5. Major features of the experimental programme

13. One of the most famous photographs in the history of high energy physics. It was in this photograph, taken in the 80 inch bubble chamber at Brookhaven in 1964, that a track of an omega minus particle, whose existence was a crucial prediction of unitary symmetry theory, was first found. Negative kaons entered the chamber from below in the photograph and the sequence of interactions from which the omega minus was identified can be seen on the right.

High energy physics research began at the AGS in December 1960 with an extensive survey of secondary particles produced by 10 to 30 GeV protons incident on aluminium or beryllium targets.

The first experiments designed on the basis of this survey programme were total cross-section measurements investigating the behaviour of p-p, $\bar{p}$-p K^+-p and K^--p at momenta up to 20 GeV/c. A search (unfortunately negative) was made for magnetic monopoles produced by the 30 GeV protons. Simultaneously, the effects on particle yields of possible secondary interactions in the target nucleus were investigated. The diffracted proton beam at 30 GeV was used to make a number of emulsion stack exposures for several institutions. The same beam was used to establish the absolute cross-section for the production by protons of C^{11} from carbon and of Na^{24} from aluminium giving very useful information for calibrations and for monitoring beam intensities.

The first six months period was the beginning of an ever expanding experimental programme. A comprehensive review would be much too lengthy here and instead, a few examples of different lines of research to which the AGS has made significant contributions will be described.

Neutrino experiments

Pauli postulated the existence of the neutrino in 1930. This elusive and seemingly unobservable entity enabled Fermi to construct a theory of beta decay of the nucleus which reconciled the observed facts with the conservation of energy and angular momentum.

Muons are also coupled to neutrinos in weak interactions; muons can be absorbed by nuclei with the resultant emission of a neutrino in an analogous way to the electron capture form of beta decay. Muons also decay into an electron and *two* neutrinos. But here, a puzzling contradiction became apparent, since if these two neutrinos from the muon decay are of the same type, the muon should also be able to decay into an electron and a gamma ray.

The gamma-decay mode has never been seen in millions of experimentally observed decays. Feinberg, Lee and Yang pointed out that this could be explained by postulating two types of neutrinos — one coupled to the muon ($\nu\mu$) and the other coupled to the electron (νe). A test of this hypothesis can be made using the neutrinos produced when pions decay into muons plus neutrinos. These neutrinos, which must be coupled to the muon (the $\nu\mu$ type) can be captured in nuclei with emission of a fast muon. Capture of the neutrino with emission of a fast electron would not be seen unless the neutrinos $\nu\mu$ and νe are the same type.

The experiment only became feasible with the advent of high energy accelerators because the interaction probability increases rapidly with neutrino energy. At the AGS, a Columbia University-Brookhaven group set up a large spark chamber, containing a total of 10 tons of matter, shielded from all particles, except the very penetrating neutrinos, by 5000 tons of iron. The AGS proton beam on an internal target produced copious pions which decayed in flight. The resultant neutrinos penetrated the shielding and passed through the spark chamber. In 800 hours of running time in 1961 and 1962, about 4×10^{17} protons were delivered onto the target, yielding an integrated flux through the spark chamber of about 10^{14} neutrinos. Fifty interactions were observed, 24 of them showing a single energetic muon and 26 showing muons produced with other particles. Electrons, which would have been identified by the characteristic electron-gamma ray showers, were not seen. It is concluded, therefore, that the neutrinos $\nu\mu$ which are coupled to muons do not couple to electrons, and that the neutrino νe is therefore of a different type.

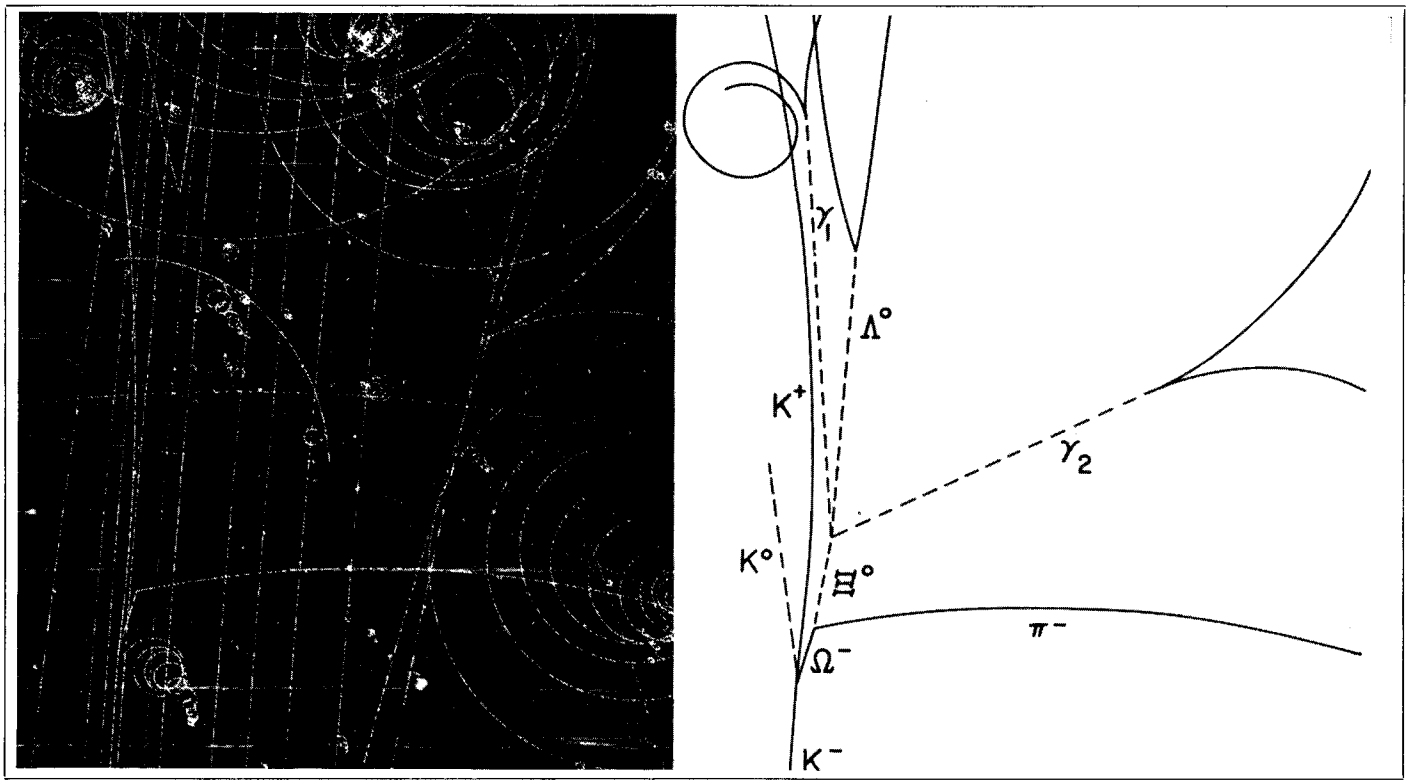
Research on neutrino interactions was continued by the Columbia-Brookhaven team in a new experimental area where a fast external proton beam on an external target was used to give higher pion yields and a pion focusing lens could be used to improve the flux density of the pions and of the neutrinos at the detector. An enlarged spark chamber array, totalling 60 tons of aluminium and iron, was constructed. The object of this experiment was a search for the existence of the intermediate boson, W, a short-lived particle hypothesized to be connected with the weak interactions.

In a fiducial volume of 24 tons in the production chamber, about 800 neutrino induced events were observed, and from these events, candidates were selected for decays of the W to electrons or muons. Detailed analysis of the data showed that none of these events could be ascribed to production of an intermediate boson. A careful neutrino flux survey was made, from which production cross-section calculations indicate that, at the 90 % confidence level, the intermediate boson must have a mass greater than two proton masses if it exists at all. This conclusion reinforced that of a CERN group using data taken at the CERN PS.

Particle resonances

The structure of the resonant mass spectrum and the quantum numbers (spin, parity, isotopic spin, strangeness) of elementary particle states have been studied since pions were first produced at cyclotrons. This study has intensified since the PS and the AGS were brought into operation. These machines give high quality beams of particles with energies great enough to reach the formation thresholds of resonant states. At even higher energies, the states are produced as fragments emerging from the collision process. Particle resonances have been studied at the AGS by two different techniques. One method measures the parameters of resonant states resulting from collisions detected in a bubble chamber. With a reasonably large sample of events, this technique is capable of making a precision determination of most of the resonance parameters.

A resonance had been discovered in the nucleon-pion system two decades previously at the University of Chicago. Now termed the Δ, it has a mass of 1236 MeV, and decays to its final states in about 10^{-20} seconds. The Σ_1 at a mass of 1385 MeV was found at the Lawrence Radiation Laboratory, Berkeley. As the evidence accumulated, it was pieced together to support the SU_3 unitary symmetry model. This model, based on relatively simple assumptions about the symmetry properties of physical laws, makes it possible to predict the properties of resonant states



13. 4.24.64

of particles. In 1962, a Syracuse University-Brookhaven collaboration exposed the 20 inch chamber to negative kaons and identified the $\Xi^{1/2}$ (1530) resonance which had been predicted by the SU_3 model.

Evidence supporting the SU_3 model continued to grow. Resonances of the strong interactions could be treated as 'particles' and grouped into remarkably orderly arrays. One array, called the baryon decuplet, neatly assembled nine known resonant states but its tenth member was missing. This tenth member, called the omega minus, Ω^-, was predicted by the mass formula to have a mass of 1680 MeV, and a lifetime of 10^{-10} seconds. Its existence was cited as a crucial test of the unitary symmetry theory of strong interactions and several laboratories were engaged in an effort to find it.

In February of 1964 a Brookhaven team announced the observation of the production and decay of the omega minus. More than 30 scientists (including three from Syracuse University and one from the University of Rochester) were directly involved in the experiment. The 80 inch hydrogen bubble chamber was exposed to 5 GeV/c negative kaons and about 100 000 pictures were taken. These pictures were analyzed for the more characteristic decay modes of the omega minus, and an event which could be interpreted as the elusive Ω^- was found.

Very careful fitting and cross checking of the momentum and bubble density measurements verified that the particle assignments were correct to a high degree of probability.The unusual and fortunate fact that two invisible gamma rays associated with the event both produced electron pairs within the liquid hydrogen, allowed a further cross-check. In view of the properties determined for the particle (charge —1, strangeness —3, and mass 1677 ± 9 MeV) it was clear that it could be identified as the predicted particle.

Another technique used in the search for resonances is the measurement of high energy collisions between various types of projectile and target particles. When the energy of the projectile is such that the resonant mass can just be formed, a peak is often observed in the total cross-section. This technique, using the high data taking rates of electronic detectors, can sensitively distinguish weak resonances masked by a background of other reaction channels. These cross-section measurements at the AGS yielded many results. Some of the 'peaks' in the cross-sections appear very small, but the statistical accuracy is so good that, on an expanded scale, they are meaningful.

Both bubble chamber and counter techniques have found a multitude of resonances. The measured masses, widths and spins have a direct bearing on the SU_3 model of the hadrons, or strongly interacting particles. The searches have by no means ended.

Studies of CP violation

An elegant experiment with a surprising and important result was carried out at the AGS by a group from Princeton University. Apparatus had been set up to study the decay of the neutral kaon. As observed in the laboratory, this meson exists in two forms, called K_S° and K_L°, which differ from one another in life-time, in decay modes, and very slightly in mass. The K_S° decays so quickly that it travels only centimetres before disintegrating into two pions. The K_L° has a longer life and travels tens of meters before decaying, usually into three particles. This particle complex has the remarkable feature that a K_L° may be converted into a K_S° in passing through matter, a process called regeneration.

The K° mesons were observed with a spectrometer which was aimed at a helium bag far enough from the target to permit essentially all the K_S° particles to decay. Only a very few produced by regeneration of K_L° in the helium would be observed. Since the K° is neutral, it can be detected only by making measurements on its decay products. Prior to this experiment, the K_L° was thought to decay only by a 3-body mode whereas the K_S° nearly always decays into two pions. In contrast, decay of the K_L° into two pions was forbidden by a fundamental principle of physics, CP (charge conjugation, parity) invariance. By inserting a piece of dense metal in the helium bag in the region of K° decay, it was possible to regenerate K_S° mesons which then quickly decayed into two pions. The apparatus was calibrated with sufficient exactness to establish this decay mode for the K_L°, should it occur. The regeneration material was then removed, and decays were still observed that were identical with those from the regenerated K_S° mesons.

It was very important to eliminate the possibility that these events were in some way simulated by the normal 3-body decay modes of the K_L°. Careful analysis eliminated this explanation and the experimenters concluded, as the most reasonable explanation of the observed events,

14. The spectrometer installed at the AGS for an experiment on neutral kaons by a team from Princeton University. This experiment discovered 'CP violation' for the first time by showing that the long-lived kaon can decay into two pions. The reverberations of this discovery in 1964 have still not died down.

that the K_L° meson decays into two pions at the rate of about 2 in every 1000 decays. This process violates CP invariance and strongly implies that time (T) reversal invariance does not hold, since CP and T are interdependent through the invariance of CPT, which appears to be firmly established for all interactions. Previously, it had been believed that the direction of time had no influence upon the laws of physics.

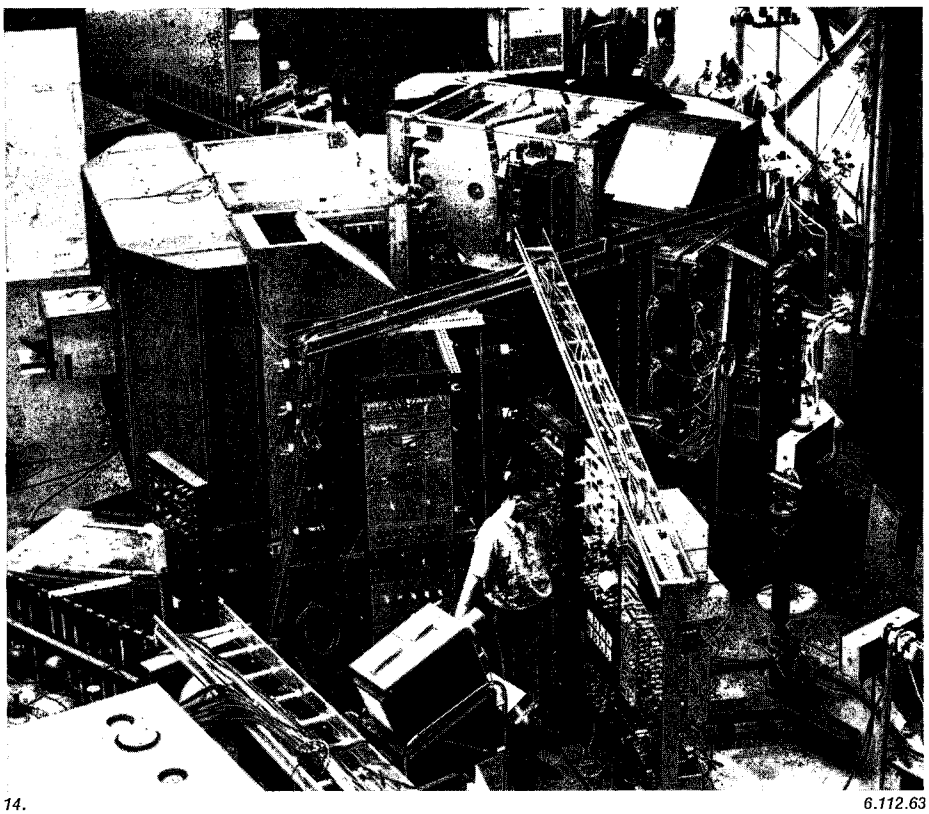
Almost immediately thereafter many experiments produced further understanding of the newly discovered violation.

Nuclear Chemistry

Nuclear chemists have made extensive use of the internal proton beam of the AGS to measure the distribution of products formed by the interaction of high energy protons with complex nuclei. By mapping yield distributions from a wide variety of targets at a number of energies an over-all picture of the mechanisms which are important in these reactions has been obtained. Spallation (the emission of many nucleons or small nuclei leaving a single, large residual product) and fission (break-up into two comparably sized products) are chiefly responsible for the observed yields.

Details of these mechanisms have been studied by a variety of techniques both with internal and external beams. Measurements of the angular and energy distributions of recoiling products, measurements using emulsion and mica track detectors, and counter experiments have been employed in these studies.

Major interest at the present time is centered on the nature of the processes which lead to the observed high yields of energetic fragments with masses between 15 and 30 from heavy target nuclei such as gold or uranium. The yield distributions for such fragments do not yet fit in with our present ideas of spallation and fishion. At the same time it is difficult to consider such large fragments being evaporated directly from highly excited nuclei in much the same way as are neutrons, protons, He and Li nuclei. Recoil measurements and counter experiments now in progress are specifically aimed at a better understanding of this problem.



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6. The future

Studies have been under way at Brookhaven for several years searching for means to increase the energy of particle accelerators into the TeV (thousands of GeV) range. The pulsed proton synchrotron still appears to be the leading contender when built with conductors operating at very low temperature and producing high magnetic fields.

The pilot production materials already at hand would reduce the synchrotron ring diameter by half compared with the size given by simply extrapolating an AGS type of construction. Superconductors which are likely to be available in the foreseeable future will make possible rings one third the diameter of those built with copper for the same energy. Techniques for operating at a few degrees Kelvin are becoming commonplace, and refrigerators of adequate size can be obtained.

One can already visualize a multi-thousand GeV synchrotron built of magnets smaller in cross-section than a dinner plate, housed in a few kilometers of Dewar within a small and inexpensive tunnel encircling the Brookhaven site. The vacuum chamber would be only a few centimeters in diameter — requiring injection energy above 20 GeV for good intensity. There are practical problems remaining to be solved, but they are scarcely more formidable than those confronting the constructors of the PS and AGS in the early nineteen fifties.

A study group at Brookhaven is exploring these possibilities in detail, making use of recent cryogenic magnet developments. The Brookhaven site has room for a ring with a radius of 1.5 to 2 kilometers. With pulsed magnets that give peak fields of 40 to 60 kG the site could accommodate an alternating gradient synchrotron with an energy of about 2000 GeV.

The present studies towards this end include the following:
A group is developing designs of pulsed dipole and quadrupole magnets using finely stranded superconducting cable; such magnets appear feasible for up to 60 kG.
Another approach under study is the development of 'window-frame' magnets