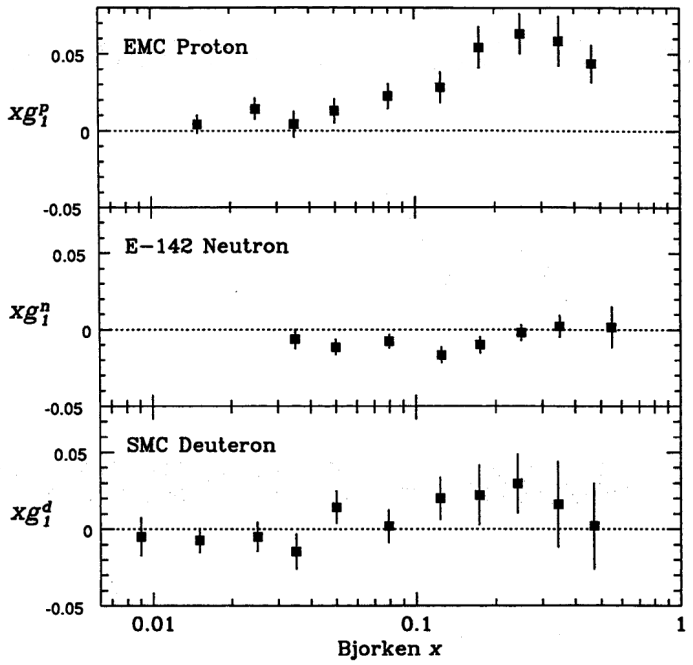

Figure 1. Shown are data from EMC, SLAC E142, and SMC on the nucleon spin structure function $g_1(x)$.

cell, containing up to around 10 atmospheres of ^{3}He, about 70 Torr of N_2, and on the order of one hundred milligrams of metallic Rb. The magnitude of the challenge that faced E142 is illustrated in Fig.2 which shows two E142 target cells, ready to be filled with ^{3}He, together with a cell just over 2 cm in diameter which was more typical of samples used for spin-exchange optical pumping at that time. The SLAC cells have volumes of around $150\,\mathrm{cm}^3$, whereas the smaller cell has a volume around $10\,\mathrm{cm}^3$. Targets for use at TRIUMF and Bates were under development with volumes as large as $35\,\mathrm{cm}^3$, but their performance had not yet been established. The E142 target thus represented an ambitious goal.

4. SLAC E154

The second SLAC ^{3}He experiment, E154, made a dramatic improvement in precision over what was achieved during E142. Several factors contributed

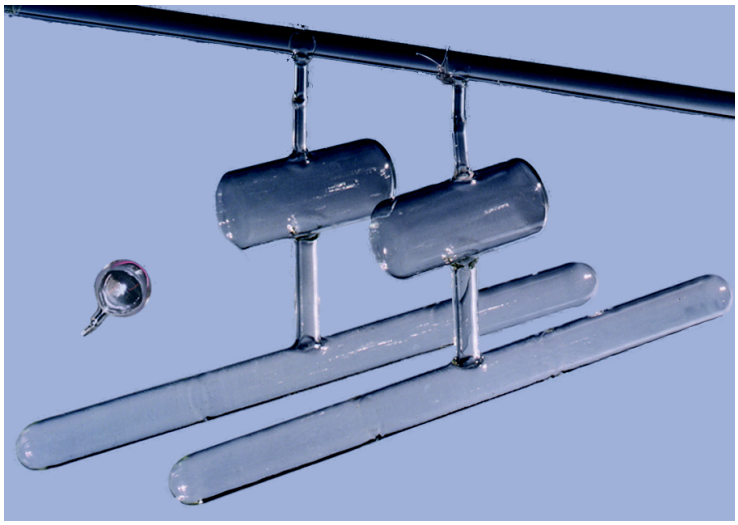

Figure 2. Shown are two glass cells that were used for the SLAC E142 polarized ^{3}He target together with another glass cell that was more typical at that time of experiments involving spin-exchange optical pumping.

to the improvement. The polarization of the electron beam was 0.82 ± 0.02, an improvement of over a factor of two. The dilution factor, defined as the fraction of electrons that scattered from ^{3}He, was improved to 0.55 ± 0.03, an improvement of a factor of 1.7. Perhaps most important of all, however, is the fact that the experiment was run at 48.3 GeV, more than twice the energy at which most of the data were taken during E142. The higher energy made it possible to extend the lowest value of Bjorken x at which data were taken down to 0.014, and to increase the average Q^2 to $5\,\mathrm{GeV}^2$. The impact of these improvements is readily apparent in the comparison of E154 data with that of E142 shown in Fig. 3.

The E154 polarized ^{3}He target used many of the same components as E142, but also included some important improvements. The target cells, for instance, incorporated concave windows of only $50\,\mu$m thickness, less than half the thickness of the convex windows shown in the E142 cells in Fig. 2. The thinner windows were responsible for the improved dilution factor mentioned above. I note that the concave configuration permitted using thinner windows because glass is stronger under compression than tension. Target polarimetry was also improved in part because of the incorporation of a technique in which the ^{3}He polarization was measured by observing the shift it caused in the electron paramagnetic resonance of the rubidium[16]. In

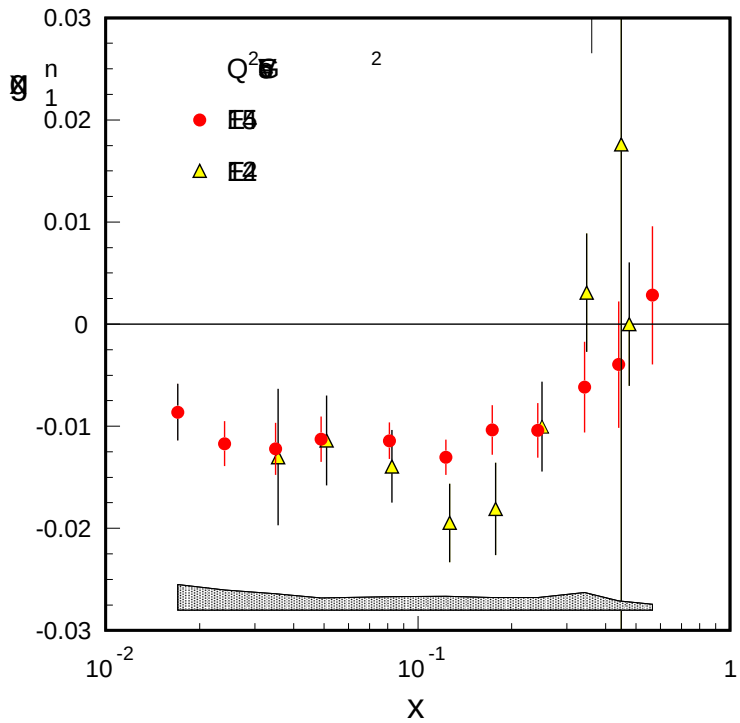

Figure 3. Plotted are data from E154 showing the product of Bjorken x with the longitudinal neutron spin structure function g_1^n together with data from E142.

other aspects of the experiment, two new spectrometers were constructed, one at 2.75°, and one at 5.5°. It should also be mentioned that the reason the experiment was able to run at the higher energy was that the beam line going to End Station A was upgraded. The impact of the precision of the E154 data on the field of nucleon spin structure is illustrated in Fig. 4, which shows a comparison with SMC data[17] at the time that E154 was published. Of particular note was the behavior of g_1^n at low x, a subject discussed in the next section.

5. Low-x extrapolations and NLO analyses

Kinematic constraints always limit the lowest value of Bjorken x at which an experiment can obtain useful data. Because of this, it is necessary to extrapolate to $x = 0$ in order to evaluate the integrals of the spin-structure functions. Both SMC and E154, however, showed a striking trend

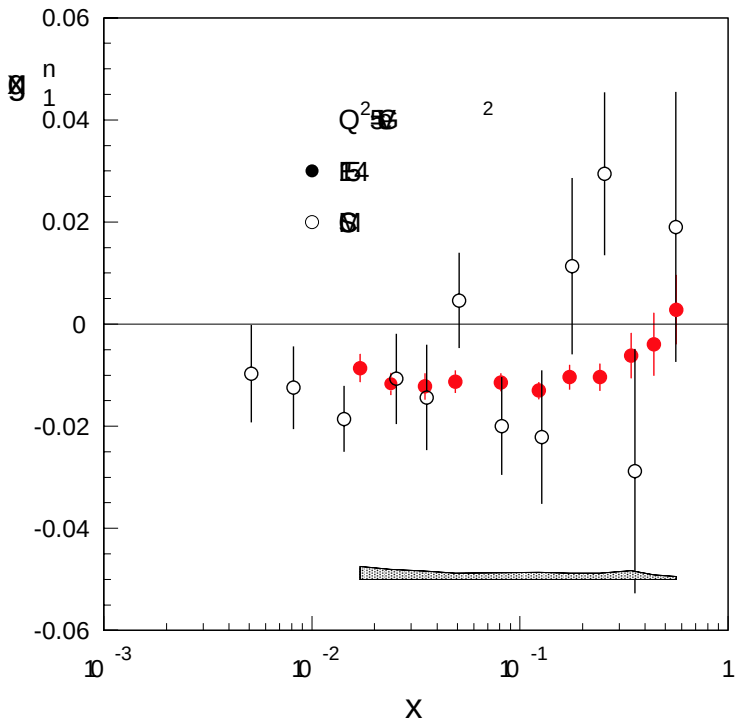

Figure 4. Plotted are data showing the product of x and g_1^n including data from both E154 and SMC.

of g_1^n becoming increasingly negative at low x, as is shown in Fig. 5. As a result, the simple methods of extrapolation that had been used by EMC and E142 were not sufficient for obtaining a reliable value of the integral $\Gamma_1^n = \int_0^1 g_1^n dx$.

As is illustrated in Fig. 5, the E154 and SMC data are inconsistent with the simplest Regge theory interpretation that g_1^n is constant at low x. The E154 collaboration considered several alternative possibilities. One was a Regge theory extrapolation with a constrained power-law fit in which it was assumed that $g_1^n \sim x^{-\alpha}$, and $-0.5 < \alpha \leq 0$. This results in a determination of the first moment of g_1^n of $\Gamma_1^n = -0.041 \pm 0.004 \pm 0.006$, but only fits well the lowest three points. Another was to consider an unconstrained power law fit, fitting the data for $x < 0.1$. It was found that $\alpha = 0.9 \pm 0.2$ resulting in a determination of $\Gamma_1^n = -0.2$, where it is not possible to give an error, because if $\alpha = 1$, the integral of g_1 diverges. A Pomeron-type fit was also

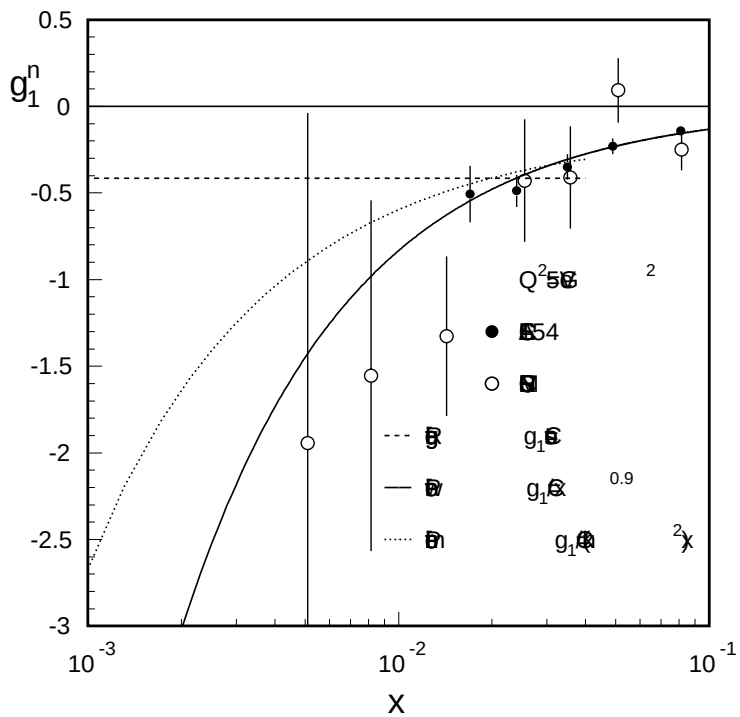

Figure 5. Shown are data on g_1^n from E154 and SMC for the region $x < 0.1$, together with several fits, as indicated on the plot.

considered and is shown in Fig. 5, but was not particularly successful. From these considerations, it is clear that the E154 data, taken by themselves, are not sufficiently constraining to yield a reliable low-x extrapolation, and hence, a determination of Γ_1^n.

It is now generally accepted that the best way to determine the integrals of g_1^n and g_1^p is to perform a next-to-leading-order (NLO) QCD fit in which the spin-structure functions are parameterized at low Q^2, where Regge theory is believed to be valid, and evolved to a Q^2 at which the data were obtained. There have been many such fits, as has been nicely summarized recently by Filippone and Ji[11]. When performing an NLO fit, it is first necessary to choose a factorization scheme, which among other things, affects wether or not the singlet quark distribution $\Delta\Sigma$ contains a contribution from the gluon spin, ΔG. In the quark-parton model, $\Delta\Sigma$ is the fraction of spin carried by the quarks. In the $\overline{\text{MS}}$ factorization scheme,

in which $\Delta\Sigma$ does not contain a contribution from ΔG, $\Delta\Sigma$ is found to be constrained to the range $0.05 - 0.3$, depending on which published fit one considers. Qualitatively, one can certainly say that the original discovery that started the proton spin crisis has held up. It appears that rather little of the spin of the nucleon is carried by the quarks. NLO QCD fits of the world's inclusive DIS data are less definitive regarding ΔG. While most fits seem to indicate that ΔG is positive, a reliable determination will need to await new experiments.

One further point is worth discussing on the subject of the interpretation of the existing data on polarized DIS scattering. The integrals of g_1^p and g_1^n are strongly influenced by the behavior of the spin-structure functions at low-x, a region where there is little precision data. It seems reasonable to ask whether there are any further studies that can be performed even before a new generation of accelerators becomes available. For instance, in an NLO analysis, the spin structure functions are parameterized at low Q^2 and evolved upwards. But how well is the Regge behavior at low Q^2 tested? It would seem that studies in this regime, where both x and Q^2 are small, might be useful. Such studies would presumably also teach us something about higher twist effects. Further theoretical studies might also be useful to better understand how deviation from assumed Regge behavior would affect the world NLO analyses. Some guidance on how to proceed might be gleaned from the recent SLAC experiment E158, which is studying parity violation in Møller scattering. E158 utilizes a detector which operates at very forward angles and could be adapted to explore the low-x low-Q^2 kinematic region. To best study this regime it might be interesting to study both parity conserving and parity non-conserving spin-dependent scattering.

6. Technology spin-offs of E142 and E154

The ability to produce liter-type quantities of polarized ^{3}He had technological implications that went well beyond the building of polarized targets for electron scattering. In 1993, the year after E142 took data, a Princeton/Stony Brook collaboration demonstrated that spin-exchange polarized noble gases could be used for a new type of magnetic resonance imaging (MRI)[18]. In conventional MRI, the source of signal is protons in water, which become polarized at the level of a few parts per million when the subject is placed in a large magnetic field of a Tesla or more. In the new technique, the source of signal is the nuclei of noble gases, which can be

polarized using laser techniques at the level of 3-50%, or even more. The subject inhales the gas, and using a conventional MRI whole-body scanner, an image is made of the gas space of the lungs. While the first modest images were of the excised lungs of a mouse, by September of 1995 a Princeton/Duke collaboration had made images of human lungs[19]. In doing so they drew heavily on the technology developed for use at SLAC. In virtually a simultaneous demonstration, a European group, using the technique of metastability exchange, also demonstrated the imaging of human lungs using polarized ^{3}He[20]. The value of the new technique becomes quickly apparent when one compares noble-gas imaging with the nuclear medicine techniques with which it competes. in Fig. 6 below, in the left-hand panel, a nuclear medicine scan is shown of a patient's lung. The subject had inhaled a sample of radioactive ^{133}Xe, and using a gamma camera, the image shown was made. In contrast, the image in the right-hand panel is an MRI of a healthy volunteer's lungs using polarized ^{3}He. The improvement in resolution is dramatic.

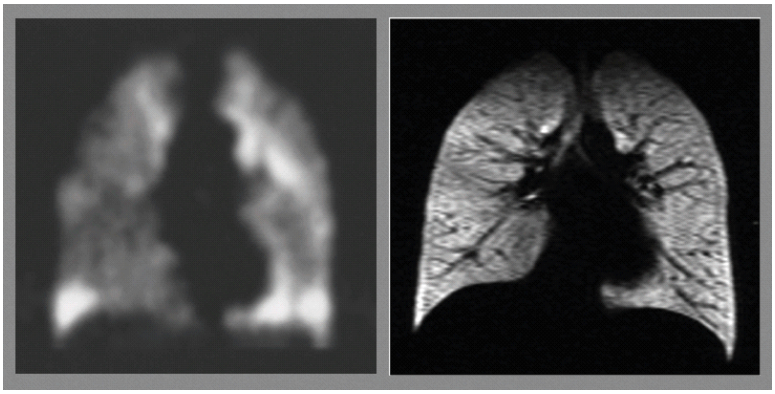

Figure 6. Shown are two images off the gas space of human lungs (from different subjects). At left is a traditional ventilation scan in which the subject inhales radioactive gas and an image is made using a gamma camera. At right is an MRI in which the signal source is inhaled nuclear-polarized ^{3}He. Both images were made at UVa.

At first, noble gas imaging required an intensive effort on the part of physicists in order to supply the necessary polarized gas. It was also difficult to perform large numbers of studies, because of the complexity of the polarization process. In 1996 a prototype commercial polarizer was built, shown in Fig. 7, which made it possible to produce polarized noble gas for

medical studies on a routine basis. The intimate connection between this prototype commercial polarizer and the technology developed for SLAC is evident in many details. For instance, the "pumping chamber", the upper of the two chambers visible in the cells developed for E142 and shown in Fig. 2 can be seen to be nearly identical to the polarization chamber, shown in the inset to Fig. 7, used in the prototype commercial polarizer.

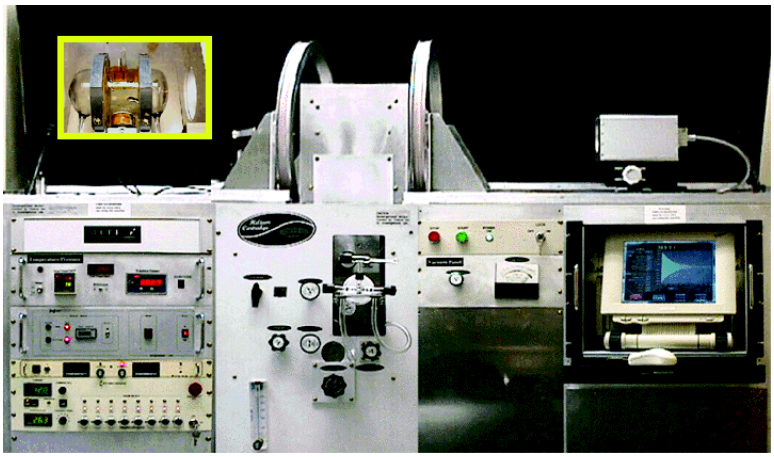

Figure 7. Shown is the first prototype commercial noble-gas polarizer. Shown in the inset is the "polarization chamber", used for polarizing ^{3}He by spin exchange. The polarization chamber can be seen to be similar to the polarization chamber of the SLAC target cells shown in Fig. 2.

7. Summary

SLAC E142 and E154, through measurements of the scattering of polarized electrons from a polarized ^{3}He target, provided valuable data on the spin structure of the neutron. Even today, the data from E142 and E154 stand as some of the most precise measurements available, and are critical in constraining next-to-leading-order (NLO) QCD analyses of spin-structure data. The NLO QCD fits, when interpreted through the quark-parton model, give us a picture of the nucleon in which surprisingly little of the spin is carried by the quarks, in keeping with the original EMC findings.

One of the striking features of the E154 data, a feature that is also clearly apparent in the SMC data, is that g_1^n becomes surprisingly negative as x becomes small. Extrapolations of the E154 data to $x = 0$ are sensitive

to the details of the model used for the fit, making it clear that a reliable evaluation of the integral $\Gamma_1^n = \int_0^1 g_1^n \, dx$ requires a consideration of the world spin-structure data using something akin to an NLO QCD analyses. The low-x behavior of g_1^n also makes the prospect of obtaining more low-x data appealing. The author also raises the question of whether, with the current generation of accelerators, useful information can be gleaned by studying the behavior of g_1^n in the kinematic regime of low-x and low-Q^2, a regime in which Regge theory is believed to be valid. Studies of this sort would be interesting in part because the NLO analyses generally involve parameterizing the spin structure functions at low Q^2, and evolving upwards to the Q^2 of interest. At present it would be straightforward to vastly improve the data base at low x and low Q^2. It would be interesting to see how well such data can be described by Regge theory.

Finally, it is worth noting how the development of a polarized ^{3}He target of unprecedented size played a critical role in E142 and E154. In the late 1980's, at a time when it was important to learn more about the neutron, spin-exchange optical pumping provided an important solution to providing a target rich in spin-polarized neutrons. Furthermore, the utility of the technology represented by the polarized ^{3}He target went well beyond nuclear and particle physics and impacted medical imaging. The development of techniques to polarize liter-type quantities of ^{3}He played a central role in the inspiration and practical development of MRI using polarized noble gases.

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