30

Other facilities

The previous and subsequent chapters go into detail on TJNAF (CEBAF) because that is the project in which the author was most deeply involved and about which he is most knowledgeable. Many other accelerator laboratories have played, and continue to play, an important role in electron scattering studies of nuclei and nucleons. Worth highlighting from the early years are the Nuclear Physics Laboratory at the University of Illinois, where the betatron provided a tool to do the very first study of nuclear structure with electrons [Ly51, Il87], and the High Energy Physics Laboratory at Stanford (HEPL), where Hofstadter carried out his pioneering work on charge and magnetization densities [Ho56, Ho63]. Many other important facilities sprang from the work at HEPL, including those at Amsterdam, Darmstadt, Mainz, Saskatchewan, Tohuko, and the Saclay Laboratory, which played a particularly important role in the development of the field. The Stanford Linear Accelerator (SLAC), under Wolfgang Panofsky's inspired leadership, found its roots in HEPL, as did TJNAF. A prototype of the CEBAF superconducting accelerator was first constructed at HEPL. An excellent discussion of the early years of electron scattering is to be found in [Il87].

It is the Bates Laboratory at M.I.T., where a variety of precision experiments truly demonstrated the power of electron scattering to study the nucleus, and the Stanford Linear Accelerator Center (SLAC), where high-energy experiments demonstrated the pointlike, asymptotically free, substructure of the nucleon and examined its weak neutral current, that are responsible for the role that electron scattering plays in nuclear and particle physics in the U.S. today.

The principal centers today for nuclear structure studies with electrons are TJNAF in Newport News, the Bates Laboratory at M.I.T. in Boston, and the Mainz Microtron (MAMI), in Germany. High energy studies, which probe the very short-range structure of nucleons are carried out principally at SLAC, in Stanford, and at the Deutches Electronen-Synchrotron (DESY) in Hamburg. Electromagnetic studies with very high energy muons are carried out at CERN in Geneva. The European community has an ongoing effort to design and fund a high-current electron accelerator to study physics in an energy regime intermediate between the few- and multi-GeV machines.

This book attempts to lay out the basic motivation, analysis, and goals of electron scattering studies of nuclei and nucleons. It is impossible in a work of this length to go into detail on all the existing facilities and programs. In fact, up-to-date information is always better, and more easily, found on the websites for the laboratories [TJ00, Ba00, Ma00, SL00, DE00]. It may be of some use, however, to provide a brief overview as guide to the four other principal current electron scattering centers: Bates, Mainz, SLAC, and DESY.

The Bates Linear Accelerator Center is a university-based facility for nuclear physics which is operated by the Massachusetts Institute of Technology for the Department of Energy as a National User Facility. Construction funding started in 1967. The accelerator is a room-temperature linac with a single-pass energy of 515 MeV at an average current of 100 μA with a 1% df. A single recirculation was subsequently added which brought the maximum unloaded energy to 1060 MeV, with a maximum average current of 40 μA. The energy spread in the beam for 80% current is 0.3%. From the beginning, the Energy Loss (dispersion matching) Spectrometer System (ELSSY) produced data of unprecedented resolution.[1] The best resolution achieved, for an extended period and limited by target thickness, is $\delta E/E = 4 \times 10^{-5}$. This was on $^{154}_{64}$Gd [He83, Tu00]. We have already demonstrated the type of nuclear information that can be obtained with this resolution in Fig. 12.7 and the accompanying discussion. The author considers that the work on the charge distribution in deformed nuclei at Bates, with ELSSY, was predominant in convincing the nuclear physics community in the U.S. of the power of electron scattering for nuclear physics. A 180° scattering facility at Bates allowed one to isolate the transverse contributions to the cross section and study magnetization distributions in elastic and inelastic scattering (Figs. 12.4, 12.6 and accompanying discussion).[2] A major recent addition to the detectors at Bates

---

[1] William Bertozzi and Stanley Kowalski led the effort to design and construct ELSSY. Note that the dispersion matching technique, whereby the incident beam is dispersed and the various components of the beam followed through the scattering, allows one to obtain scattering resolution orders of magnitude better than that in the primary beam itself.

[2] A magnet in front of the target bends the beam through a small angle θ; the backscattered beam is then bent through an *additional* angle θ, which removes it from the incident beam.

is an array of out-of-plane spectrometers (OOPS), which allows one to separate all the contributions in inclusive coincidence scattering (chapter 13). The polarized beam capability at Bates led to the ground breaking parity-violation experiment discussed in chapter 16, and to the study of the strange quark contribution to the intrinsic magnetism of the proton in the SAMPLE experiment. A major effort at Bates involved a parallel study of the three-body systems ${}_2^3\text{He}$, ${}_1^3\text{H}$. The latter involved an extensive radioactive target effort.[3] These studies resulted in data of the type shown in Fig. 23.13.

A storage ring was subsequently constructed in the South Hall at Bates. This gives rise to a continuous external beam capability for coincidence experiments through slow spill of the stored beam. More importantly, with a large circulating current of 200–300 mA, it allows experiments on very thin, polarized, *internal* targets. A major new detector, the Large Acceptance Spectrometer Toroid (BLAST) is under construction at Bates to take advantage of this opportunity and to measure spin-dependent electron scattering from polarized nuclei.

Even with the low duty factor, heroic, pioneering coincidence studies have been carried out with the Bates linac.

The Mainz Microtron MAMI is an electron accelerator which delivers a c.w. beam (100% df) of 100 μA at a maximum energy 855 MeV. Built under the guidance of H. Herminghaus and coming into operation in 1991, it consists of three cascaded racetrack microtrons with a 3.5 MeV injector linac. The last stage delivers beam from 180 to 855 MeV in 15 MeV steps with excellent emittance and stability.[4] The energy spread in the beam is 50 KeV for an impressive energy resolution of 6×10^{-5}. There is a polarized source.

At Mainz, the electron scattering Hall A contains three spectrometers, rotating about a common pivot, with resolution $\delta p/p = 10^{-4}$. The maximum momenta are 735, 870, and 551 MeV c^{-1}, with solid angle acceptances of 28, 5.6, and 28 msr, respectively. The angular coverages are 18°–160°, 7°–62°, and 18°–160°, and all have angular resolution at the target of less than 3 mrad. The second spectrometer has the capability of going out-of-plane. This is an exceptional set of spectrometers, and with the accelerator capability, MAMI provides a superb facility for doing nuclear structure studies that provide a lower-energy complement to the work that will done at TJNAF. There is also a tagged photon facility at MAMI.

---

[3] Because electron scattering cross sections are small, radioactive targets are ordinarily not a serious problem at electron scattering facilities, and one can re-enter the experimental areas relatively quickly while conducting experiments.

[4] Mainz is currently adding a fourth stage to the microtron which will take the maximum energy to 1.5 GeV.

Current experiments at Mainz include nuclear $(e, e'p)$ measurements, with polarizations, and $(e, e'\pi)$ studies on the nucleon. There are also ongoing experiments on the form factor of the neutron and on parity violation.

The Stanford Linear Accelerator Center (SLAC) is located near the Stanford University campus. The 10,000-feet-long (2-mile) accelerator was originally designed to operate at a peak energy of 22.2 MeV with an RF frequency of 2856 MHz. It was designed with a (macroscopic) pulse length is 2.5 μsec and peak current of 25–50 mA, with an average current of 15–30 μA ($df \sim 10^{-3}$) [Ba65]. It met the design characteristics beautifully during the first year of operation, achieving an energy of 20.16 MeV with 43 mA peak current for a 1.6 μs pulse length [Lo67]. The linear accelerator has been continually upgraded over the years so that today the machine can achieve an energy of 48 GeV with 6×10^{11} particles in a 370-ns-long beam pulse (260 mA peak current) [De99].

End Station A at SLAC, designed for electron scattering experiments, was originally equipped with a complement of three spectrometers of maximum momenta 1.6 GeV c^{-1}, 8 GeV c^{-1}, and 20 GeV c^{-1}, respectively. They rotated about a common pivot and covered an angular region matched to their maximum accepted electron momenta (25°–165°, 12°–100°, and, 0°–20°). The spectrometers had solid angle acceptances of 4.1×10^{-3}, 10^{-3}, and 10^{-4} sr, respectively. The original resolution of the 1.6 GeV c^{-1} spectrometer was 0.08%, and of the higher energy spectrometers, $\sim 0.15\%$ [Pa70, Ki75].

The contribution of the SLAC deep-inelastic scattering experiments to the understanding of the quark–parton structure of the nucleon has been extensively discussed in this book. Many spectrometers have been assembled and disassembled in End Station A over the years for particular experiments. The 8 GeV c^{-1} spectrometer, in particular, has proven to be a workhorse over this period.

The physics contribution of SLAC over the years from colliding beam (e^+–e^-) experiments, where the annihilation creates a pure, virtual *time-like* quantum of electromagnetic radiation with definite quantum numbers, is well-known; nevertheless, important electron scattering experiments on hadronic targets continue to be done in End Station A up to the highest machine energies.

As one example, the measurement of the spin structure function in deep inelastic scattering was discussed in chapter 12. Polarized-beam,[5] polarized-target experiments to provide precision measurements of this quantity for both the proton and neutron are currently underway at SLAC using the highest energy of the accelerator. To illustrate the quality

---

[5] SLAC has played a key role in the successful effort to obtain high beam polarizations.

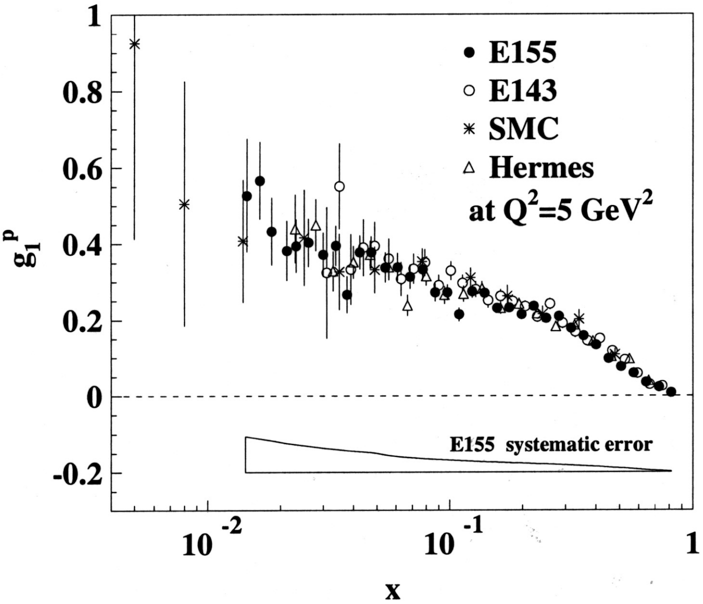

Fig. 30.1. Measurement of $g_1^p(x)$ from experiments E143 and E155 in End Station A at SLAC, together with some other results. The data are evolved to $Q^2 = 5\,\mathrm{GeV}^2\,\mathrm{c}^{-2}$ [An00]. The author is grateful to K. Griffioen and G. Mitchell for providing this figure.

of the currently available data, Fig. 30.1 shows results for $g_1^p(x)$ from experiments E143 and E155, evolved to $Q^2 = 5\,\mathrm{GeV}^2\,\mathrm{c}^{-2}$ [An00].[6]

Deep inelastic electron scattering (DIS) experiments are also carried out at the HERA collider at the Deutsches Electronen Synchroton (DESY) in Hamburg. The HERA collider can store electrons (positrons) of up to 30 GeV and protons of up to 820 GeV in two rings of 6.3 km circumference. The C-M energy is 314 GeV and the maximum achieved luminosity is $1.4\times 10^{31}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. HERA has four interaction regions. The general purpose detectors H1 and ZEUS study the interactions between electron (positron) and proton colliding beams. The HERMES collaboration measures the spin structure of nucleons by the interaction of the polarized electron (positron) beam with polarized nucleons (nuclei) of a gas-jet target [Wo97].

The proton structure function $F_2(x, Q^2)$ has been measured at HERA over a wide range of x and Q^2, with values of Q^2 as high as 5000 $\mathrm{GeV}^2\,\mathrm{c}^{-2}$ and x as low as 10^{-5}. The most striking feature of the HERA data is the rapid rise of F_2 as $x \to 0$ which is seen to persist down to Q^2 values as small as $1.5\,\mathrm{GeV}^2\,\mathrm{c}^{-2}$. The Alterelli–Parisi (DGLAP)

---

[6] The Alterelli–Parisi QCD evolution equations relate the DIS structure functions at different Q^2 [Al77]; this is discussed in [Ro90, Wa95].

evolution equations describe the evolution of the parton densities with Q^2 [Al77, Ro90, St93, Wa95]. In order to solve these equations one must provide the parton densities as a function of x at some reference scale Q_0^2. With the assumption of a Regge behavior at very small x, perturbative QCD then implies that F_2 grows faster than any power of $\ln(1/x)$ as $x \rightarrow 0$ [Wo97]

$$\begin{aligned} F_2(x, Q^2) \approx\ & C_0 \left\{ \frac{33 - 2n_f}{576\pi^2 \ln(1/x) \ln[\alpha_s(Q_0^2)/\alpha_s(Q^2)]} \right\}^{1/4} \\ & \times \exp \sqrt{\frac{144 \ln(1/x)}{33 - 2n_f} \ln[\alpha_s(Q_0^2)/\alpha_s(Q^2)]} \end{aligned} \tag{30.1}$$

Here α_s is the strong coupling constant and n_f is the number of quark flavors. Improved evolution schemes which can give a faster rise for small x are under current investigation [Mu97, Wo97].