Dr. Lindenbaum describes a particle-physics experiment performed last year at Brookhaven National Laboratory in which one and a half million events per hour were analyzed with an on-line computer while the experiment was in progress. The author, a senior physicist at Brookhaven, believes that similar on-line computer-counter techniques might usefully be applied to other types of physics experiments.

THE ON-LINE COMPUTER COUNTER AND DIGITALIZED SPARK-CHAMBER TECHNIQUE

By S. J. Lindenbaum

In the fall of 1962[1,2] at the Brookhaven Alternating Gradient Synchrotron, a remarkable event took place. A highly complex elastic-scattering experiment involving high-energy (7–20 BeV/c) protons and pions scattered by a hydrogen target was investigated by a system of several hundred scintillation-counter hodoscopes* covering a large fraction of the solid angle in the investigated angular region. The system was all in fast (a few to 30 nsec) coincidence with complicated-logic trigger requirements, and it automatically trigger-selected, compiled, stored, and finally transmitted the data to an on-line computer. The computer then processed the data automatically and rapidly in real time according to a carefully pre-programmed analysis, stored the desired results in suitable bins, and transmitted the program-requested data displays back to the display scopes of the experimental group. Desired physical answers based on cumulative statistics (such as computed cross sections, errors, background values and distribution, displays of counter-efficiency uniformity, etc.) were also available in detailed print-out tabular (or, if desired, graphical) form, upon initiation by the experimenters of a simple output routine.

This was the first on-line computer-counter experiment and, in fact, the first truly on-line computer experiment in physics, since the event trigger selection, the recording of the basic pulse data from the detectors, the transmission of data to the computer, and its evaluation in the desired processed form to give answers to crucial theoretical questions were all controlled by electronic devices without human bias or interruption except for the prestored programs, control commands, entering of summaries of monitors, parameters of location of the counters, the beam momentum, etc. This technique was developed and the experiment was performed by the author's High-Energy Counter Research Group* at Brookhaven.

The impact of this new technique on the experimenters themselves was unusual. We had the feeling that we were doing a new kind of physics which was exciting and characterized by tremendous potential for future applications in many scientific investigations, not only in high-energy physics. We were gathering data at orders-of-magnitude higher rate than had ever before been attained in this class of experiment**. Yet, at the

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* A hodoscope is an array of adjoining long, thin, rectangular-slab detector elements which locate a Cartesian coordinate of a particle traversing its plane surface. The actual position of the particle in space is determined by the intersection of perpendicular elements of two such arrays.

* At that time the members of the group were K. J. Foley, S. J. Lindenbaum, W. A. Love, S. Ozaki, J. J. Russell, L. C. L. Yuan.

** Up to 50 000 trigger-selected events were handled and analyzed on-line per hour.

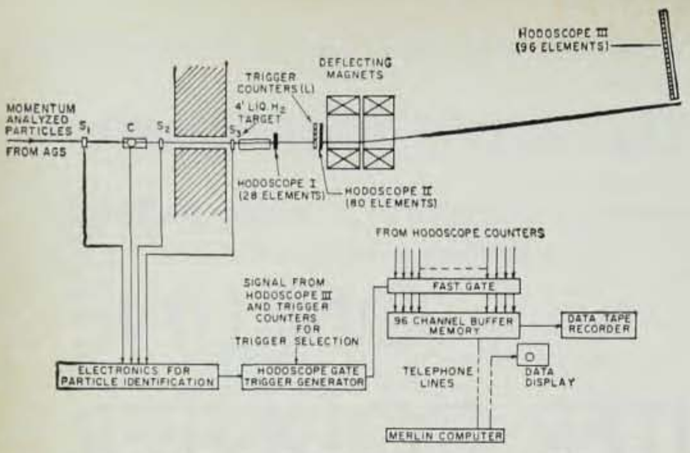


Fig. 1a. The magnetic spectrometer, counter hodoscope on-line computer system for selecting (7-20) BeV/c small-angle elastic scattering (arrangement I).

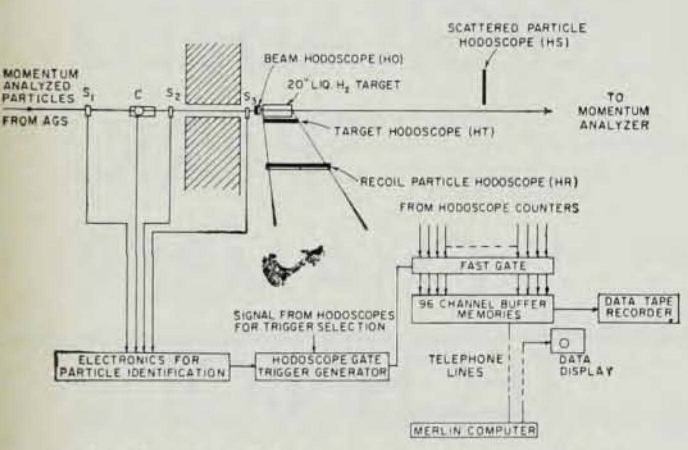


Fig. 1b. The counter hodoscope on-line computer system for selecting larger angle elastic scattering utilizing the reconstruction in space of the incident particle and the scattering plane (arrangement II).

same time, we were attaining a much higher systematic accuracy than had been achieved before, while the data were processed almost instantaneously by the on-line computer; any desired cross section, or other final computation and summaries of the data, were available within two minutes. Simply by changing the on-line program we could investigate any question which occurred to us. The power of this technique was clearly illustrated by the fact that after having run the experiment for only a few days we had accumulated much more information on $p+p$ and $\pi+p$ elastic scattering in this energy range than existed from the sum total of all previous experiments.

At these high energies the de Broglie wavelength of the incident-beam particles is a small fraction of the proton radius. Therefore, just as in optics, the gross features of the elastic scattering are describable by a Fraunhofer diffraction pattern whose width measures the size of the proton. The Regge-pole theory predicted that the high-energy $p+p$ and $\pi^{\pm}+p$ elastic-scattering diffraction pattern would exhibit a universal shrinkage with increasing energy, corresponding to an ever-expanding radius. Shortly after the start of the experiment we were able to demonstrate that, while the high-energy (>10 BeV) proton-proton elastic scattering does exhibit the shrinkage predicted by the Regge-pole theory, the high-energy $\pi^{\pm}+p$ elastic-scattering diffraction pattern does not, and hence we were able to disprove the theory.

The almost continuous feedback of both display and quantitative print-out information, coupled with the tremendous data rates obtainable, enabled us for the first time to make a reasonable survey, in one experimental run, of high-energy elastic scattering by protons of all known nuclearly interacting charged particles with lifetimes greater than 10^{-8} sec. This was clearly worth the several years of prior planning and the massive effort which we had made to achieve this goal*.

The on-line computer

The first experimental arrangement used in October 1962 for selecting small-angle high-energy elastic scattering in hydrogen (p) of (7–20 BeV/c) pions ($\pi^{\pm}$), kaons ($K^{\pm}$), protons (p), and antiprotons ($\bar{p}$) is shown in Fig. 1a. It was necessary to divide the experiment into two parts, small and large angles (See Fig. 1b), to maximize accuracy and efficiency. The three components of the momentum-analyzed incident beam were individually identified by a counter telescope including a gaseous Cerenkov counter (a gas-pressure setting selecting the desired particles). The position and direction of the particle before scattering was selected by the counter telescope. The vertical picket-fence hodoscopes I and II measured the horizontal coordinate of the particle after it was scattered in hydrogen. Hodoscope III (25 sq. ft.) which involved 96 crossed horizontal and vertical slab counters, determined both the horizontal and vertical position of the particle. Hence, the direction in space (θ,ϕ) as well as the momentum of the scattered particle were determined. Thus elastic scattering events could be selected from the inelastic background since the detected particle from these events had a reduced momentum.

When the predetermined trigger requirement (the desired particle in fast coincidence with a

* Among those contributing to the effort were several members of the Instrumentation Division of BNL, with whom we jointly developed some of the required equipment.

scattering-type event) was satisfied, 96 gates, thirty nsec (10^{-9} sec) wide, through which the counter signals were fed, were opened in parallel. Then the counters which had been struck by a particle transmitted a pulse in coincidence to the 96 input flip-flops of the digital data-handling system. These events were stored sequentially in the buffer memory (whose capacity was 32 words or events, of 96 bits each), until the memory was filled at the end of the AGS beam burst (about every two or three seconds the beam spills out for 100-200 milliseconds). During the time between pulses, the contents of the buffer store were read out in 6-bit characters, placed on magnetic tape and sent on-line (over telephone wires) to the Merlin computer,* the program flow chart of which is shown in Fig. 2.

The data display desired in this case was the momentum spectrum of the scattered particles in a small region of polar angle ($d\theta$). This was automatically displayed both at the computer and in our data trailer at the AGS on an oscilloscope, with a push-button that allowed us to see each one of twelve angular bins in sequence. A typical display of a momentum spectrum is shown in Fig. 3a with its characteristic elastic peak and low inelastic background. The flow chart (Fig. 2) clearly shows the intimate real-time on-line relationship between the experiments and the computer, and the further interaction involving the experimenters. The experimenters started the run by typing in the momentum, description of particles, locations of various counters, etc. As the data arrived at the computer's data-arrival trap, the computer was interrupted and each single event was processed as shown and finally stored in an elasticity (momentum) spectrum distribution. The data display at the AGS was kept up to date on a pulse-by-pulse basis; thus we could watch the elastic peaks grow with each pulse and make sure that equipment was working. When sufficient data were accumulated** the experimenters stopped data transmission and pushed the button to inform the computer that the run was ended. Control then passed to the output routine and the computer asked for necessary scaler information by typing requests on the console typewriter. This information having been typed in, the computer calculated the following quantities: the total number of AGS pulses, events, single-scattering-type events, incomplete events, processed events, etc.; the elastic-scattering cross sections $d\sigma/dt$ versus t, where t is the invariant four momentum transfer squared;* the background which was automatically subtracted; counter-profile distribution to check uniformity of efficiency, etc.; the parameters used; and all spectra.

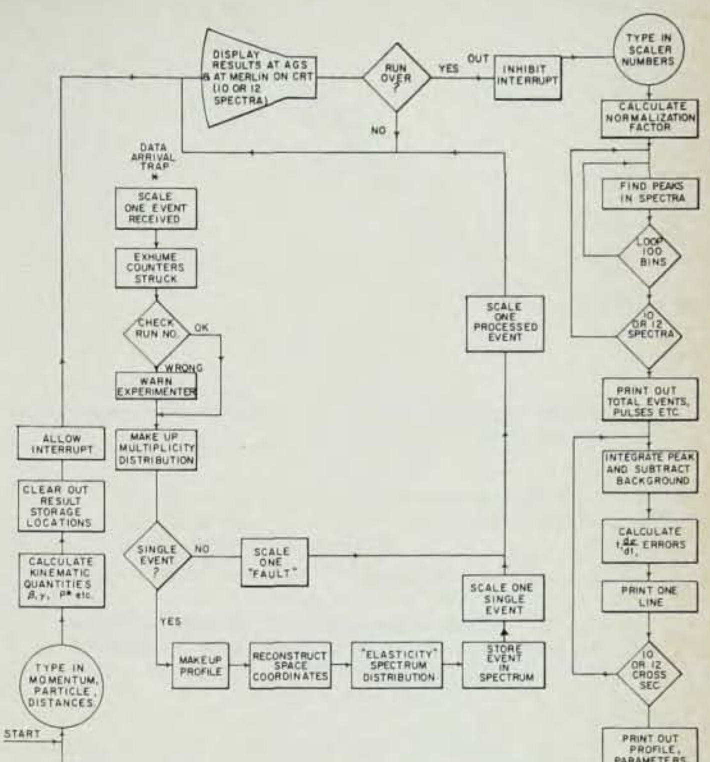


Fig. 2. The program flow chart of the first on-line counter experiments described in Figs. 1a and 1b.

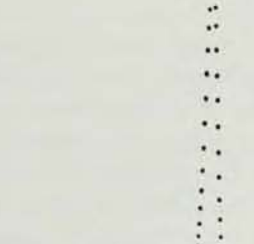


Fig. 3a. Typical on-line scope display of momentum spectra showing elastic-scattering peak.

* A general-purpose computer built at Brookhaven with 8192 words of 48 bits each and an average computing speed one-seventh that of an IBM 7094, was located about a mile from the experiment.

** A typical run took a few minutes to a few hours, depending upon data rates.

* At small angles this is approximately equal to the negative of the square of the angle times the square of the incident momentum.

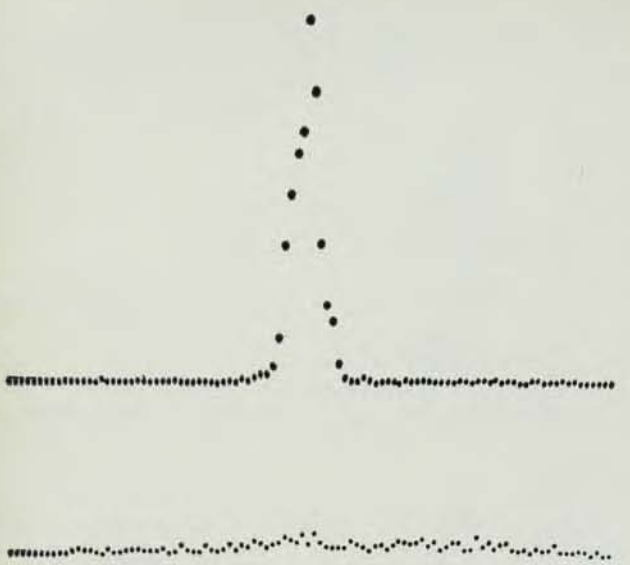


Fig. 3b. Typical on-line display of elasticity condition for scattering angle showing elastic peak in coplanar events (upper) flat background in noncoplanar events.

The whole output routine took two minutes. At the larger angles another experimental setup was used (Fig. 1b) in which the elasticity of the event was determined by reconstruction of both the incident particle and the scattering plane of the outgoing two particles. The usual coplanarity and kinematic-angle criteria for elastic scattering were used. The typical data displays in this case are shown in Fig. 3b. The upper curve represents the kinematic-angle relationship for coplanar events and clearly shows the elastic-scattering peak. The lower curve shows the same relationship for the noncoplanar events. The on-line computer system and program flow chart were similar. The programs in both cases were completely written by a physicist in the group, in machine language with maximum flexibility, and embodied a flow chart entirely worked out within the group; the program could be easily changed when necessary. This flexible programming approach is, in our opinion, a necessary feature of on-line computer experiments if the full power of the technique is to be utilized.

Fig. 4a shows typical results obtained for p + p elastic scattering, and Fig. 4b shows typical results obtained for π^- + p elastic scattering combined from both arrangements. These were unusual data in that all known resolution effects and corrections were measured or calculated. The fully processed data obtained are a result corrected for all resolution effects, and allow direct comparison with theoretical calculations. Furthermore, interpolations on the data were done using least-square parametric fits to the points only.

When $d\sigma/dt$ is plotted versus t, loosely speaking, the average slope (or equivalently, width) of the diffraction scattering curves gives the effective radius of the interaction. Therefore, the increasing slope (shrinkage of the diffraction pattern) with increasing momentum of the curves (Fig. 4a) implies a radius increasing logarithmically with energy. This was predicted by the Regge-pole theory in late 1961 and 1962. The increasing radius was supposed to be accompanied by a decreasing density of nuclear matter in such a way that the total cross sections remained approximately constant to fit the experimental high-energy and cosmic-ray observations. This was predicted to be a universal characteristic of all elastic-scattering interactions at energies high enough to be dominated by the so-called vacuum pole. An energy greater than 10 BeV was thought to be high enough. We found shortly after starting the experiment that the π^- + p interaction did not exhibit this effect (i.e., show a shrinkage of the diffraction pattern). One can easily observe that in Fig. 4a (p + p) there is a monotonic increase in slope (or equivalently, decrease in width of the diffraction pattern) as the incident energy increases, which causes a wide fan-like pattern for the various curves; this does not happen in Fig. 4b (π^- + p). In Fig. 4b all curves, within statistical-error variations, are the same, independent of energy. There is no energy dependence (shrinkage) of the diffraction pattern, and hence the resultant radius of the interaction is independent of energy. We also found that π^+ + p does not shrink. These observations eliminated all simple versions of the Regge-pole theory [2,4] and although there are still conceivable arbitrary complex versions, these involve so many arbitrary parameters that they are not convincing or useful and are at best only of academic interest.

In these same experimental runs, which spanned several hundred hours, we also studied K^+ + p and $\bar{p}$ + p elastic scattering and found that K^+ + p shrinks and $\bar{p}$ + p expands. We found the antiproton to have the biggest radius ($r \sim 1.35f$*) and the highest mean opacity (~ 0.85), while the proton comes next in size ($r \sim 1.12f$) with medium opacity** (~ 0.7); the pions have

* f=fermi=10^{-13} cm

** Opacity is a measure of the absorption of the incident particles, and is one for complete absorption and zero for no absorption.

about the same radius ($r \sim 1.1f$) as the protons but are less opaque (~ 0.55); the K^+ is the smallest particle ($r \sim 0.95f$) and has the same opacity as the other mesons. The K^- has about the same radius as the pions and protons and about the same opacity as the other mesons.

All that was required to go from measurements of one incident particle to a different particle was a change in gas pressure in the Cerenkov counter. The momentum and sign of the beam was controlled by the magnet settings. Because of the on-line processing, we knew in great detail the results obtained, their statistical precision, the important conclusions, etc. However, after the run was over, we carefully rechecked all of the computations and made second-order corrections to the data before final publication.

Because the experimental arrangement covered a large part of the solid angle simultaneously, this was a new and different kind of counter experiment; it had some of the three-dimensional vision of a bubble chamber or spark chamber, coupled with the high statistical and systematic accuracy of counters. The inelastic background and the various resolution effects were calculable directly from the observations. The accumulated data tapes even had a library aspect in that the inelastic momentum spectra which were not even utilized in the program were saved and could be used to search for nucleon isobar or other inelastic elementary-particle production.

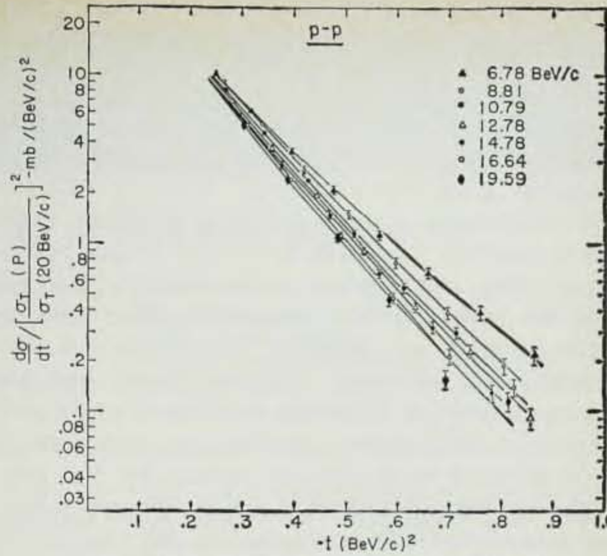
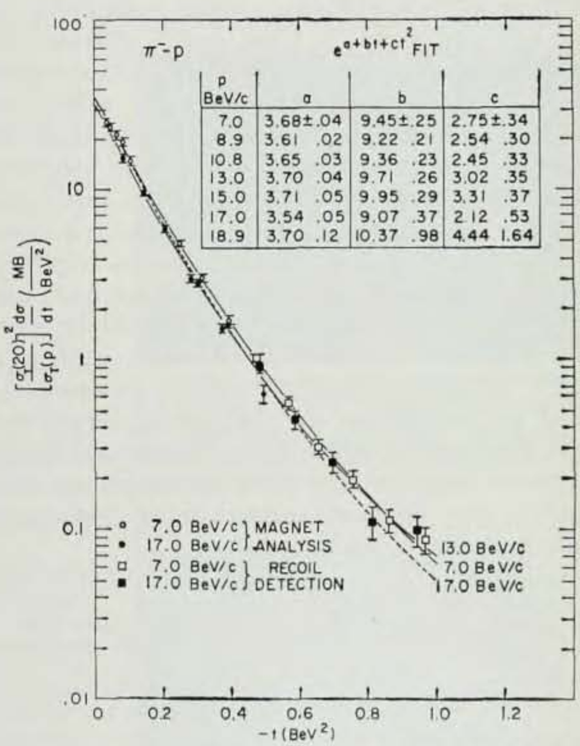


Fig. 4a. Typical p+p elastic-scattering data (arrangement II, Fig. 1b). The ordinate is approximately proportional to $d\sigma/dt$.



p BeV/c	a	b	c
7.0	3.68±.04	9.45±.25	2.75±.34
8.9	3.61 .02	9.22 .21	2.54 .30
10.8	3.65 .03	9.36 .23	2.45 .33
13.0	3.70 .04	9.71 .26	3.02 .35
15.0	3.71 .05	9.95 .29	3.31 .37
17.0	3.54 .05	9.07 .37	2.12 .53
18.9	3.70 .12	10.37 .98	4.44 1.64

Fig. 4b. Typical π^-+p elastic-scattering data combined from both arrangements, Figs. 1a and 1b. The ordinate is approximately proportional to $d\sigma/dt$.

The digitized detectors

The three most important digitized detectors are the scintillation-counter hodoscopes, the digitized spark-chamber hodoscopes (or wire chambers), and the digitized sonic spark chambers. Each of these will be discussed.

The first digitized detectors employed were the scintillation-counter hodoscopes described previously. These units had been made up of slab counter elements placed side by side so that they are bounded by parallel planes of large dimensions compared to the thickness. Typically, one hundred elements of 1/4″ width by 1/4″ thickness by 6″ length have been used in a plane to determine one Cartesian coordinate (x or y). Two planes can be crossed (rotated 90°) for single-particle location in a small rectangle specified by the intersection of vertical and horizontal hodoscope elements. If two particles simultaneously strike a plane, a third diagonally crossed element is necessary for unique particle identification. In fact, it is a general theorem that $n+1$ crossed planes are necessary for n particle tracks. However, with three crossed planes, unresolved ambiguities are rare up to several tracks.

Large areas have been covered by scintillation-counter hodoscopes. In the elastic-scattering experiments described previously, the hodoscope III in Fig. 1a contained four groups of 12×12 crossed-counter hodoscopes, each element of which was 30″ long × 2½″ wide × ½″ thick, to cover an area 10′ wide by 2½′ high (25 sq ft of scintillation-counter hodoscope) such that a particle crossing it would be uniquely located in one of the 576 squares (each measuring $2\frac{1}{2}'' \times 2\frac{1}{2}''$). The major advantage of these scintillation-counter hodoscopes is that they have much greater time resolution than the digitized spark-chamber detectors (a few nanoseconds is attainable), faster recovery time (tens of nanoseconds), the known and well-understood uniformity of scintillators, and the minimization of cross-talk between counter slab elements. The major disadvantages, compared to the digitized spark-chamber hodoscopes that have recently been developed,[5,6] are the greater absorption and multiple scattering in the scintillators and the difficulties involved in obtaining the ½-millimeter spatial resolution of the spark-chamber hodoscopes. So far, we have obtained ± 3 millimeters in scintillation-counter hodoscopes, although this is not a limit but is dictated by practical considerations in these particular experiments. However, since the response across the counter is uniform and known, the effects of the resolution can to a great extent be corrected and the effective resolution thus is better in most cases. Also, in most applications, it is angular resolution which is most critical, and this can be improved by separating elements further. The cost and complexity of the scintillation-counter hodoscope make it a generally reasonable system where perhaps as many as several hundred counter elements are used per hodoscope; but, in general, where several thousand or several tens of thousands of elements are required and lower data rates are satisfactory, the digitized spark-chamber hodoscopes will probably be more useful.

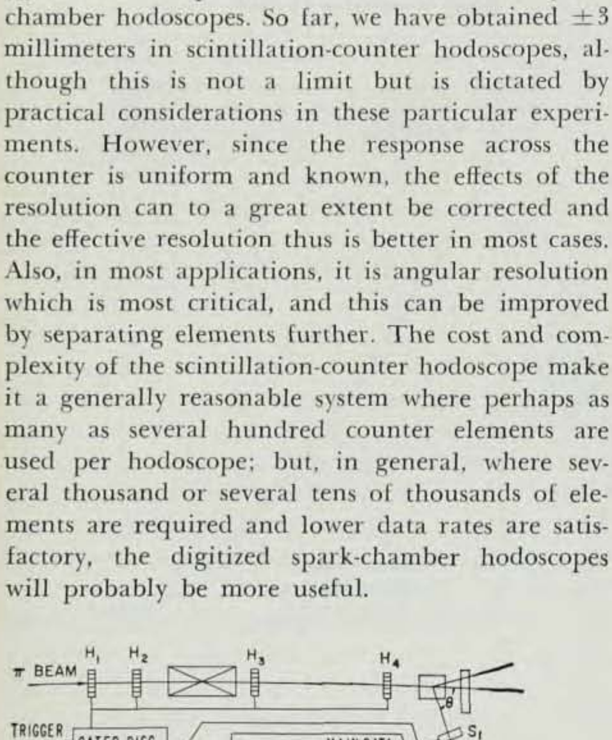


Fig. 5. Simplified schematic of Maglic et al.,[6] sonic spark-chamber setup for studying missing mass inelastic reaction $\pi^- + p \rightarrow p + X^-$ by measuring the direction and velocity of the recoil protons. Then, by applying the conservation of energy and momentum, the mass of the missing particle X^- is deduced.

Even before the first on-line counter experiments, it was clear to us[1] that any electronic pulse detector, in which the position of a particle was presented in digitized form, could be substituted for the scintillation-counter hodoscope elements in a digital data-handling and on-line computer system of this type. Although the first reports on developments of prototypes of digitized sonic spark chambers and proposals of digitized wire chambers were made in the CERN international instrumentation conference of 1962,[4] it has been only recently that working systems have been successfully developed.[5,6] In the sonic spark chambers, the time of flight and the velocity produced by a spark are measured by several microphones at different space locations, and the position of a single track is thereby deduced in a gap. Although multiple track location is possible with enough microphones, it has so far proved cumbersome and impractical to accomplish. The sonic chambers have recently been successfully employed in both on-line and off-line computer systems[4,5] at CERN, Harwell, etc., for single tracks (see Fig. 5). They give good space resolution (about half a millimeter for single tracks) and low nuclear absorption and multiple scattering. However, their recovery time is long, especially for large chambers where it is a few milliseconds, and there are variations in resolution over the chamber. At best they appear to have limited application for multiple tracks and they are sensitive to sound-velocity changes and quite often require built-in calibrations.

The "wire chamber" is really a spark-chamber hodoscope, and I prefer that term. One plane of a conventional spark chamber is replaced by a series of parallel wires about a millimeter apart, each threaded through an individual magnetic core. When an ionizing particle passes through the chamber, if the voltage is applied, the spark generated is confined to one or to a few wires in its vicinity, and the current pulse flips the magnetic core. Therefore, the location of the sparks can be read out later by reading or interrogating the cores. This generally locates the incident particle to within one-half to one millimeter. Printed and etched circuit techniques and computer type core memory planes, instead of individual cores, have been used recently. Two spark-chamber hodoscopes can be crossed to locate single particles, and triple-crossed hodoscopes are useful for location of several particles. Many other varieties of spark-chamber hodoscopes, including magnetostrictive wires, have been proposed and

CHARGED PARTICLES

Extending the capabilities of research equipment

Results from Tandem Research Program

The Tandem Research Group has made notable progress in the past year. Significant experimental results from the program are:

1. 250 mA high-brightness positive ion beam from an expanded-plasma source operating at 38 kv.

2. 270 μA analyzed beam of H_1^+ ions out of the Research Tandem with 320 μA H^- injection and water-vapor stripping.

3. 2.0 μA analyzed dc beam of He^- ions. The previous maximum current routinely available has been 0.1 μA with the EN source.

Doubly Charged Helium Ions

Components are now available for converting 3, 4 and 5 MeV machines to produce He^{++} ions at higher energies. Specifications: 30 μA at 5.0 MeV; 10 μA at 7.0 MeV; 5 μA at 10.3 MeV. More than double this current performance has been demonstrated but with some loss in stability and reliability. Multiple-charge states (2, 3 and 4) of neon, oxygen and nitrogen have also been produced with the new kit installed in a 3 MeV Van de Graaff. Beam energies from 50.4 MeV to 9.8 MeV and beam currents from 0.1 to 10 μA were observed. For details on the new HE^{++} kit and experimental results, write for Technical Note #13.

Optical Spectroscopy of Excited Atomic States

When an energetic beam of ions is passed through a thin foil, the charge state of the ion may change, either up or down. The emitted particles may be left in states of electronic excitation from which visible light is subsequently emitted during de-excitation. The emitted light spectrum is characteristic of the excited ion. When particle beams of approximately 0.4 μA or more are used, the light is sufficiently intense for spectroscopic analysis.

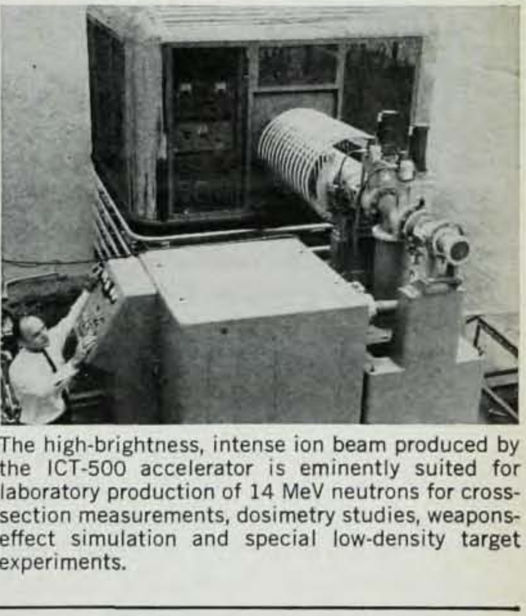
The refinement and application of this technique promises to be of major importance in the theory of atomic structure, in measuring hot plasma temperatures, and in acting for the means of energy loss in fast fission fragments in an absorber. Perhaps most importantly, it will help determine the relative abundance of the elements in the sun and other stars, which is the basis for theory of stellar evolution, the origin of the chemical elements, the age of astronomical objects and the nature of the stellar energy. For further details, ask for Technical Note #10.

A nitrogen beam, 0.8 μA at 2 MeV, passes from right to left through a carbon foil approximately 9 $\mu g/cm^2$ thick.

Intense Ion Beams at 500 kv

The ICT-500 keV positive ion accelerator now being built by High Voltage Engineering operates at energies from 100 to 500 keV dc and pulsed. In performance tests, the machine has produced analyzed ion beam currents from 4 mA at 100 keV to 10 mA from 300 to 500 keV. 10 mA dc positive ion beam currents of H^1, H^2, and D^1 have been produced at a target located 6 feet from the end of the acceleration tube. Beam diameter is 15 millimeters maximum for all particles over the entire energy range. Performance tests are now underway to achieve similar results at a target located 40 feet from the tube-end. Previous experience with a similar machine of *300 keV maximum energy showed 15 mA of* d_2^+ *and* a 3 centimeter beam diameter. The ICT-500 positive ion accelerator is designed for dc and pulsed operation in the nanosecond and microsecond range with a minimum pulse length of 2 nsec. at a repetition rate of 2.5 Mc/s. Pulse content is 1 mA protons and 0.7 mA deutrons.

The particle source utilized with the ICT-500 positive ion accelerator is an expanded plasma type which has produced 70 mA total beam at 500 kv.



The high-brightness, intense ion beam produced by the ICT-500 accelerator is eminently suited for laboratory production of 14 MeV neutrons for cross-section measurements, dosimetry studies, weapons-effect simulation and special low-density target experiments.

For detailed information, write to Technical Sales, High Voltage Engineering Corp., Burlington, Mass. or HVE (Europa) N.V. Amersfoort, The Netherlands. Subsidiaries: Electronized Chemicals Corporation, Ion Physics Corporation.

HIGH VOLTAGE ENGINEERING

recently investigated.[5] The latter type allows one coordinate to be located by using the time of flight and the known velocity of the pulse on a wire; the other coordinate is located by the fact that the wire recorded a spark.

Compared to the scintillation-counter hodoscopes, the major advantages of the spark-chamber hodoscope are the low mass and consequent low nuclear absorption and multiple scattering per plane, and the easier attainment of thousands to tens of thousands of digitized elements per chamber with the order of one millimeter spacing of elements. They appear particularly promising in triple-crossed-wire plane arrays (and perhaps, in the future, the magnetostrictive types) for application to typical photographic bubble- and spark-chamber multiparticle-event experiments, such as the search for new elementary particles (see Fig. 7, page 28). They have faster recovery times ($\frac{1}{2}$ millisecond) than sonic chambers, because of the smaller stored energy per wire which participates in the spark. However, their recovery time is very slow compared to scintillators, and the above figure is only expected to be usable for pulsed accelerators like the AGS. For steady-state conditions, heating and gas-poisoning effects of chambers trouble them. Their practical resolution time is about 300 nanoseconds, compared to a few nanoseconds in scintillation-counter hodoscopes.

Even before the first experiments, it was clear to us that our original digital data-handling system was not adequate to deal with the many classes of complex high-rate events generated at the Brookhaven AGS, and we immediately set out, after the first experiments, to develop a general digital data-handling system useful for all digitizable detectors, including spark-chamber hodoscopes as well as scintillation-counter hodoscopes.[4,5,6]

One might ask the question: Why have a digital data-handling system at all? Why not go directly on line to the computer? This is certainly desirable in some instances. However, the digital data-handling system acts as an immediate fast trigger logic and as a storage for selected events; it makes a permanent tape record of the data on the spot, and simultaneously, by an on-line connection, feeds the computer. If the computer should temporarily fail or be occupied for some other run, the experiment continues with tape records. In fact, using digital data handlers, several experiments with different experimental arrangements can be handled in combinations of on-line and off-line computer support as necessary. For example, our group* has recently performed two experiments simultaneously in the same beam at the AGS with two data-handling systems using the Merlin computer for on-line sampling of the data alternately from both. Off-line processing was done on Merlin for the lower-rate experiment, and on an IBM 7094 for the higher data-rate experiment. Figure 6 shows the second-generation digital data-handling system with an on-line computer used in the series of small-angle $\pi^{\pm} + p$ and $p + p$ elastic-scattering experiments performed at the Brookhaven AGS last spring and summer. The purpose of these experiments was to go down to such small scattering angles (approximately 2-3 milliradians) that at these energies the Coulomb scattering (amplitude), which is inversely proportional to the square of the scattering angle $(1/\theta^2)$, would become larger than the nuclear scattering (amplitude), which is proportional to exp $(-\text{const } \theta^2)$. We would then probe the angular region where the two amplitudes become comparable and also where the nuclear amplitude dominates. This would allow the observance of the direct interference between the Coulomb amplitude (which is real) and any possible real nuclear amplitudes. Until recent experiments started to indicate that there may be real amplitudes at high energy (greater than the order of 10 BeV) most theorists assumed they would be small compared to the imaginary amplitude.

This new data handler accepts 4096 words (events) of 48 bits each per pulse, and, by selector switch, a single trigger event can be arranged to contain up to fifteen 48-bit words of digital information which are then automatically stacked successively in memory. This data-handling system can be used with wire spark-chamber hodoscopes (see Collins in reference 5). We have developed a complete set of interfaces for data inputs from scintillation-counter hodoscopes, wire spark-chamber hodoscopes, and digitized sonic chambers, and thereby have made it a general-purpose digital data-handling system.

In these small-angle scattering experiments at the Brookhaven AGS we found sizeable[6] ($\sim 25\%$ of the imaginary) negative real amplitudes in the 8–12 BeV/c $\pi^{\pm} + p$ interactions and strong evidence for sizeable negative real amplitudes in $p + p$. Similar evidence for $p + p$ at high energies was reported at last year's high-energy physics

* K. J. Foley, R. S. Gilmore, R. S. Jones, S. J. Lindenbaum, W. A. Love, S. Ozaki, E. H. Willen, R. Yamada, and L. C. L. Yuan.

	NUMBER OF COUNTER ELEMENTS	WIDTH (INCHES)	HEIGHT (INCHES)	THICKNESS (INCHES)
HOI	6	.250±.002	1.125	.30
	4	1.125	.250±.002	.30
HO2	4	.250±.002	1.125	.30
	4	1.125	.250±.002	.30
HO3	4	.250±.002	1.125	.125
	4	1.125	.250±.002	.125
H2	80	.250±.005	6.0	.30
H4	120	.486±.005	13.0	.50
	24	61.0	.486±.005	.50

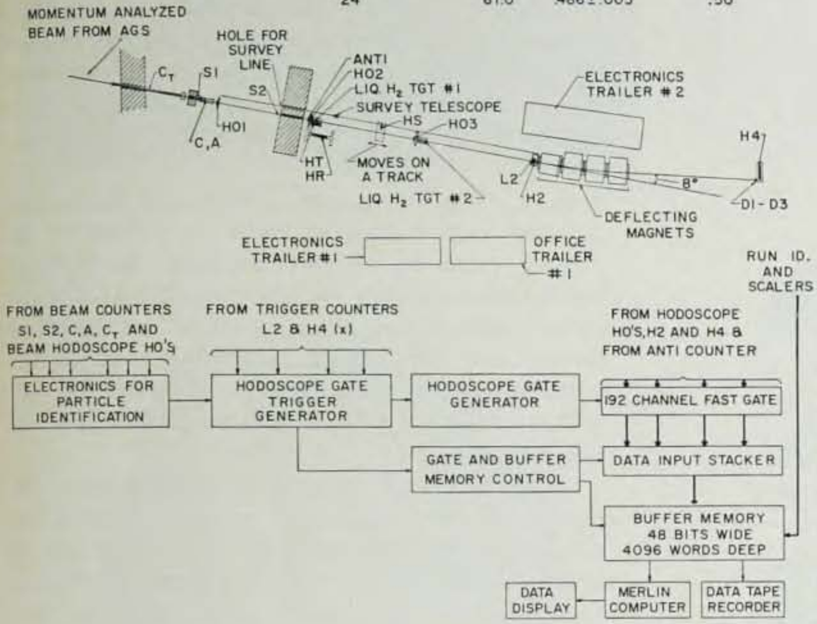


Fig. 6. High-energy small angle $\pi^{\pm}+p$ and $p+p$ scattering using the new high-scattering digital data-handling system and on-line computer. Hodoscopes H_{02}, H_{03}, H_2, and H_4 form a small-angle-scattering magnetic spectrometer. In addition, H_{01}, H_{02}, H_T, and H_R, and their data-handling system (not shown), are similar to Fig. 1b, and we could study the larger angle scattering simultaneously.

conference at Dubna by CERN and Harwell groups using sonic-chamber systems, and by a Dubna group (emulsion).[6] An interesting summary of the Dubna conference by N. Samios appeared in the December 1964 *Physics Today*.

In our AGS experiments with scintillation-counter hodoscopes, we actually handled and recorded on tape 1.5 million triggered events per hour, which is a thirty-fold increase in data rate since the time of the original on-line counter experiments. We had to use two highest performance (112.5 inches per second) magnetic-tape transports alternately in a semiautomatic changer arrangement and, at these high rates, completely covered a 2500-foot reel of tape every ten minutes. The Merlin computer, which computes with about one-seventh the speed of the IBM 7094, could only handle about one-fourth of the data on-line; the remainder had to be processed off-line on the IBM 7094. Even here we found that we needed about two-thirds of the computing capacity to keep up with our data rates. Since there are many other users of this computer, we were computer-bound*.

This will be one of the problems of the future with this technique. The combinations of high data rates and the natural evolution of experiments from the simple two- to three-body detectors used so far, to the multibody bubble-chamber or spark-chamber-type events (primarily studied so far only on film), and the simultaneous rapid spread of the technique, will lead to stringent requirements on the computer systems and capacities. It is our opinion that in order to take full advantage of this technique, one needs a powerful general-purpose computer with a sophisticated order structure and with software offering multiuser real-time-sharing capabilities, which is completely committed to this type of research. Among other things, this avoids dual machine programming and minimizes programming effort, which is a tremendous bottleneck.*

At the Brookhaven Physics Department, we have recently set up an On-Line Data Facility for counter and spark-chamber experiments to meet the anticipated future needs of high-energy physics groups, including university users. We have purchased a Digital Equipment Corporation PDP-6 computer system for these purposes, mounted in a trailer which will be located at the accelerators for this type of research.

* Of course, the sonic-chamber experiments could only handle rates which were lower by more than two orders of magnitude and hence did not have this heavy computing load.

* It is true that in the previous on-line experiments only a few man-months of programming were required after the logic was decided in detail. In the future, more complicated experiments will considerably increase the programming time.

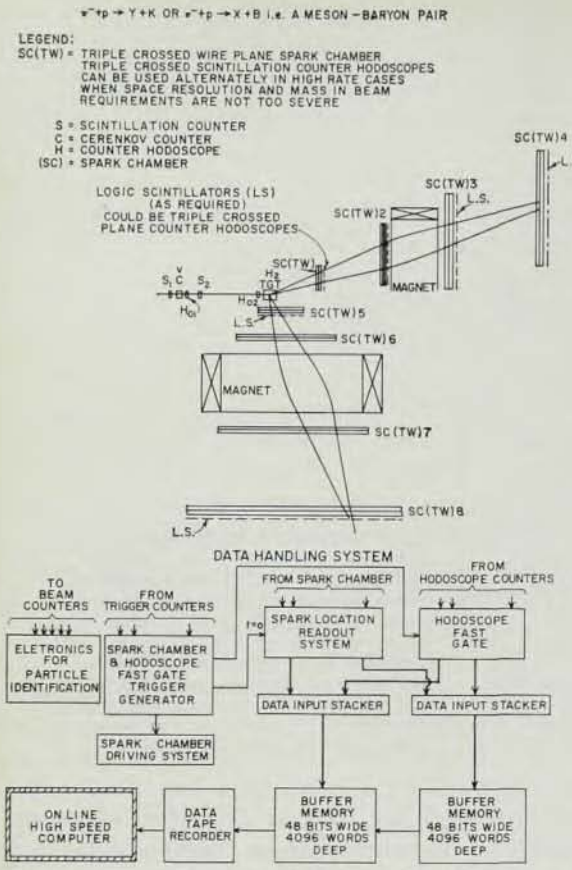


Fig. 7. A double V-particle magnetic spectrometer using counter hodoscopes, digitized spark-chamber hodoscopes, and on-line computer system[6], shown detecting an associated production event.

We believe that the technique will very rapidly enter the era of studying multiparticle final-state interactions. Figure 7 illustrates our conception of the simplest setup for detection, for example, of the event $\pi^- + p \rightarrow \gamma + \theta$ (associated production) or of $\pi^- + p \rightarrow X + B$ (production of a meson-baryon pair). A search for new elementary particles could be made in this way.

Note that we have used combinations of counter hodoscopes and digitized spark-chamber hodoscopes to make a double V-particle magnetic spectrometer. Of course, several additional final-state particles can also be detected. In those cases where the rates are high and the maximum resolution and lowest mass are not required, the counter hodoscopes will be most useful. In those cases where the rate is low, the digitized spark chamber will probably be most useful and the counter hodoscopes can be used as trigger logic.

Perhaps yet undiscovered detector elements or even a complete specific system for identifying particle position in space from interactions in hydrogen (with or without magnets), in digitized form, will eventually become prominent. The detector concepts may change but the data-handling system and the proper combination of on-line (sampling at least) and off-line computer support will undoubtedly be a necessary integral part of the system.

After the original success of the Brookhaven on-line computer-counter experiments of 1962, it became clear that this technique was applicable to broad classes of physics experiments, including those of low-energy nuclear research. The low-energy physicists had at that time been using pulse-height and other very simple multiparameter analyzers. They have recently been making limited use of on-line computer-counter techniques and have been rapidly moving more and more in this direction for their future counter experiments. This is a good example of how a high-energy physics development can stimulate other research of more immediate general practical interest.

It is the author's opinion that this on-line computer method of doing physics research with electronic pulse detectors will become increasingly universal as time goes on. Even now, the impact of being able to do a complete investigation of a broad field of physics research in days or weeks and of doing it better than could previously be done in years, if at all, by older techniques, has already revolutionized research.

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