trons at the walls and reenter the plasma to be reionized. Ionization is not expected to depolarize the nuclei, but recombination with an electron of opposite spin could be a problem. Such spin flip is, however, effectively inhibited in a magnetic-confinement reactor because the magnetic field, even at the walls, is much stronger than the critical field strength at which the Zeeman splitting becomes equal to the hyperfine splitting.

For polarization of a reactor plasma to be useful, Kulsrud explained, one needs to maintain 95% nuclear polarization for at least 20 seconds. With the unlikely exception of instability-generated large field fluctuations, none of the spin-flip mechanisms considered by the group appears to be able to depolarize the plasma on this time scale.

Polarizing the nuclei. Happer and his Princeton colleagues Nat Bhashkar and Thomas McClelland use alkali atoms to mediate between a circularly polarized dye-laser beam and the nuclei ultimately to be polarized. Their recently published paper describes the polarization of xenon nuclei through the mediation of rubidium; but Happer told us that the technique should prove even more efficient for polarizing the nuclei of the hydrogen isotopes. One would excite a mixture of some alkali vapor and monatomic hydrogen (produced by electric discharge or heating) with circularly polarized laser light at the S–P optical transition frequency of the alkali valence electron. The electrons thus polarized transfer their polarization by collision to the hydrogen electrons. In about a nanosecond (one hyperfine period) this electron polarization polarizes the hydrogen nucleus. One cannot efficiently polarize the hydrogen directly by laser light because the relevant transition frequency (the Lyman-α line) is in the ultraviolet.

Optical pumping, Happer argues, is an intrinsically efficient way to polarize atoms and nuclei. Each polarized laser photon, with an energy of about 1 eV, polarizes a nucleus that ultimately returns MeV of fusion energy. To achieve the necessary amperes of polarized deuterons or tritons required by a reactor, he told us, would require only about a watt of laser output. Even if the laser efficiency were only a tenth of a percent, he points out, the power input required to polarize the plasma would be a trivial fraction of the fusion output. More than twenty years ago, Happer told us, Francis Pipkin and his students at Harvard were able to produce about a milliamp of spin-polarizated deuterons with polarized light from relatively weak resonance lamps.

Because xenon is a noble gas, its electron configuration has no net spin that one could polarize. Thus the recent experiments of Happer and his colleagues involved the direct transfer of polarization from the rubidium valence electron to the xenon nucleus, a much less efficient transfer mechanism than one would have with hydrogen. "Having done it with xenon," Happer told us, "we can do it with helium—and much more efficiently with D or T."

The MIT group has for some time been using high magnetic fields and very low temperatures to stabilize spin-polarized atomic hydrogen against recombination into H_2 molecules—primarily to study cold atomic hydrogen as a quantum fluid. Last year they discovered a spin-off of this technique that may prove to be a practical way of providing large quantities of polarized deuterons for a fusion reactor. The spin-polarized atomic hydrogen stabilized in their apparatus begins as a 50-50 mixture of a pure spin-1 state, with nuclear and electron spins aligned, and a "mixed" state in which the nuclear spin is antiparallel to the electron spin.

The wave function for the mixed state has a small component for finding the electron spin polarized opposite to the predominant polarization of the stabilized atomic hydrogen in the strong magnetic field. It is only through this component that the hydrogen can recombine into molecules. Thus if one waits long enough, all of the mixed-state atoms will eventually recombine and adsorb on the vessel walls, leaving a monatomic gas with more than 99% of its nuclei aligned.

Greytak told us that the group is now attempting to do the same thing with deuterium; tritium will be more difficult, and the MIT group has not yet considered He^3. Greytak is confident that one should be able to produce amperes of polarized deuterons at acceptable power cost by this method.

One would introduce the polarized nuclei into a reactor as a neutral gas, because the confining magnetic field of the reactor would keep charged particles out. If one chooses to introduce the gas as an energetic "neutral beam," one requires an intermediate stage of ionization, acceleration and reneutralization before injection. Kulsrud and his colleagues have calculated that the preinjection stages would not significantly depolarize the nuclei if they do not experience abrupt changes of magnetic field strength or direction.

"We don't yet know whether all this will work," Furth told us, "but it illustrates that there are still fundamental new ideas to be explored in magnetic-confinement fusion. It's not all just engineering details. This is, I believe, a message of good cheer." —BMS

References

1. R. M. Kulsrud, H. P. Furth, E. J. Valeo, M. Goldhaber, PPPL Report 1912 (1982).
2. N. D. Bhaskar, W. Happer, T. McClelland, Phys. Rev. Lett. 49, 25 (1982).
3. R. W. Cline, T. J. Greytak, D. Kleppner, Phys. Rev. Lett. 47, 1195 (1981).

Electroweak interference confirmed

Before 1973, all observed weak interactions had involved charge exchange between the participating particles, implying that the carriers of the weak force were themselves always electrically charged. But if one is to unify the weak and electromagnetic interactions in a single gauge-invariant framework, one requires a weak analog of the uncharged photon—an electrically neutral, weak, spin-one boson. The discovery of the neutral-current weak interactions at CERN in 1973 (for example, the elastic scattering of neutrinos off nucleons) was thus a crucial piece of evidence for the Weinberg–Salam–Glashow electroweak gauge theory—the scheme that has since come to be regarded as the "standard theory" for the unification of the electromagnetic and weak interactions. Sheldon Glashow and Steven Weinberg (both then at Harvard) and Abdus Salam (Imperial College, London and International Centre for Theoretical Physics, Trieste) shared the 1979 Nobel Prize in Physics for this work.

If the neutral weak boson (called Z^0, and expected to have a mass of about 90 GeV) does indeed exist, one should be able to see interference effects between electromagnetic and weak exchange mechanisms. Whenever a photon is exchanged, a Z^0 can be exchanged in the same reaction. The key experimental signature would be the observation of a forward–backward asymmetry due to the interference of the axial-vector part of the weak interaction with the purely vectorial electromagnetic interaction. (This should not be confused with parity violations observed in purely weak processes; these come from interference between the vector and axial-vector parts of the weak interaction alone.) At collision energies much below the Z^0 mass, however, the interference of the weak interaction with electromagnetic processes would be very small.

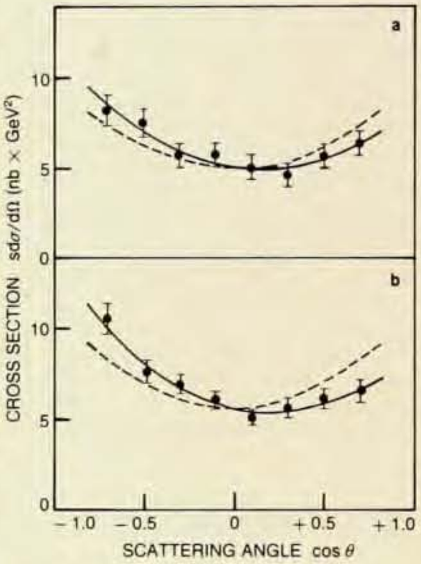
But PETRA, the e^+e^- colliding-beam storage ring at DESY (Hamburg), has for more than a year now been operating reliably with high luminosity at collision energies around 35 GeV. At this center-of-mass energy (more than a third of the supposed Z^0 mass), the Weinberg–Salam–Glashow theory predicts that the production of lepton pairs in e^+e^- collisions should exhibit a forward–backward asymmetry of about 10%. In recent months, four experimental groups at PETRA have in fact reported[1,2,3,4] seeing a forward–backward asymmetry of about 10% in the reaction $e^+e^- \rightarrow \mu^+\mu^-$.

At these energies, the weak–electromagnetic interference asymmetry grows as the square of the collision energy. Running at 29 GeV with somewhat lower luminosity, two groups at the PEP e^+e^- storage ring (at SLAC) have also reported[4,5] preliminary findings of $\mu^+\mu^-$ asymmetries consistent with the W–S–G theory. The theory also predicts essentially the same asymmetry for the reaction $e^+e^- \rightarrow \tau^+\tau^-$, assuming as it does that the three generations of charged leptons (e, μ and τ) are identical except for mass. The PETRA and PEP groups have found $\tau^+\tau^-$ asymmetries consistent with W–S–G, but the statistics for this final state are still meager.

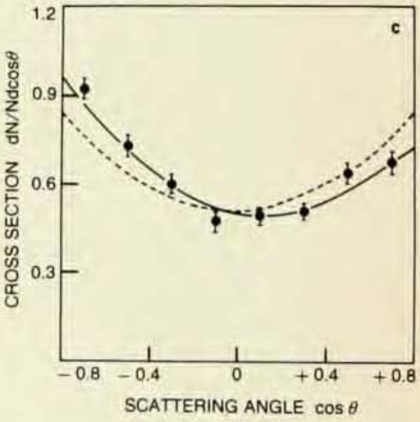
These e^+e^- experiments extend the testing of the Weinberg–Salam–Glashow theory into a new regime. The theory has been tested over the past decade primarily in neutrino scattering experiments. Although the results have been in good agreement with the theory, such experiments have been restricted to virtual masses of the exchanged Z^0 (the four-momentum transfer) far from the physical Z^0 mass. In the e^+e^- experiments, by contrast, the two projectiles combine to form a virtual Z^0 rather than simply exchanging one. Thus one has a timelike virtual Z^0 (energy greater than momentum) whose mass equals the total e^+e^- collision energy. As the Z^0 mass approaches its physical value, the weak force approaches the electromagnetic force in strength. The total center-of-mass energy in the e^+e^- colliding-beam experiments at PETRA and PEP is also more than twice that available in the neutrino experiments at CERN and Fermilab. The experiments thus provide the first opportunity for distinguishing between W–S–G and various proposed generalizations that yield indistinguishable predictions for low-energy, low-momentum-transfer experiments. Several such theories propose multiple varieties of the Z^0.

These experiments are not the first observations of weak interference in electromagnetic processes. In 1978, a SLAC–Yale collaboration led by Richard Taylor and Charles Prescott (both at SLAC) observed a parity-violating asymmetry in the helicity dependence of the inelastic scattering of polarized electrons off deuterons and protons (PHYSICS TODAY, September 1978, page 17). But with a center-of-mass energy of less than 7 GeV (at the SLAC linac), the weak contribution was very small, giving a predicted asymmetry of only about one part in 10^4. The observed result, in excellent agreement with the prediction, was generally regarded as an experimental triumph and a strong verification of the W–S–G electroweak theory.

The far larger interference asymmetry expected in lepton-pair production at PETRA and PEP energies is much easier to see. At 35 GeV, the weak force has grown to about 10% of the strength of the electromagnetic force, manifesting itself by a 10% forward–backward asymmetry. (Its contribution to the total cross section for $\mu^+\mu^-$ production, however, remains small—only 0.1%.) The experimental procedure for observing this asymmetry in the reaction $e^+e^- \rightarrow \mu^+\mu^-$ is rather straightforward, and more or less the same at each of the six large detectors currently studying this reaction at PETRA and PEP. One looks for a pair of roughly collinear muons of opposite sign emerging simultaneously from the beam collision region, each carrying a large fraction of the beam energy. Muons are distinguished from pions and other hadrons by the fact that they can pass through a thick iron barrier surrounding the central detector, and from electrons by their failure to generate a cascade of photons and e^+e^- pairs when passing through a lead shower counter. The momentum and charge sign of each muon is determined by its curvature in the detector's magnetic field. Expecting an asymmetry of about 10%, one must insure that any spurious asymmetry contributed by detector biases is kept below 1%.



Angular distribution of $\mu^+\mu^-$ pairs produced by 35-GeV e^+e^- collisions at PETRA display forward–backward asymmetry manifesting electroweak interference. Data from Jade (**a**), Tasso (**b**), and Mark J (**c**) detectors. Solid curves indicate asymmetric fits to Weinberg–Salam–Glashow theory. Cos θ is the center-of-mass angle between incoming e^+ and outgoing μ^+. Dashed curves show the (approximately) symmetric prediction of QED, without weak interference. (In **a** and **b**, s is the collision energy squared.)



The fundamental measurement in these experiments is the forward–backward asymmetry A, given by $A = (N^+ - N^-)/(N^+ + N^-)$, where $N^\pm$ is the number of $\mu^\pm$ emerging within 90° of the e^+ beam direction. In practice, the detectors cannot cover the entire 4π solid angle surrounding the collision region; spaces must be left open in the beam directions. One therefore measures the differential cross section $dN/d\cos\theta$ at various values of the scattering angle θ between the incident $e^\pm$ and emerging $\mu^\pm$. The overall asymmetry A is then determined by fitting a curve of the form predicted by W–S–G through the cross-section measurements and extrapolating to the full angular range.

The W–S–G theory predicts that the angular dependence of the differential cross section will have the general form $C_1(1 + \cos^2\theta) + C_2 \cos\theta$. The second term, antisymmetric in θ, gives the forward–backward electroweak interference asymmetry. Its coefficient C_2 depends on the axial-vector coupling constant g_A of the Z^0 to the charged leptons, and on the Z^0 mass and the collision energy. The theory predicts that $g_A = 1/2$, with a much smaller vector coupling constant. With a Z^0 mass of about 90 GeV, inferred primarily from the neutrino experiments, one gets a predicted asymmetry A of about −9% for both the $\mu^+\mu^-$ and $\tau^+\tau^-$ final states at 35 GeV. Note that the sign of A is *negative*; each emerging lepton tends to follow the direction of the incident $e^\pm$ of the *opposite* sign. This will be the case so long as the center-of-mass energy is below the Z^0 mass.

This tendency of the emerging leptons to "remember" the directions of the incident charges is not *ipso facto* a violation of parity conservation. But the dominant electromagnetic reaction mechanism—a single-photon intermediate state—forbids such memory.

Higher-order quantum-electrodynamic mechanisms involving two-or-more virtual photons (the so-called radiative corrections) do in fact predict a purely electrodynamic asymmetry of about $+1\%$. The raw data must therefore be corrected for this effect before comparison with the electroweak theory.

The three long-running detector systems at PETRA, colorfully named Jade, Tasso and Mark-J, have been taking $e^+e^- \to \mu^+\mu^-$ data at various energies for almost four years, all with roughly the same integrated luminosity (events per unit scattering cross section) and detector capabilities. Because the luminosity of PETRA was increased by an impressive factor of $3\frac{1}{2}$ early last year, the statistics with which the three groups have published depends strongly on the publication date.

The most recent, and therefore highest-statistics report[1] of the $\mu^+\mu^-$ asymmetry comes from the Mark-J group, an Aachen, Amsterdam, Caltech, DESY, Madrid, MIT, Peking collaboration led by Samuel Ting (MIT). Having measured 2435 muon pairs (corresponding to an integrated luminosity of 48.3 events per picobarn) at an average center-of-mass energy of 34.6 GeV, the group finds an overall forward–backward interference asymmetry (extrapolated to all angles and corrected for higher-order QED) of $-(9.8 \pm 2.3)\%$. This is to be compared with a W–S–G prediction of $-(8.7 \pm 0.6)\%$. This predicted value includes an additional radiative correction; photon emission in the *initial* state reduces the effective collision energy and hence the predicted asymmetry. (The precise initial-state correction involves some controversy. Not all the groups have chosen to include it.)

Extrapolating the asymmetry data to all angles is a bit of a cheat. The analytic form of the fitted curve with which one extrapolates to the forward directions does, after all, assume the correctness of the theory being tested. Thus Ting prefers to quote his model-independent raw asymmetry result, determined by simply counting positive and negative muons with $|\cos\theta| < 0.8$. "This result, $A = -(8.1 \pm 2.1)\%$, is good even if the theory turns out to be wrong," he told us. With the same angular cut, the W–S–G theory predicts $A = -(7.6 \pm 0.6)\%$.

At 14 and 22 GeV, where the W–S–G theory predicts an asymmetry too small to be observed in these experiments, the PETRA groups have found none. These results yield a lower limit of 51 GeV for the Z^0 mass, at a confidence level of 95%.

The Mark-J detector differs from the others in having no magnetic field in the central detector region. The magnetic field is confined to the iron hadron absorber through which the muons pass unhindered. One determines the muon momenta by measuring their curvature in the iron. To minimize spurious asymmetries resulting from inadvertent difference in the treatment of positively and negatively charged muons by the system, half the data were taken with the magnet polarities reversed. By this means, and by looking at cosmic rays in the detector, the group concludes that systematic biases contribute less than 1% to the observed charge asymmetry.

The Tasso group, an Aachen, Bonn, DESY, Hamburg, London, Oxford, Rutherford Lab, Weizmann Institute, Wisconsin collaboration (whose spokesman is Gunther Wolf, DESY) published[2] their $\mu^+\mu^-$ and $\tau^+\tau^-$ data earlier this year with an integrated luminosity of 35 events per picobarn at an average center-of-mass energy of 34.2 GeV. They report a $\mu^+\mu^-$ asymmetry of $-(16.1 \pm 3.2)\%$, more than two standard deviations above the W–S–G prediction. But Sau Lan Wu (Wisconsin) told us that the group does not yet take this discrepancy seriously. "After the 1978 Taylor experiment, everyone expects the $\mu^+\mu^-$ asymmetry to agree with the theory."

Like Tasso and Mark II at SLAC, the Jade detector has a central magnetic field provided by a large solenoid coaxial with the beam directions. The momenta and charges of the muons are determined by their curvatures in the central detector region. The Jade group, a DESY, Hamburg, Heidelberg, Lancaster, Manchester, Rutherford Lab, Tokyo collaboration (whose spokesman is Rolf Felst, DESY) reported[3] last November an extrapolated and radiatively corrected $\mu^+\mu^-$ asymmetry of $-(12.8 \pm 3.8)\%$. Their integrated luminosity was 19 events per picobarn at an average center-of-mass energy of 33.5 GeV. The W–S–G prediction for the asymmetry at this energy is -9.2%. Like all the other groups, the Jade collaboration estimates that its systematic errors contribute less than 1% to the observed asymmetry.

The fourth DESY detector, Cello, run by a DESY, Karlsruhe, Munich, Orsay, Paris, Saclay collaboration, is a relative newcomer to the PETRA ring. With as yet very limited statistics, the group reports[4] a $\mu^+\mu^-$ asymmetry of $-(6.4 \pm 6.4)\%$ and a $\tau^+\tau^-$ asymmetry of $-(10.6 \pm 5.4)\%$, both at 34.2 GeV. The relatively small $\tau^+\tau^-$ error results from a special effort by the Cello group to exploit a large fraction of the tau decays.

Lumping together all the $\mu^+\mu^-$ data from all the PETRA detectors as of June, Beate Naroska (DESY) reported at the June Stockholm conference on colliding-beam physics a grand average of $-(11.9 \pm 1.5)\%$ for the $\mu^+\mu^-$ asymmetry, extrapolated to all angles and QED corrected. For comparison she quoted a W–S–G prediction of -9.1%, without any initial-state radiative correction. The PETRA groups were expecting to report on larger data samples in July at the XXI International Conference on High Energy Physics in Paris.

Two groups at PEP have reported preliminary lepton-pair asymmetry data at 29 GeV, with integrated luminosities of about 15 events per picobarn. Although PEP is capable of running at e^+e^- center-of-mass energies up to 35 GeV, the Mark-II and MAC detector groups chose to run primarily at the lower energy, where the operation of the storage ring has been more reliable. An attempt to increase the machine's luminosity last fall, by moving some of the focusing quadrupole magnets closer to the e^+e^- intersection regions, was somewhat disappointing. A more substantial luminosity increase is hoped for when two more quadrupoles are moved this summer.

The Mark-II group, a SLAC, Lawrence Berkeley Lab, Harvard collaboration, reports[5] preliminary results of $A = -(6.0 \pm 4.0)\%$ for the $\mu^+\mu^-$ asymmetry and $-(4.8 \pm 7.3)\%$ for $\tau^+\tau^-$. At this lower energy, the W–S–G theory predicts an asymmetry of about -6% for both. They also find a value of 0.19 ± 0.29 for $g_A{}^\tau g_A{}^e$. The superscripts, denoting the axial-vector couplings of the different leptons to the Z^0, should be irrelevant if the lepton couplings are "universal" as expected by the theory, which predicts $g_A{}^2 = \frac{1}{4}$. The group expected to report on a much larger statistical sample (35 events per picobarn) at the Paris conference.

The MAC detector identifies muons primarily by their lack of energy deposition in its hadron calorimeter/absorber. The MAC group, a Colorado, Frascati, Northeastern, SLAC, Stanford, Utah, Wisconsin collaboration, has recently reported[6] a $\mu^+\mu^-$ asymmetry of $-(3.2 \pm 2.8)\%$ and a value of 0.13 ± 0.11 for $g_A{}^e g_A{}^\mu$, which again equals $\frac{1}{4}$ if one believes in lepton universality and the Weinberg–Salam–Glashow theory. —BMS

References

1. Mark J Collaboration, B. Adeva *et al.*, Phys. Rev. Lett. **48**, 1701 (1982).
2. Tasso Collaboration, R. Brandelik *et al.*, Phys. Lett. **110B**, 173 (1982).
3. Jade Collaboration, W. Bartel *et al.*, Phys. Lett. **108B**, 140 (1982).
4. Cello Collaboration, H. Behrends *et al.*, DESY preprints 82-019 and 82-020 (1982).
5. R. Hollenbeek, SLAC preprint 2829 (T/E) (1981), J. Strait, SLAC preprint 2914 (T/E) (1982).
6. MAC Collaboration in *Proc. 5th Int. Conf. on Novel Results in Particle Physics*, Vanderbilt (1982), R. S. Panvini, ed., to be published by AIP. □