

the ZGS could die "with a bang, not with a whimper."

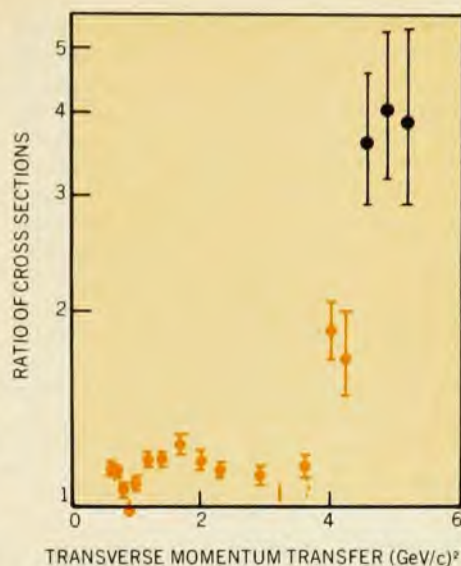
The polarized proton target consists of beads of ethylene glycol doped with potassium dichromate. The beads are maintained at 0.5 K in a magnetic field at 25 kG; however, because of radiation damage, they slowly lose their nuclear polarization, and must be annealed every few hours and replaced twice a week. In this way the group was able to keep the target polarization at an average value of 65%. The mechanism for polarizing the protons involves a temporary spin-pairing between a proton from ethylene glycol with a polarized electron from a chromium atom. (At 0.5 K the electrons are 99.5% polarized.) An rf field of the appropriate frequency induces what is, in effect, a hyperfine transition in the temporary pair, thus transferring the electron polarization to the protons. The group monitored the proton polarization in the target with nmr techniques. To monitor the beam polarization they measure the left-right asymmetry in the p-p elastic scattering from a hydrogen target placed in the beam before the polarized target.

At the ZGS the polarized beam is produced from a thermal beam of hydrogen atoms. A Stern-Gerlach magnet focusses atoms with electrons in one spin state, defocussing those in the other, and an rf field then transfers the polarization to the protons via a hyperfine transition. The atoms are then ionized and sent to the accelerator. Although the protons are normally polarized transverse to the beam, they can, with further manipulation, be polarized along the beam direction.

The Michigan-Argonne group used a double-arm spectrometer to measure the angle and momentum of both the forward and recoil protons. By varying the currents in the spectrometer magnets and occasionally reversing the target magnetic field they were able to obtain data for a large range of transverse momentum transfers without moving the counters.

The Michigan-Argonne polarized target can be polarized only vertically, so Krisch and his collaborators measured the spin dependence of elastic scattering for the four possible spin-up, spin-down combinations of beam and target. For transverse momentum transfers in the range 1 to 3 (GeV/c)² the group found considerable spin-orbit coupling and some spin dependence, but both parameters diminished above 3(GeV/c)². For $P_{\perp}^2 > 4(\text{GeV}/c)^2$, however, the spin-spin correlation increases dramatically, while the spin-orbit coupling remains small.

The interpretation of these results will depend considerably on whether the observed behavior continues to higher values of $P_{\perp}^2$ than the 5.09(GeV/c)² Krisch's group has been able to obtain. Another group at Argonne, led by Akihiko Yokosawa, has used a different polarized proton target to measure the polarization



Ratio of differential cross sections for elastic proton scattering with spins of beam and target protons aligned parallel and anti-parallel. Both spins are normal to the scattering plane. Beam momentum is 11.75 GeV/c; the most recent data are in black. (Figure from ref. 2)

effects for spins in the scattering plane.³ These experiments were done for values of $P_{\perp}^2$ less than 3(GeV/c)² and display a considerable amount of structure. These data, as well as earlier data on the total cross sections from Yokosawa's group, have been interpreted by some theorists as indicating a di-proton resonance, and the Yokosawa group therefore has been spending much of its efforts on a search for that resonance. If such a resonance is confirmed, it is an exciting development. Gerald Thomas, a theorist at Argonne, told us that σ_T data are especially interesting for helping to elucidate whatever internal structure the proton has. Yokosawa's group has recently begun taking data to extend their experiment to higher energies, so that they will be able to look for further effects of the possible di-proton resonance and for longitudinal spin effects comparable to those found by Krisch's group for transverse spins.

The momentum dependence of differential cross sections is, in a sense, the Fourier transform of the spatial structure of the scattering particles. In that sense, the high- $P_{\perp}$ scattering probes the deep internal structure of the proton. Most proton-proton scattering data show a very steep drop at low $P_{\perp}$ and a much slower decrease at high $P_{\perp}$, with a transition region exhibiting various kinds of complex behavior. At large $P_{\perp}$ one is presumably seeing some relatively "hard," small scattering centers, Krisch told us, and the asymmetric scattering may be attributable to some spin dependence of the scattering of these hard constituents of the proton. Just what these constituents are and whether one can draw any conclusions about quark-quark scattering from the results is not yet clear. Thomas said that preliminary quark models can

provide reasonable fits to the Yokosawa group's data, but that the asymmetries found by Krisch's group are much larger than the models predict.

Future experiments may provide further data to resolve the problems. At present, the polarized proton beam at the ZGS makes these experiments possible. The ZGS is now planned to close on 1 October, 1979. When it closes, no comparable facilities will be available. At this time it seems feasible to provide polarized proton beams for other accelerators, and in fact, a 3 GeV polarized-proton beam source is under construction at Saclay and planned to open in about a year. There is a proposal and design study for providing a polarized beam for the 33-GeV Alternating Gradient Synchrotron at Brookhaven, a proposal to provide a polarized-beam capability at Fermilab, and Japan is considering a polarized beam source for the KEK 12-GeV accelerator.

—TVF

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High-flux neutron source for fusion studies

In all of the fusion reactors currently under active consideration, an intense flux of 14-MeV neutrons will bombard the inner walls of the reactor. One expects a 14-MeV neutron flux of about 10¹⁴/cm² sec. This is an order of magnitude below the typical flux in fission power reactors, but the much more energetic neutrons from the deuterium-tritium fusion reaction can generate significantly different kinds of damage to the materials of the reactor.

The detailed nature of the damage done by such an energetic neutron flux is a major unknown in studies of the engineering feasibility of fusion reactors. In the absence of a working fusion test reactor, until now one has had to make do with 14-MeV neutron sources delivering a maximum flux less than 2 × 10¹²/cm²-sec. With such a limitation on available neutron sources, it would take more than 50 years to simulate the damage suffered by a test material in one year of real reactor time.

With the opening of a new Department of Energy facility at the Lawrence Liver-

more Laboratory in January, fusion-reactor researchers now have access to 14-MeV neutron sources six times as intense as any previously available. The Rotating Target Neutron Source-II, replacing the RTNS-I, which has been used at Livermore for neutron damage studies since 1972, provides experimenters with two independent 10-mm wide, 14-MeV neutron sources, each providing a maximum flux of 10^{13} neutrons/sec cm^2 .

Energetic neutrons damage reactor materials in several ways. Recoiling atoms produce cascades of vacancies and interstitial atoms in the lattice structure of crystalline materials. The neutron-induced production of hydrogen and helium in (n,p) and (n, α) reactions can lead to the formation of gas bubbles in the materials. Interstitial migration can change alloy microstructure, altering the electrical and mechanical properties of materials. Superconductors may fail, and radiological containment structures or insulators can be dangerously weakened. Surface damage may release material into the plasma, cooling it and thus quenching the thermonuclear burn.

One of the two RTNS-II sources has been available to experimenters since January, at which time a group from Argonne National Laboratory began a study of neutron-flux effects on the kind of fused silica windows that may be installed on the Princeton Tokamak Fusion Test Reactor. Three other neutron-damage studies were scheduled to begin in March. Groups from Brookhaven and Livermore are investigating the effect of 14-MeV neutrons on various superconducting materials being considered for confinement magnets. Detrimental changes in structural steels and other high-strength alloys are being looked for by a group from Pacific Northwest Laboratories.

The 14-MeV neutrons are released in the standard fusion reaction in which a deuteron and a triton combine to form a helium nucleus. At RTNS-II, a 150-milliamp beam of 400-keV deuterons impinges upon the titanium-tritide coating of a spinning copper target. The 1-cm-wide deuteron beam, accelerated by a Cockcroft-Walton accelerator, is so intense (75 kW/ cm^2) that it would melt almost any material in its path. Therefore the tritium-containing target requires a very elaborate cooling system. The titanium tritide coats the face of a 50-cm-diameter copper-alloy disk, which spins at 5000 rpm and has an intricate and rather pleasing pattern of cooling channels etched into its rear surface. (See the cover of this issue of PHYSICS TODAY.) With a flat copper disk bonded to this etched surface, water must be forced through the channels at about a liter per second to dissipate the heat deposited by the deuteron beam.

The neutron flux emerging from the Rotating Target Neutron Source-II is still an order of magnitude less intense than

what the inner walls of a fusion reactor will eventually have to suffer. Therefore the next generation neutron source is currently in the design stage at the Hanford Engineering Development Laboratory. This facility would use a 35-MeV deuteron linac and a liquid-lithium target to produce a total neutron source strength in excess of 10^{16} neutrons/sec with maximum flux of order $10^{15}/\text{cm}^2$ sec. These neutrons will not however be monoenergetic, but will have a broad spectrum of energies up to 45 MeV. Design studies for the facility are underway. Construction would take about five years.

The Hanford facility would be able to

undertake real lifetime studies of fusion-reactor materials. Jay Davis, who supervised the design and construction of the RTNS-II, told us that the emphasis of the Livermore facility is somewhat different. With its still limited flux it is intended primarily to provide data for comparison with theoretical models of fundamental damage processes initiated by 14-MeV neutrons. Frank Coffman, head of DOE's fusion technology program, points out that the flux of RTNS-II will be sufficient for lifetime studies of reactor components such as the magnet insulators, which are separated from the plasma by the inner walls. —BMS

Superlattices show quantum effects

Recent advances in controlling the epitaxial growth of semiconductor heterostructures have made possible the observation of man-made quantum-size effects in such structures. By sandwiching a layer of gallium arsenide about 100 Å thick between confining layers of aluminum-gallium arsenide, one creates a potential well about 300 milli-electron volts deep in which confined, discrete energy levels can be observed for electrons above the conduction band edge. By expanding this sandwich to hundreds of GaAs layers, with interspersed $\text{Al}_x\text{Ga}_{1-x}\text{As}$ layers of comparable thickness, one has created a superlattice, with an artificial periodicity one or two orders of magnitude longer than the atomic spacing, superposed on the natural periodicity of the crystal (see PHYSICS TODAY, August 1975, page 17). This results in a splitting of the conduction bands into mini-bands corresponding to the mini-Brillouin zones of the longer periodicity. When such a superlattice is doped with donor impurities, a pseudo-two-dimensional electron gas will be confined in each GaAs layer.

In recent months a University of Illinois-Rockwell International collaboration has reported continuous-wave laser action from confined, discrete electron levels several hundred meV above the conduction band edge in quantum-well heterodiodes,¹ and a group at Bell Labs has found greatly enhanced electron mobility along the planes in periodically doped superlattices.²

Quantum wells. Daniel Dapkus and Russel Dupuis at Rockwell International have since 1977 been growing $\text{GaAs-Al}_x\text{Ga}_{1-x}\text{As}$ quantum-well heterostructures by the epitaxial technique known as metallo-organic chemical-vapor deposition. The active GaAs layers, 50 to 200 Å thick, have proven so free of crystal defects that their collaborators at the University of Illinois, led by Nick Holonyak, have been able for the first time to achieve continuous-wave lasing transitions from high-lying discrete electron energy levels confined in the active layers. The bottom of

the conduction band in GaAs lies about 300 meV below that in $\text{Al}_x\text{Ga}_{1-x}\text{As}$, when x (the fraction of aluminum) is about 0.3. Thus each GaAs layer represents a 300-meV deep, one-dimensional potential well for electrons (and a shallower well for holes at the top of the valence band). When these wells are sufficiently thin (≤ 300 Å), they generate an observable series of discrete quantum states for electrons and holes. Dapkus and Dupuis have produced heterostructures with single and multiple (up to six) GaAs layers. When the interleaved $\text{Al}_x\text{Ga}_{1-x}\text{As}$ coupling layers are sufficiently thin (≤ 100 Å), the coupling between confined quantum states results in a fine splitting. This splitting ultimately generates bands in the limiting case of an infinite superlattice, just as the coupling between discrete atomic electron levels generates bands in an ordinary crystal.

Conventional semiconductor heterodiode lasers, where the active central layer is thousands of angstroms thick, are usually grown by liquid-phase epitaxy. This technique grows crystals sufficiently free from lattice defects to allow continuous-wave laser action at room temperature. But with liquid-phase epitaxy one has not been able to produce the sharp interfaces required for the ultra-thin layers that can give rise to quantum-size effects. On the other hand, molecular-beam epitaxy, which was introduced at Bell Labs in 1969, can produce extremely sharp interfaces, with layer thickness down to mono-atomic dimensions (see PHYSICS TODAY, February 1977, page 17). But heterostructures grown by molecular-beam epitaxy have not yet proven capable of cw laser action at room temperature.

In the opinion of Charles Duke of Xerox, the Illinois-Rockwell results demonstrate that metallo-organic chemical-vapor deposition has to some extent combined the virtues of the other two epitaxial techniques, making possible for the first time practical quantum-well laser devices. In metallo-organic chemical-vapor deposition, the $\text{Al}_x\text{Ga}_{1-x}\text{As}$ layer