Discovery of the Z^0 at CERN also yields anomalous events

Once the W particle was reported in January, it was almost inevitable that the Z^0 particle would eventually be found, provided that both the CERN collider and the two detector groups worked long and hard enough. The discovery of Z^0, the neutral intermediate vector boson, was announced on 1 June; the UA1 group said[1] it found five Z^0 events. The 270-GeV protons colliding with 270-GeV antiprotons had produced four events in which the Z^0 decayed into an electron–positron pair and one in which the Z^0 decayed into a $\mu^+\mu^-$ pair. On 15 July, the UA2 group also reported[2] finding the Z^0.

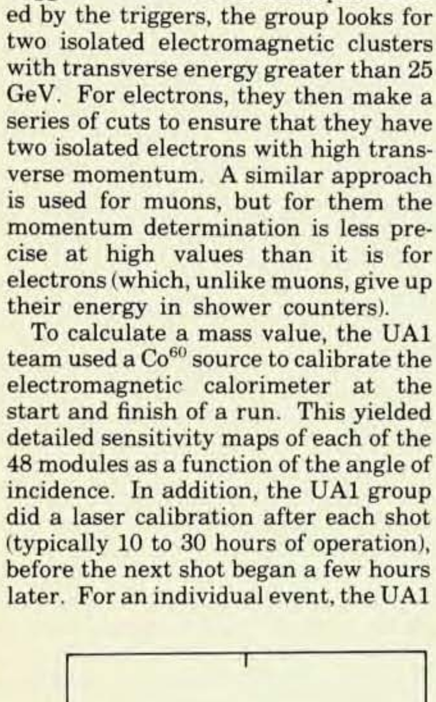
The Z^0 discovery came during the third running period of the CERN $p\bar{p}$ collider, this time with about six times greater integrated luminosity than the run last December. As a result, both detector groups have found many more W events and are able to see signs of an asymmetry in the angular distribution of charged leptons produced in W decay. Such a parity violation is good evidence that the observed particles are indeed the carrier of the electroweak interaction.

Among the sixteen Z^0 events found by September, the UA1 group has two anomalous events and the UA2 group has one. In these events the Z^0 decays into a photon plus a lepton pair. Internal bremsstrahlung, in which a charged particle shakes off a photon, has a probability of roughly 1% for the event observed. One possible explanation for the three anomalous events is a completely unexpected new particle with mass of about 50 GeV.

Mass of Z^0. After the December run, collider operation began again early in April and ended on 3 July. The next experimental run is not scheduled to begin until September 1984. In the interim, the Super Proton Synchrotron will do fixed-target physics while the collider and two detectors are improved.

Both the UA1 and UA2 detector collaborations look for a pair of energetic charged leptons, back to back. In the UA1 experiment, as in the search for the W (PHYSICS TODAY, April, page 17), four types of triggers were used, two of which are relevant to finding the Z: an electron trigger and a muon trigger. Within the data sample selected by the triggers, the group looks for two isolated electromagnetic clusters with transverse energy greater than 25 GeV. For electrons, they then make a series of cuts to ensure that they have two isolated electrons with high transverse momentum. A similar approach is used for muons, but for them the momentum determination is less precise at high values than it is for electrons (which, unlike muons, give up their energy in shower counters).

To calculate a mass value, the UA1 team used a Co^{60} source to calibrate the electromagnetic calorimeter at the start and finish of a run. This yielded detailed sensitivity maps of each of the 48 modules as a function of the angle of incidence. In addition, the UA1 group did a laser calibration after each shot (typically 10 to 30 hours of operation), before the next shot began a few hours later. For an individual event, the UA1 group must correct the mass value depending on the particular modules involved and the incidence angle. Because the scintillators darken with time, losing sensitivity by about 10% per year, one must also correct for the time when the event was recorded. The group is still calibrating and says that at present there could be an absolute mass error of 3%. For its mass determination, the UA1 group used only its electron events, because of the relatively large errors in determining muon momentum. Their latest value for Z^0 mass is (95.6 ± 1.5) GeV (statistical error).



Strong backward–forward asymmetry in W decay found[3] by UA1 was expected, in which electrons (positrons) are preferentially emitted in the direction of the proton (antiproton). θ is the angle between the electron and proton directions in the rest frame of the W. This plot is based on 27 to 30 events.

UA2 announced on 15 July that it had confirmed the discovery of the Z^0 with eight events. Of these eight, four are "gold-plated," clearly electron–positron pairs with no additional energy nearby. The UA2 group has no muon detector. Luigi DiLella of the UA2 group told us that his team uses radioactive sources and light flashers to calibrate their calorimeter. In December, he said, the UA2 group recalibrated and found the 80 counters had drifted by $1\frac{1}{2}$% or less. On the other hand, he said, the UA1 group did not calibrate their counters before the spring run. The UA2 group says their calibration error is lower, claiming an absolute mass uncertainty of ± 1.3 GeV. Based on the four gold-plated events, the UA2 group reports a Z^0 mass of (91.2 ± 1.7) GeV (statistical error).

Recent theoretical mass predictions based on the Glashow–Salam–Weinberg model with radioactive correction included give (94.0 ± 2.5) GeV/c^2.

Despite the success of the standard model, some theorists had proposed modifications containing two neutral intermediate bosons, at higher and lower masses than the single Z^0 of Glashow, Salam and Weinberg. Until the CERN measurement of the Z^0 mass, the more elaborate theories were consistent with all experimental evidence—electron–deuteron scattering, atomic parity violation and neutrino scattering.

The most spectacular prediction of the minimal SU(5) grand unification model for strong and electroweak interactions, proposed by Howard Georgi

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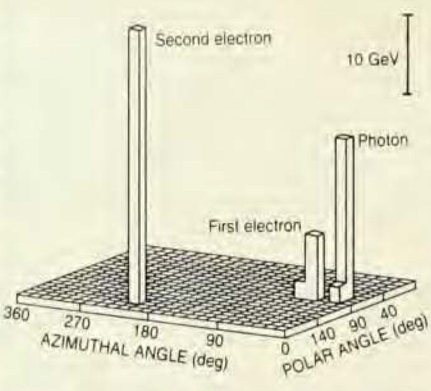
and Sheldon Glashow a decade ago, is that of proton decay, which remains unconfirmed. In fact, the apparent discrepancy between theory and experiment is now too big by a factor of at least 200 (PHYSICS TODAY, September, page 20). Minimal SU(5) also makes a prediction on $\sin^2\theta_W$, where θ_W is the electroweak mixing angle; the theory says $\sin^2\theta_W = 0.214$ ($+0.004$ and -0.003). The next $p\bar{p}$ collider run, from which the mass measurements of W and Z are expected to improve by a factor of two, will offer a better test of SU(5) predictions and those of more elaborate GUTs models. Meanwhile, Paul Frampton (University of North Carolina) and Glashow have a new paper, "Staying Alive with SU(5)," that suggests a new fermion representation in better agreement with present experimental results.

An upper limit to the number of (almost) massless neutrino varieties (or families) can be obtained from the total Z^0 width measurement by UA1; the answer is 31. In addition, just the fact that the Z^0 decay into e^+e^- has been observed at all implies that the number of neutrino varieties cannot be large. The UA1 group combined these two pieces of information, used a method of Francis Halzen and K. Mursula to estimate the ratio of production cross sections for the W and Z, and then obtained an upper limit of 18 neutrino varieties. This result was reported by Bernard Sadoulet of UA1 at the Symposium on Lepton and Photon Interactions at High Energies in August at Cornell. One of the major tasks for both the Stanford Linear Collider and the Large Electron–Positron collider at CERN will be to measure precisely the Z^0 width and thereby to obtain a true value for the number of neutrino varieties rather than just a limit.

Although the initial report of the W discovery was widely believed, the CERN experimenters still needed to demonstrate that the particle they found was the carrier of the electroweak interaction, by showing that the particles are maximally parity violating. In the three-month collider run that ended in July, both detector groups verified that the angular distribution of the charged leptons produced in W decay has an asymmetry and that the particle has spin 1; this verification comes from an analysis of electron angular distribution in the rest frame of the W. (See figure.) On the basis of 27 to 30 events, UA1 sees an asymmetry, and on the basis of about 10 events, so does UA2. The asymmetry[3] can be studied more completely by UA1 because it has a magnetic field over the full solid angle and can distinguish between an electron and positron in about 80% of the W decays. UA2, however, is essentially a calorimeter



Anomalous Z^0 event found by UA2 group. The plot[2] shows the distribution of energy transverse to the beam for the photon and electron–positron pair as a function of polar and azimuthal angles. The invariant mass of the electron–positron pair is (49 ± 2) GeV.

experiment and only has a magnet available in the forward direction, where the asymmetry effect is expected to peak. At present, both the UA1 and UA2 data are compatible with either a $V+A$ or $V-A$ interaction. Weak-interaction decays involve only the negative helicity states of particles, that is, a $V-A$ interaction.

The first anomalous Z^0 event was in the data reported by UA1 in June. It was an electron–positron pair plus a photon; the group originally thought it could be either due to internal bremsstrahlung or external bremsstrahlung in the corrugated vacuum chamber and detector walls. Upon further study, the group found that the angle between the electron and photon was (15 ± 5) deg, excluding external bremsstrahlung, which would require both particles to be collinear. The invariant mass of the e^+e^- pair is (42.7 ± 2.4) GeV ($\pm 3\%$ systematic error).

Early in September, the UA1 group found a Z^0 event with a photon and $\mu^+\mu^-$ pair. The invariant mass of the muon pair, at this writing, was about (61 ± 9) GeV, but the group is working hard to determine this value more precisely. In both the anomalous events, the photon has the same energy—about 30 GeV.

Of the eight Z^0 events found by UA2, one of the four gold-plated events is a photon plus an e^+e^- pair. The invariant mass of the e^+e^- pair is (49 ± 2) GeV.

At the APS Division of Particles and Fields meeting held in Blacksburg, Virginia, in mid-September, both Anne Kernan of UA1 and J. R. Hansen of UA2 described the anomalous events; audience reaction ranged from mild interest to great excitement. Although some remarked that a photon of that energy plus a lepton pair had a 1% probability of being produced, Kernan notes that the present score of such events is three out of the sixteen Z^0 events.

One possible explanation of the anomalous events is formation of a new particle that could be a quarkonium state decaying into the observed lepton pair. Another possible explanation would be the decay of a light Higgs boson (strongly coupled to the Z) into several photons mistaken as a single photon. Both explanations appear extremely unlikely. A third possibility is that the Z^0 is decaying into a known lepton plus a new heavy lepton (5–10 GeV in mass), which then decays to a π^0 (which can't be distinguished experimentally from a photon) plus a known lepton. But it's hard to accommodate this explanation with results from SLAC and DESY on high-energy e^+e^- annihilation, where you'd expect such heavy leptons to be formed. "The most likely possibility," stressed by a well-known particle experimenter, "is that you're seeing the improbable tail of dull physics."

If there *is* a new neutral particle, it may or may not have a charged counterpart. Both groups are now looking for the charged counterpart in the W data sample, to see if the possible particle also decays into a hard photon plus a quark–antiquark pair, such as an up and an antidown or a charm and an antistrange. Originally the two groups had looked for a W decaying to a charged lepton and neutrino. In the new phenomenon, a photon might carry away some of the energy, allowing the lepton energy to be lower than the criteria had allowed. Other events would appear as a hard photon plus a pair of jets. The invariant mass of the jet–jet system would be in the vicinity of 50 GeV, just as the lepton pair had in the hard-photon events seen in the Z^0 decay. The electron–positron collider PETRA at DESY is having its beam energy raised to about 25 GeV per beam and might be able to see a 50-GeV particle, if there is one.

Not much more information will be available on the anomalous events in $p\bar{p}$ collisions until the CERN collider starts running again next September, when it is expected to have each beam energy raised from 270 to about 320 GeV and to have greater luminosity. The SLAC Linear Collider, with 50-GeV electrons colliding with 50-GeV positrons, has been fully funded as of this summer and is scheduled to start doing Z^0 physics in late 1986. At CERN, LEP Phase I, which is to be an electron–positron collider with 60 GeV or less in each beam, is expected to be a "Z^0 factory," providing about 10 000 observable events each day, unlike the $p\bar{p}$ collider, which can now provide about a dozen events each year. In a few years, the CERN $p\bar{p}$ collider is expected to have even greater luminosity. But by 1986 or 1987, Tevatron I is expected to provide $p\bar{p}$ collisions at comparable luminosity at 2000 GeV center of mass (where the cross sections for single W and Z production are expected to be much higher than at the CERN $p\bar{p}$ collider energy). LEP Phase I is scheduled to produce a first beam two years later than SLC, in late 1988. When the two new lepton colliders are running, it should at last be possible to study Z^0 decay processes in detail.—GBL

References

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Coherent sources of extreme uv

Light sources in the extreme ultraviolet wavelength regime—from 104 nanometers down to the start of the x-ray region at about 10 nm—are of particular interest for molecular spectroscopy and solid-state surface studies. But this xuv domain poses special difficulties. The beams must be propagated in vacuum, but at these wavelengths there are no longer any solid materials available for vacuum windows or the harmonic generation of xuv light from longer wavelength sources. Crystalline lithium flouride, the last of the solids to maintain its transparency in the ultraviolet, becomes completely opaque at 104 nm. Beams of xuv can of course be generated by synchrotron light sources, but their usefulness is limited: The synchrotron beams do not provide coherent xuv light. Their spectral brightness (power per unit wavelength interval) is at present marginal for high-resolution molecular spectroscopy. Furthermore, synchrotron beams are available only at large storage-ring facilities; they cannot be brought into the experimenter's home laboratory.

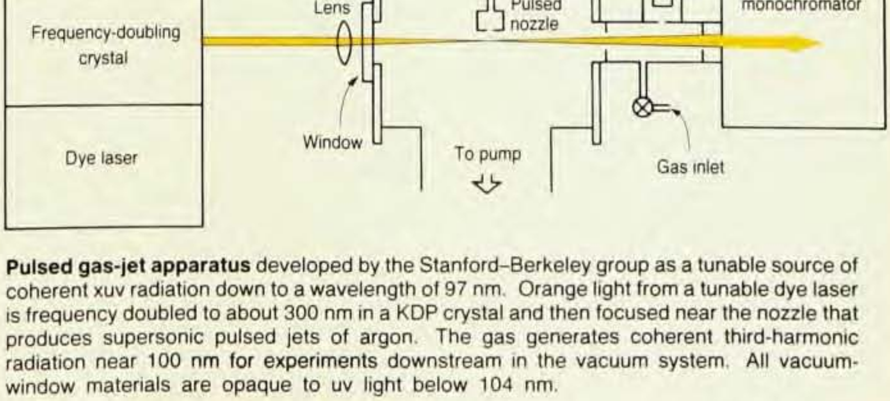
Until this year, there have been no lasers capable of producing xuv light. With regard to non-laser sources of coherent xuv light, the production of such beams by nonlinear harmonic generation in gases has required elaborate and cumbersome differential pumping schemes to maintain adequate vacuum in the presence of high gas flow rates.

This year, however, results coming out of several laboratories have brightened the prospects for the convenient generation of coherent ultraviolet beams at wavelengths below 104 nm—the "lithium flouride cutoff." Andrew Kung[1] at Berkeley and a Bell Labs group[2] headed by Jeffrey Bokor, independently of one another, have introduced the use of supersonic pulsed gas jets to generate high-frequency harmonics of longer-wavelength coherent ultraviolet light. With this technique, which circumvents the serious inconveniences posed by high-capacity differential pumping, Kung, collaborating with a Stanford group led by Richard Zare, has developed[3] an easily reproducible, practical system for generating tunable coherent xuv light of extraordinary spectral brightness in laboratories doing molecular spectroscopy. The Bell Labs group, employing a higher pulsed-power system involving mode-locked picosecond dye lasers and excimer laser amplifiers, has set a short-wavelength record for the harmonic generation of coherent xuv light—35.5 nm, the *seventh* harmonic of 248 nm ultraviolet light focused on their pulsed helium jet. Charles Rhodes and his colleagues at the Chicago campus of the University of Illinois have recently reported[4] what appears to be the first true laser emission in the extreme ultraviolet. Their 93-nm stimulated emission came from krypton atoms in a differentially pumped gas cell (not a pulsed jet), optically pumped by the exotic mechanism of *four*-photon excitation with a high-power excimer laser.

Harmonic generation. Because there have until now been no lasers emitting in the extreme ultraviolet and only a very limited selection in the vacuum ultraviolet regime (the wavelength interval between 200 nm, where oxygen becomes absorbent, and the lithium fluoride cutoff at 104 nm), coherent light below 200 nm has generally been produced by frequency mixing and the generation of harmonics in nonlinear crystals and gases. When subjected to sufficiently intense light, any material will exhibit nonlinear polarization; its polarization will no longer be simply proportional to the incident electric field. Thus the time-dependent polarization will contain Fourier components at multiples (harmonics) of the incident light frequency, and at sum and difference frequencies when more than one frequency is incident. This nonlinear response of the polarization will radiate light at these harmonic and mixing frequencies.

If a material with sufficiently nonlinear polarizability is subjected to intense laser light, such a scheme provides a practical source of coherent light at shorter wavelengths. KDP (potassium dihydrogen phosphate) crystals, for example, are widely used for frequency doubling of near-ultraviolet laser light. In the case of gases, by contrast, parity conservation permits only the generation of *odd* harmonics; frequencies can be trebled but not doubled. These nonlinear coherent sources should not be thought of as lasers, because they do not exhibit the gain characteristic of true stimulated emission. The efficiency of this kind of harmonic generation is, in fact, well below one percent.

One cannot, of course, use crystalline nonlinear materials like KDP to generate ultraviolet wavelengths below 104 nm; all solids are opaque in the xuv region. Harmonic generation in nonlinear gases, on the other hand, presents its own problems. Coherent har-



Pulsed gas-jet apparatus developed by the Stanford–Berkeley group as a tunable source of coherent xuv radiation down to a wavelength of 97 nm. Orange light from a tunable dye laser is frequency doubled to about 300 nm in a KDP crystal and then focused near the nozzle that produces supersonic pulsed jets of argon. The gas generates coherent third-harmonic radiation near 100 nm for experiments downstream in the vacuum system. All vacuum-window materials are opaque to uv light below 104 nm.