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DATA SIMULATION WITH AN ON-LINE COMPUTER AS A
DIAGNOSTIC AND ANALYTICAL TOOL*

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Summary

A hybrid approach has been adopted in the use of an on-line computer in setting up and analyzing nuclear physics experiments. In addition to the usually cited advantage of on-line flexibility and the ability to do off-line calculations, the general purpose computer can simulate data by presenting the results of off-line calculations to the experimenter in a format identical to that used for data display. As compared with off-line calculations at a computer center with subsequent hand or machine plotting, the use of the built-in display hardware provides a more convenient comparison of theory with experiment, as well as greater ease and speed. The advantages of on-line data transformation are preserved without accompanying limitations on the rate of data taking. The data from the experiment consisted of energy correlations in two-particle coincidence experiments. The loci of points in energy-energy space fulfilling energy and momentum conservation were calculated, displayed, and photographed before each experimental run. Interpretation of the experimental data was assisted by modulation of the loci (i.e., of the number of counts per channel) according to the predictions of various models.

During the last ten or fifteen years the data handling equipment used in nuclear physics experiments has increased in complexity from simple scalers to pulse height analyzers and recently to multi-parameter data handling systems. Simultaneously, the need for complex computing equipment for theoretical calculations and for reduction of data has grown at an equal pace. It is the purpose of this paper to discuss certain of the profits anticipated and already realized from the merger of two formerly independent electronic systems, computers and pulse height analyzers.

The data handled in multiparameter experiments are in general characterized by two features; relatively modest input rates, since the data come from coincident events; and complexity of the data, which are functions of two or more independent parameters. The consequent needs of the experimenter are basically the following: fast-access data storage with live

display features for monitoring the experiment; a larger but slower-access memory (such as a magnetic tape) for preserving all information received in the experiment in cases where the data arrays are large; a means of routing the data into and out of storage; and finally, computation facilities for doing theoretical calculations and working up the data. The advantages of the stored program analyzer over the wired machine for the data handling function have been summarized by Kane and Spinrad;^{1,2} obviously the wired program machine is unsuited for general computation.

A small on-line computer with display and readout facilities meets all the above requirements, both in storing and routing data and in computation. Furthermore, such a system has a great advantage in its ability to simulate data--to present to the experimenter the results of its computations on the analog data display hardware, in the same format as the data itself. The usual impedance mismatch between computer and experimenter (customarily bridged by print-out and by hand or automatic plotting) can be greatly reduced in this way. Heretofore it has been customary to transform the experimental data into the representation used by theory, but the computer is quite able to perform the inverse transformation and present theoretical calculations in the data coordinates of channels and counts per channel.

As a result, it is possible to determine what the data should look like in advance of the experiment, given a particular model. Such calculations have the benefit of infinite statistics, and as the data trickle in they can be compared directly with the theoretical predictions. One also avoids the limitations on data taking rate which are imposed by complicated on-line data transformations. By means of simulation, features of special interest or experimental difficulties can be recognized much more readily than by poring over large tables of computer printout. With turnaround times of three minutes or less, various experimental conditions can be simulated in the middle of experimental runs to determine the best way to proceed, given the data already in hand.

Such a system has been placed in operation at Brookhaven in collaboration with J.V. Kane and P.F. Donovan of Bell Telephone Laboratories. The equipment consists of semiconductor particle detectors, amplifiers, coincidence circuitry, two 4096-channel analog to digital converters, and an SDS 910 computer with 4096 words of memory and 5-inch CRT display facilities. It is used mainly in the study of nuclear reactions involving breakup into three particles. If the energies of two of these three are measured at known angles, conservation of energy and momentum determine the energy and angle of the third. Furthermore, when the numbers of events are plotted as a function of the two energies, all events from a given reaction lie on a narrow curved line, whose width is determined by the angular aperture of the detectors. If there are several competing reactions, leading to a variety of three-body final states, the result is a profusion of lines, each of which must be identified.

This identification is simplified by allowing the computer to determine the positions of the lines for all relevant combinations of charged particles from the expected reactions, and then to add counts to all channels lying on the lines. As an example, Fig. 1 shows experimental data for the reaction $D+P \rightarrow P+P+N$ and also the locus of the kinematic line for the innermost and outermost edges of the counters, as calculated before the experiment. In the second figure, the counters have been moved backward a few degrees. The energy spread due to the counter width is greater, while the three peaks seen in Fig. 1 are not as strong. At these angles the relative momenta necessary for strong resonance behavior are not permissible. In the third example (Fig. 3), showing the reaction $P+D \rightarrow P+P+N$, the target thickness has smeared the line somewhat, but the calculation indicates which channels should contain the data from this reaction. Figure 4 shows a similar comparison of data with the displayed kinematic curves; here only the central angles of the detectors were used in the calculations. Note the faint inner line in the data, which is identified as the result of hydrogen impurity in the target.

With displays of this type it is possible to add an additional coordinate of information in the z direction. When displaying data, the dots are moved up by an amount proportional to the number of counts in that channel. In the calculations, one can insert a number of counts in each channel proportional to any desired function of the two energies represented by the channel numbers. For example, in Fig. 5 the z axis represents three different functions of the particle energies for the reaction of Figs. 1 and 2 — namely the available breakup energy for each possible two-particle intermediate system. Where these energies are small one expects to find the

singlet dinucleon resonances. Moreover, the predictions of various models for the cross section may be used to generate a function which modulates the number of counts per channel.

One may thus embark on experiments knowing what details to look for in situations sufficiently complicated to confound one's intuition. In Fig. 6 this method is applied to the same reaction seen in the first two illustrations. The line is shown in (a) modulated according to the phase space density along it, the distribution expected from random three-body breakup for constant or zero nuclear matrix elements. The experimental results of Fig. 1 show the same behavior in the regions between the peaks. In 6(b) we see the inclusion of a resonance at 0.06 MeV with a width of 130 keV, corresponding to the formation of singlet state deuterons. Again the similarity to Fig. 1 may be noted. We interpret the data as the three singlet resonances (the neutron interacting with the proton seen in counter 3, the neutron with the proton of counter 4, and the two protons), with random breakup elsewhere.

In addition to functions of two variables, it is of course possible to generate and display functions of one variable, using the second energy axis to display the values of the dependent variable at integral channel increments of the independent variable. With typewriter input of parameters this can provide a quick and reasonably accurate method of curve fitting.

We have seen that it is possible for a small general purpose computer with data display hardware to perform functions which would be impossible for a wired program analyzer and relatively expensive and inconvenient on a large computer remote from the experiment. The planning of experiments, the diagnosis of experimental difficulties, and the interpretation of data have already been greatly facilitated by data simulation. Additional uses being planned for our system include automated data analysis. For this purpose a light pen will be used to indicate to the computer what channels or kinematic lines are to be analyzed; the computer will then proceed to analyze the data in a conventional way, but with a considerable advantage in time and trouble over systems which require communication with a distant computer by means of magnetic tape or cards.

1. J.V. Kane and R. Spinrad, Proceedings of the Conference on Utilization of Multiparameter Analyzers, Report CU [PNPL] - 227 (1962); Nuc. Instr. Methods 25, 14 (1963).
2. R. Spinrad, Nucleonics 21, 46 (1963).

Figure Captions

1. Comparison of experiment with calculated kinematics for $D+P \rightarrow P+P+N$ at $\theta_3 = 26^\circ$ and $\theta_4 = -26^\circ$.
2. Comparison of data with calculated kinematics for $D+P \rightarrow P+P+N$ at $\theta_3 = 34^\circ$ and $\theta_4 = -34^\circ$.
3. Data and calculated kinematics for $P+D \rightarrow P+P+N$ at $\theta_3 = 30^\circ$ and $\theta_4 = -75^\circ$.
4. Data and kinematics for $D+D \rightarrow D+P+N$ at $\theta_3 = 24^\circ$ and $\theta_4 = -46.3^\circ$. Note that two lines appear since the deuteron can enter either counter, with the proton going into the other. The inner line is for $D+P \rightarrow P+P+N$.
5. Calculated energies above breakup threshold for the three possible intermediate systems in $D+P \rightarrow P+P+N$ at $\theta_3 = 26^\circ$ and $\theta_4 = -26^\circ$.
6. Cross sections predicted for $D+P \rightarrow P+P+N$ by phase space, and by assuming a resonance between particles 4 and 5 (P and N) with phase space background under the peak.

EXPERIMENT

THE REACTION IS $1+2 \rightarrow 3+4+5$
 $D + P \rightarrow P + P + N$

$$T_1 = 21.1 \text{ MeV}$$

$$\theta_3 = 26.0^\circ$$

$$\theta_4 = -26.0^\circ$$

ANGULAR WIDTHS OF DETECTORS = 2.5°

KINEMATICS CALCULATED FOR ANGULAR EXTREMES OF DETECTORS

12.0 MeV IN CHANNEL $x=y=48$

RESONANCES DUE TO VIRTUAL SINGLET DEUTERONS AND
 VIRTUAL DIPROTON.

KINEMATICS

EXPERIMENT

KINEMATICS

THE REACTION IS $1+2 \rightarrow 3+4+5$

$D+P \rightarrow P+P+N$

$T_1 = 21.1 \text{ MeV}$

$\theta_3 = 34.0^\circ$

$\theta_4 = -34.0^\circ$

ANGULAR WIDTHS OF DETECTORS $= 2.5^\circ$

KINEMATICS CALCULATED FOR ANGULAR EXTREMES OF DETECTORS

10.0 MeV IN CHANNEL $x=y=48$

DETECTOR ANGLES SLIGHTLY REMOVED FROM RESONANCE
CONDITIONS

EXPERIMENT

KINEMATICS

THE REACTION IS $1+2 \rightarrow 3+4+5$
 $P+D \rightarrow P+P+N$

$T_1 = 10.6 \text{ MeV}$

$\theta_3 = 75.0^\circ$

$\theta_4 = -30.0^\circ$

ANGULAR WIDTHS OF DETECTORS $= 2.5^\circ$

KINEMATICS CALCULATED FOR ANGULAR EXTREMES OF DETECTORS

3.5 MeV IN CHANNEL $x=24, y=48$

SMEARING OF EXPERIMENTAL CURVE DUE TO TARGET THICKNESS

RESONANCE DUE TO VIRTUAL SINGLET DEUTERON

PARTICLES 3 AND 5

PARTICLES 4 AND 5

PARTICLES 3 AND 4

AVAILABLE BREAKUP ENERGIES
FOR POSSIBLE INTERMEDIATE SYSTEMS

$$\theta_3 = 26^\circ \quad \theta_4 = 26^\circ$$

12.0 MEV IN CH. $X=Y=48$

Z SCALE ARBITRARY

A.

B.

MODEL PREDICTIONS

A. PHASE SPACE

B. RESONANCE IN 4,5 (I.E., P-N) SYSTEM
AT 0.06 MEV ABOVE BREAKUP THRESHOLD