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MASTER

DATA PROCESSING FOR ELECTRONIC TECHNIQUES
IN HIGH ENERGY EXPERIMENTS *

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I would like to say that I think the title of the Seminar Course, "Computing as a Language of Physics," is both an appropriate and interesting one. Of course, what constitutes a language and how it is employed are subject to wide variations.

Language can be a varied subject ranging from primitive man's sign signals to a powerful modern language with rich vocabulary, written as well as vocal.

Furthermore, language communications can range from exchange of letters to a rapidly changing dialogue between individuals or public meeting type of interactive debate. Thus, although there is no doubt that computing is by now a language of physics for all disciplines, I believe that in the field of Data Processing for Electronic Techniques in High Energy Physics, computing has reached its most advanced and prolific level as "a language of physics." In particular, in the use of the ON-LINE COMPUTER TECHNIQUE, coupled with a massive array of directly digitizable detectors, computing can be characterized as an interactive language of enormous information exchange capability between the physicist and his rather sophisticated detector devices. In fact, as a result of this intensive dialogue capability, the physicists are now able to make enormous escalations in the complexity of their apparatus and the scope and accuracy of their measurements. Thus the resultant intensification of the investigation of nature by the electronic detector and computer techniques has been truly impressive and fruitful for the research physicist.

The simplest type of modern (high energy) detector is the scintillation counter telescope. These devices tell the physicist each

time a particle (which he generally would have selected by beam transport to have near monochromatic momentum and would have identified by using velocity measuring Cerenkov counters) passed through each counter in time coincidence (after allowing for travel time). Those numbers were displayed on scalers, which one must remember were originally developed in what was then, high energy physics (i.e. nuclear physics). These basic scale of two elements made possible the development of the modern digital computer. In the late forties and through the next decade of the fifties, many important experiments were done this way. (See figures 1 a-c for explanations of these techniques.)

In addition to H_2 physicists used other absorber material targets including a technique called range curve analysis to determine the nature of the incident beam. Their dedicated off-line computer was usually a slide rule or a mechanical desk calculator. Sometimes an off-line digital computer was used in Monte Carlo type simulations or other calculations of corrections. In particular, detailed phase shift analyses of differential elastic scattering required the use of an off-line digital computer.

In 1962, after several years of development a new approach was taken⁽¹⁾ which completely changed the style of doing digitizable electronic detector physics. The motivation for this was simply how does one obtain a large fraction of the solid angle in elastic scattering combined with high resolution in angle and momentum and the high counting rates typical for electronic detectors.

In principle, one could replace each counter in the downstream part of the telescope by a large area of more counters. However, due to

technical difficulties and the absolutely impossible task of employing a sufficient quantity of conventional electronic logic and scalars; and the impossibility of using the usual techniques of analysis in such a complex system, a new approach was needed, and the next few slides (figs. 2 a-d) will show the method developed. The counters in fig. 1b and 1c were replaced by a set of counter hodoscopes. 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 a single particle in space is determined by the intersection of perpendicular elements of two crossed hodoscopes (i.e. x and y hodoscope planes). If there is more than one particle incident on a hodoscope array, a third crossed plane of elements parallel to some intermediate angle (i.e. 45° to the x and y directions) is added to uniquely identify the coordinates of each particle.

Figures 2a and 2b show the two counter-hodoscope arrangements used and Figure 2c shows a typical hodoscope.

The only practical way of handling the debugging and data from such a complex array of elements was to use digital computer data handling and analysis techniques. For this system, the on-line computer technique⁽²⁾ was first developed. This was 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, and entering of summaries of monitors,

parameters of location of the counters, the beam momentum, etc. The program flow chart is shown in Figure 2c. Figure 2d shows a typical on-line scope display feedback to the experimentalists a mile away.

As a result of these on-line computer experiments, it was shown that the high energy diffraction type elastic scattering did not shrink universally as predicted by the then popular dominance of the vacuum pole Regge theory. Rather, as shown in Figures 3a and 3b, $p + p$ did shrink, while $\pi^{\pm} + p$ did not.

The experiments just described used the Merlin computer, a general purpose computer which was patterned after the Maniac II and built at Brookhaven with 8,192 words of 48 bit core and with an average computing speed about 1/7th of an IBM 7094. It was located about a mile from the experiment. A local digital data handler accepted and separately stored the digital data from the experimental detectors each beam burst from the 33 Bev Alternating Gradient Synchrotron (AGS) and then between pulses placed the data on tape and simultaneously transmitted it to the Merlin computer via a two-way telephone line in a link which fed back desired scope display data.

Later applications of the on-line computer technique involved a CERN missing mass spectrometer⁽³⁾ (figure 4) which employed, in addition to counter hodoscopes, sonic chambers as part of the digitizable detectors.

As a result of the rapidly increasing interest from the Brookhaven user community in these new on-line computer techniques, the author and some of his colleagues and the Brookhaven Physics Department organized

in 1964, a general user facility called the On-Line Data Facility which contained a PDP-6 interactive time sharing computer which was put into service early in 1965.⁽²⁾ The computer was located in one, and then eventually two, 40' long by 10' wide road type truck trailers at the AGS.

Fig. 4 shows a typical arrangement of this facility several years later when the bulk of the electronic detector experiments at Brookhaven were utilizing it. The time sharing of two real experiments first occurred in 1965-66 and the proliferation of multi-user use by 1969 is indicated in Fig. 4. Two to three on-line users were accommodated simultaneously and the remainder of users who were debugging and preparing for the next phase went in rotation in an off-line queue via the disc.

The experiments included a study of small angle scattering⁽⁵⁾ of $\pi^{\pm}+p$ and $p+p$ in the Coulomb interference region, to determine the real part of the scattering amplitude in order to test the pion-nucleon forward dispersion relations. A typical result is shown in Figure 5.

Other experiments included: a check of CP invariance in the $K^{\pm}$ decay via the μ mode which was consistent with no violation,⁽⁶⁾ a study of the effective mass of charged muon pairs which appear to support electronic scaling, a study of nucleon isobars produced in $p-p$ collisions,⁽⁷⁾ a precision study of $\pi^{\pm}-p, p-p$, and $\bar{p}-p$ cross-sections which, together with the small angle scattering experiments, demonstrated that the Pomanchuk theorem would not come true to somewhere in the range beyond 25,000 GeV to perhaps 5,8 9 one million GeV, and a study of polarization in $K^{\pm}+p$ by a Yale group.

Any one of the typical experiments shown in Fig. 4 was supported by the following equipment: a local digital data handler or small satellite computer (often supplied by the experimental group), an on-line

link to the PDP-6 complex when the experiment is running with local teletypes for communication with the PDP-6. Generally, only a sample (typically at least 10%) of the data is processed on-line and individual scope displays are provided each user. Printers and high performance tapes are located in the computer trailers and in some instances remote I/O stations near users. A typical user on-line program varies from 20K - 45K of 36 bit words and requires from approximately 25% to 50% of the processor time available.

The ever increasing demand for on-line computer services at Brookhaven National Laboratory led to the addition of a PDP-10 computer in the summer of 1969 and Fig. 4b shows the total PDP-6/10 complex available since the latter part of 1969.

We now have the capability of serving 4-6 on-line users simultaneously, with many off-line users also making use of the disk rotation system to debug their programs and process necessary data before their scheduled experimental runs. The time sharing (or multi-programming) capability is a very valuable technique for a scientific user facility.

At CERN, the application of the on-line computer technique has been primarily via smaller local computers at each experiment. Earlier attempts to hook on-line to the CDC6600 (6500 complex) led to excessive demands on the central facility and "bycycle on-line", i.e. shorter turn around off-line for tapes delivered to the central facility has been utilized. Recently, more direct on-line use of the CDC6600 has been developed via the focus remote access system shown in Fig. 7, in which a CDC 3100 computer with 32K of 24 bit words serve as an interface between the on-line user and the CDC6600/6500 complex.

For a number of years attempts to use the Brookhaven CDC6600 complex directly from a local satellite computer have been in progress. It is the author's opinion that both better and more economical service can be obtained if the CDC6600 complex is reserved for off-line batch with as rapid turn around time as possible. To this end a low price link is being provided from the PDP6/10 complex to the CDC6600 complex. The direct almost instant turn-around, on-line support in this system would still be provided by the PDP6/10 complex, but batch processing would be entered routinely and automatically to the CDC6600 complex and returned automatically. This system economizes enormously on the memory and I/O required by the on-line satellites and is far more satisfactory in turn around time and general flexibility and scope of service provided.

Figure 8 shows a block diagram of the USSR computing facility⁽¹⁰⁾ for track (bubble and spark chambers) picture processing at the JINR and the Serpukhov accelerator, and probably can be taken as representative of the computer facilities available for supporting electronic detector experiments at the various laboratories.

The BESM-4 is a 3-address computer with 8K memory of 45 bit words and a 600K word drum. It operates at about 20,000 instructions per second. The Minsk 22 is a 2-address machine with a core memory of 8K of 37 bit words and a memory cycle time of 24 μ sec.

The BESM-6 computer works at a speed of one million one-address instructions per second, has 32K core memory of 48 bit words and a 512K word drum.

The TPA is a Hungarian computer with 4K basic memory of 12 bit word length and 1.0 μ sec cycle time. It can be compared to a PDP 8.

In the on-line computer systems the counter hodoscopes were soon supplemented with the (wire) spark chamber hodoscopes which are more economical and better suited for large solid angle multiparticle detectors with minimal multiple scattering. However, the time resolution of a spark chamber hodoscope is two orders of magnitude worse and it must be supplemented with a triggering system (to pulse the spark chambers), which is usually composed of scintillation counter hodoscopes or the newly developed continuously sensitive proportional chamber hodoscopes.

As an example of construction and operation of a very large digitized spark chamber hodoscope system with the on-line computer technique, we can use the BNL Double Vee Magnetic Spectrometer developed by the author and his co-workers. ⁽¹¹⁾

Figure 9(a) shows how large fiberglass frames are spun on an axis and about twenty 5 mil Al wires are wound per inch horizontally upon it. The wire is fastened to one side and cut from the other side. Two such planar frames with the parallel wires facing each other and separated by a spacer (with 2 vacuum seals and a partial vacuum between them) make an x, y or w (45°) spark chamber hodoscope. A magnetic wire runs across (but insulated from) the conducting wire. When a suitable trigger logic pulse occurs, a voltage pulse of about 7 k.v. is applied between the wire planes of each hodoscope and a spark appears wherever a charged particle has traversed the plane. The appearance of a time exposed picture of the sparks in a spark chamber module composed of 2x, 2y and one w chamber is shown in Fig. 9(b).

Each spark causes a magnetostrictive pulse to occur on the magnetostatic readout line and the time of transit of each pulse when detected by a transducer at the end allows one to determine where the

spark was. This operation is done automatically by electronic devices and the spark readout is done in both directions by the independent readout wires and the results averaged. Standard neon-helium gas is used at approximately atmospheric pressure with quenching by alcohol vapor.

A schematic illustrating how the Double Vee Spectrometer could be used to detect an event of the type

is shown in Fig. 9(c).

Figure 9(d) illustrates the arrangement used in the A_2 experiment to be described later.

Figure 10(a) shows how the on-line computer automatically reconstructs two views of a K^0 going forward before and after the forward magnet, thus allowing complete reconstruction in space (using the w-chambers to uniquely match the tracks in the two views) and hence measuring everything including the momenta.

Downstream Cerenkov Counter hodoscopes will be available soon and can be used to directly identify the π^+ and π^- .

Fig. 10(b) shows a typical missing mass spectrum accompanying the K^0 exhibiting the Λ , Σ and various γ^* peaks.

The handling of data, the reconstruction of the event, and even the complete analysis are all done automatically by the computer. Typically, $\approx 10\%$ of the data is analyzed on line by the PDP10 which takes about one second CPU time to completely process one event. The bulk of the data is reduced off line by the CDC6600 which takes about 1/4 second

of CPU time per event.

The wire spark chamber apparatus used for looking for asymmetries in the odd charge pion in $K^{\pm}$ decay via the τ mode (i.e., $\pi^{\pm} + \pi^{+} + \pi^{-}$) is shown in Figure 11. In this case a PDP-9, a local satellite, was used for diagnostic and monitoring purposes, but the raw data was still sent to the PDP-6/10 for the critical on-line and also some off-line analysis. A study of the invariant μ -pair mass produced in proton-uranium collisions was also performed by a Columbia group (Christenson et. al.) with a data handler on line to the PDP-6/10. The result was consistent with the scaling hypothesis first proposed at SLAC.

An experimental result which caused a great deal of concern was the apparent split in the A_2 meson discovered by a CERN group using the missing mass technique.³ (See Figure 12(a)). This led to many speculations including the exotic double-pole hypothesis.

Figure 12(b) shows the results obtained. A Berkeley Bubble Chamber group then found that the A_2^{+} was not split.^{12a} The forward leg of the BNL Double Vee Spectrometer was used to detect the decay products of the A_2^{-} produced in the reaction: $(20 \text{ GeV/c}) \pi^{-} + p \rightarrow A_2^{-} + p$, and demonstrated^{12b} that the A_2 was not split.

A generally similar and simultaneous experiment at CERN, which had 25% worse resolution and a 25% better statistical error, also concluded^{12c} that the A_2^{-} was not split.

A more direct repeat of the CERN missing mass experiment by a¹² Northeastern-SUNY group, using the BNL OLDF, also came to the conclusion^{12d} that the A_2 meson was not split.

Thus it is clear that these techniques have had a sizable impact on modern high energy physics research.

The SLAC 20 GeV electron accelerator has used a number of magnetic spectrometers with counters to measure the angle and momentum of particles scattered or produced from a target which is bombarded by high energy electrons or photons.

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The on-line computer system consists of an SDS 9300 with 32K of core, an extensive set of peripherals, a disc monitor, and a multiplexed interface system able to communicate with over 300 devices each having up to 24 bits of information. The computer, however, is dedicated to one experiment at a time. Figure 13 shows a photograph of the spectrometer. Figure 14 shows the interface to the SDS 9300.

The next planned important step found in these techniques can be characterized as multiparticle magnetic spectrometers with near 4π solid angle coverage. Figure 15 shows such a system being developed at BNL. It is expected to become operational in two to three years. The same automatic computer data analysis will be employed and the BNL OLDF will be utilized. Figure 16 shows the CERN OMEGA project which is a generally similar device, but in its first stage will employ optical spark chambers. A plumbicon video system is being developed to automate the data analysis. Figure 17 shows the on-line computer system. Figure 18 shows one typical module of a modular multiparticle spectrometer system proposed by the author for use at NAL.

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It is clear that these new techniques already have had an enormous impact on the progress of physics since they allow for more than four or five orders of magnitude increase in data rates accompanied by much greater systematic precision than heretofore attainable and also allow automatic data processing and analysis.

With the advent of the Multi Particle Spectrometer, another dramatic step forward will be taken. It is clear that only with a powerful enough and versatile enough on-line computer complex can one possibly undertake the debugging and successful use of these complex devices. Thus the on-line computer technique has come a long way since its inception.

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FIGURE CAPTIONS

- Figure 1(a):** A total cross section measurement (conceptual schematic only). The incident beam and the transmitted percentage of incident beam are determined (as a function of solid angle subtended by the final counter) when a known amount of liquid hydrogen absorber is placed (target full) or removed (target empty) from the beam. Thus the total nuclear interaction cross section of a proton for the incident particle can be obtained via extrapolation to zero solid angle.
- Figure 1(b):** The differential elastic scattering cross section $\frac{d\sigma}{d\Omega}$ can be determined at a particular (mean) scattering angle, by choosing an appropriate combination of magnetic field and positioning of the last two counters so that only elastically scattered particles can pass through all counters. An inelastic momentum spectrum of particles produced at a particular polar angle can also be obtained by varying the magnet currents. By repositioning the counters downstream of the hydrogen target, different polar angles can be measured.
- Figure 1(c):** The magnetic analysis method for elastic scattering shown in Figure 1(b) can, in principle, be used at all

angles or momentum transfer squared. An alternate method which depends on selecting the required kinematics between the two particles after the scattering is shown in this figure. It can fruitfully be used when enough momentum transfer has taken place so that the target proton can escape the hydrogen target without excessive multiple scattering. The combination of magnetic analysis on one or both particles as well as kinematic requirements are also used when rates are low and one wishes to discriminate against the background.

Figure 2(a): The magnetic spectrometer, counter hodoscope on-line computer system for detection of (7-20) BeV/c small angle elastic scattering (arrangement I) at the Brookhaven 33 BeV alternating gradient synchrotron. Hodoscopes H1 and H11 determine the horizontal projection of the scattered direction of an incident particle after scattering in the hydrogen target. The vertical elements of hodoscope H11 determine its reflection in the magnet and hence momentum, while the horizontal elements determine the vertical projection of the direction of the scattered particle.

Figure 2(b): The counter-hodoscope on-line computer system for selecting larger angle elastic scattering by determining

the space locations of the incident particle (telescope plus hodoscope HO), the forward scattered particle (hodoscope HS), and the recoil particle (hodoscopes HT and HR). Then coplanarity and proper kinematic angles were required to select elastic scattering.

- Figure 2(c):** A photograph of a counter hodoscope of the type labelled Hodoscope 3 in Figure 2(a).
- Figure 2(d):** The program flow chart of the first on-line computer counter experiments described in Figure 2(a) and Figure 2(b).
- Figure 2(e):** Typical on-line scope display of momentum spectra showing elastic scattering peak.
- Figure 3(a):** The quantity $(d\sigma/dt)/\{[\sigma_t(P)]/[\sigma_t(20 \text{ GeV/c})]\}^2$ in $\text{mb}/(\text{GeV/c})^2$ for 7-20 GeV/c p-p elastic scattering, which is proportional to $(d\sigma/dt)/(d\sigma/dt)_{\text{opt}}$ plotted versus t .
- Figure 3(b):** The quantity $\{[\sigma_t(20 \text{ GeV/c})/\sigma_t(P)]\}^2(d\sigma/dt)$ in $\text{mb}/(\text{GeV/c})^2$ for 7-17 GeV/c π^+ -p, which is proportional to $d\sigma/dt/(d\sigma/dt)_{\text{opt}}$ plotted versus t . The solid line is a least squares fit to all the π^+ -p data. The dotted line is a least squares fit to all the previously reported π^- -p data.
- Figure 4:** Simplified schematic of a sonic spark chamber setup for studying missing mass inelastic reaction $\pi^- + p \rightarrow p + x^-$. The direction and velocity of the recoil protons are

measured, and then the mass of the missing particle x^- is deduced by using energy and momentum conservation.

Figure 5(a): The configuration of the PDP-6 complex of the Brookhaven On-Line Data Facility.

Figure 5(b): The configuration of the combined PDP-6/10 complex of the Brookhaven On-Line Data Facility.

Figure 6: The elastic differential $\pi^- + p$ scattering cross section after subtraction of single Coulomb scattering. The dashed line represents the best fit with $\alpha = \text{Ratio } \frac{(F_N)_{\text{Re}}}{(F_N)_{\text{Im}}} = 0$.

Figure 7: Block diagram of hardware configuration of CERN focus system.

Figure 8: The system of data processing for track chambers at the J.I.N.R. and Serpukhov in the U.S.S.R.

Figure 9(a): This figure shows the wire spark chamber hodoscope winder built in the high bay area of the Physics building. It can wind up to 23 feet by 23 feet sensitive area with wire spacing adjusted to any desired distance from 0.020" and up. The wire chamber frame rotates about its vertical axis while it is positioned on ground steel beds. The wire feed point is driven by a lead screw along the vertical slide. The tension on the wire is controlled utilizing a long vacuum column to better than 5%.

- Figure 9(b): A photograph of the sparks in the chamber set, downstream of the magnet.
- Figure 9(c): $\pi^- + p \rightarrow K^0 + \Lambda \rightarrow (\pi^+ + \pi^-) + (p + \pi^-)$.
- Figure 9(d): Arrangement used in A_2 experiment.
- Figure 10(a): On-line display of four views of a K^0 decay detected in the forward spectrometer. To the left are the views before entering the magnet, plan view at the bottom, elevation at top. To the right are similar views after the magnet. The bright, short horizontal lines represent the spark positions in the chamber gaps; the dotted lines through them are the tracks fitted by the computer. On each track in the bottom righthand view, the short vertical line representing the size of the trigger counter in hodoscope H4 struck by the pion can be seen. The vertical lines at the left of each view are rulers for calibration, representing 10 inches (total length) in all views except the lower righthand view, where the ruler is 75 inches long.
- Figure 10(b): The missing mass square distribution for the process $\pi^- + p \rightarrow K^0 + MM$. Incident π^- momentum is 8.0 GeV/c. The masses and mass widths shown for the Y^* 's are from the Table of Particle Properties.

Figure 11: The setup of Piroue et. al. to measure the dependence of the decay of $K^{\pm} \rightarrow \pi^+ \pi^- \pi^{\pm}$ on the momentum of the "odd" pion.

Figure 12(a): A_2 splitting in the missing mass spectrum, MM spectrometer, and boson spectrometer, combined data.

Figure 12(b): The $K^- K_s^0$ effective (i.e., invariant) mass spectrum observed in the reaction

for 20.3 GeV/c incident π^- on hydrogen. The solid line is a Breit-Wigner type fit corresponding to $l=2$. The dashed line is a "dipole fit" which obviously is unacceptable.

Figure 12(c): The $K^- K_s^0$ invariant mass (GeV) observed in the reaction $\pi^- + p \rightarrow K^- + K^0 + p$

for 17.2 GeV/c π^- incident on hydrogen. The solid line is a Breit-Wigner type fit corresponding to $l=2$. The dashed line is a linear fit to the background.

Figure 13: Plan view of the experimental area at SLAC, showing the three magnetic spectrometers in end station A. The spectrometers pivot on rails about a common target point. A beam of electrons or photons strikes the

target, and the angle and momentum of scattered or produced particles ($e^{\pm}$, $\mu^{\pm}$, $\pi^{\pm}$, $K^{\pm}$, p , etc.) are detected by the spectrometers.

- Figure 14: Block diagram showing the interface to the SDS 9300.
- Figure 15(a): The proposed MK I(b) arrangement with x , w_1 , and w_2 wires being read out through the striated top.
- Figure 15(b): An end view of the MK I(b) readout arrangement. w_1 and w_2 (45° inclined) wire planes alternate in the arrangement. The BNL MPS is a variant of the above basoc design.
- Figure 16: Top view of target and spark chamber. CERN OMEGA project.
- Figure 17: System layout for computer system associated with the CERN OMEGA project. The main computer is a CII 10070 (French $\Sigma 7$). The smaller on-line computers are EBR 6130's.
- Figure 18(a): A proposed MK II arrangement.
- Figure 18(b): The MK II preceded by a cylindrical magnet (i.e., field along beam) for analyzing wide-angle particles.

FIGURE 1(a)

FIGURE 1(b)

FIGURE 1(c)

FIGURE 2(a)

FIGURE 2(b)

10-1000 7000

FLOW CHART FOR FIRST ON-LINE EXPERIMENTS

FIGURE 2(d)

FIGURE 2(e)

FIGURE 3(a)

FIGURE 3(b)

FIGURE 4

FIGURE 5(a)

FIGURE 5 (b)

FIGURE 6

FIGURE 7

FIGURE 8: SYSTEM OF DATA PROCESSING

FIGURE 9(4)

FIGURE 9(h)

FIGURE 9(c)

FIGURE 9(d)

FIGURE 10(4)

8.0 GEV/C $\pi^+ - p \rightarrow K^0 \gamma^*$

FIGURE 10(b)

FIGURE 11

FIGURE 12(a)

FIGURE 12(b)

FIGURE 12(c)

FIGURE 12(d)

FIGURE 13

FIGURE 14

FIGURE 15 (a)

FIGURE 15(b)

FIGURE 16

SYSTEM LAYOUT

FIGURE 17

FIGURE 18(a)

FIGURE 18(b)