Reproducibility as a Methodological Imperative in Experimental Research[1]

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1. Introduction

In experimental scientific research, such as that conducted in High-Energy Physics (HEP), there are a number of problems which are unique to the experimental endeavor in contrast to theoretical research. The preparation of a sample of data to be analyzed requires a number of complicated and interrelated procedures to insure the purity or quality of the data. Thus, for example, in an experimental study of meson-baryon [2] scattering, the separation of events of one type of scattering from others of similar configuration (see the discussion of different configurations in section II) requires intricate and sophisticated procedures along with the application of a number of criteria and standards of analysis. In the case of theoretical research, there are a number of philosophical discussions which formulate certain criteria or norms that theorists usually invoke in their evaluation of theories as well as in the actual choice of one theory over another. For example, T. S. Kuhn (1977) has listed five such criteria; simplicity, accuracy, fertility, scope, and consistency. Of course the meaning and application of these norms has been the subject of much debate. Leaving these debates aside, one can reasonably expect in any philosophical discussion of the epistemic significance of experimental research (e.g. Hacking 1983, Franklin 1986, and Galison 1987), that comparable criteria or values ought to be explicated. In short, if there are theoretical values then there ought to be experimental norms or values as well. This paper will discuss in detail one such proposed norm and will further illustrate its complex meaning by examining the routine details of a scattering experiment in HEP. The proposed norm or hypothetical imperative (see below) is that experimental results should be reproducible.

In recent philosophical discourse (e.g. Kornblith 1985, Giere 1989, Siegel 1989, and Laudan 1990) there has been much ado about the program of naturalistic epistemology. In brief, the debates have concentrated upon the descriptive role of naturalism in contrast to the normative or prescriptive aspect. In particular, L. Laudan (1990) has argued that epistemic naturalism has both a descriptive and a normative role in the analysis of the practice of science. Laudan argues that the theories of knowledge proposed by epistemologists of science must be evaluated in the same manner as scientific theories about the natural world. In particular, these epistemic theories must be made to confront the data which they purport to describe. Laudan is

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proposing an empirical evaluation of epistemic models of the practice of science, in particular its norms and goals, by a direct comparison with the details of particular episodes in the history of science. However, at least so far, this program of Laudan's has concentrated upon the formulation of hypothetical imperatives that are relevant to theoretical research. These hypothetical imperatives usually take the form

If one wants theories that are (—fill in the goal—),
then one ought to (—fill in the norm—).

The details of testing these hypothetical imperatives are still in the preliminary stages of formulation (e.g. Donovan et al. 1988) and, in addition to this, there is very little discussion of comparable hypothetical imperatives for experimental research. I propose the following hypothetical imperative as an example of an important methodological norm in experimental research.

> If one wishes to produce experimental knowledge that can be employed in the description of physical phenomena as well as in the development of successful theories about these phenomena, then one ought to conduct experiments whose results are reproducible.

The remainder of this paper will be a discussion of the significance of reproducibility in a typical, routine HEP experiment. No major experimental discoveries were made nor were any major HEP theories tested or evaluated in this experiment. The emphasis will be upon the importance of this methodological imperative in the preliminary experimental analysis.

In any HEP scattering experiment, there are a number of preliminary problems that must be resolved by the experimental physicist before new and interesting experimental questions can be pursued. Event identification and separation, various data cuts, preliminary analysis of different distributions, and the preliminary calculation of relevant experimental information must be performed. These aspects all involve the norm of reproducibility in one sense or another. After the preliminary analysis has occurred, additional tests are performed on the data that further require the reproduction of well-established results from other experiments in the same field. Finally, the analysis of new experimental results requires that these findings be reproducible both in terms of the new findings of other current experiments as well as in the postulated results of future experiments. Thus, reproducibility must be understood in several different yet interrelated ways.

The specific details of those aspects mentioned above (event identification, etc.) will be presented in the context of a particular high-energy scattering experiment so that a thorough discussion of the role of the methodological imperative of reproducibility can be analyzed in this experiment. It is precisely this type of empirical testing or evaluation of hypothetical imperatives that should be at the core of the epistemic naturalist's program. In addition to this, the particular norm under scrutiny pertains primarily to experimental rather than theoretical research, and the focus of this empirical evaluation will be on the routine aspects of preliminary research that ultimately lead to the discovery of new phenomena.

2. Experimental Details

During the 1960's and early 1970's, a great deal of experimental knowledge in HEP was obtained using the techniques of meson and baryon spectroscopy.[3] This procedure entailed the study of a large number of scattering events of a particular type as observed in some sort of target/measurement system. One of the most common techniques employed the liquid-hydrogen bubble chamber[4] (HBC) device in which the stationary target particle was the proton (P) and the incident particle was typically a lighter-mass particle such as the π meson. Many other configurations were studied and the type of scattering configuration was determined by the goals of the particular experimental investigation. One such experiment was the study of four-prong interactions in π^+P scattering at 18.5 GeV/c [5] by the HEP research group at the University of Notre Dame (ND) during the period from 1966 to 1970. In particular the interaction

$$\pi^+ P \rightarrow P\, \pi^+ \pi^+ \pi^- \pi^0 \qquad (1)$$

was analyzed to study resonance[6] production in the various multi-particle combinations. At this time, the beam momentum was the highest yet attempted in conventional bubble-chamber spectroscopy.

The ND research group sought to answer a number of experimental questions concerning resonance production in this interaction. The first group of questions concerned the feasibility of conducting such an experiment at this high energy and, in particular, of identifying a clean or pure sample of events of interaction (1). Problems of event separation and identification, measurement precision, reliability of measured parameters, and consistency with past experimental results all had to be addressed before the researchers could proceed to examine the details of resonance production at this energy. The second group of questions concerned the analysis of well-known phenomena in the new data. The production of well-known resonance states and the measurement of their physical properties at this high energy had to be examined before any new, speculative or previously unknown phenomena could be studied. It is often in the context of these more well-understood phenomena that new phenomena are examined. For example, as will be discussed in detail later, the production of new resonance states quite often involves combinations of other well-established resonance states. Thus, the goals of this experiment were the following: to determine if one could perform a meson-baryon spectroscopy experiment at this high momentum with standard techniques; if so, then measure the physical parameters of the well-known resonance states, such as the ρ meson resonance (discussed later in this section), at this new energy; and finally to search for new resonance phenomena as suggested by earlier experimental findings. These goals, in particular the last one, illustrate the exploratory nature of much of the experimental HEP research conducted at this time. This ND experiment was primarily motivated by earlier experimental results rather than by any contemporary theoretical research.

The data for interaction (1) were collected during the period from 1966 to 1968 at the Brookhaven National Laboratory (BNL), using the 80 inch liquid-hydrogen bubble chamber with a π^+ beam at a momentum of 18.5 GeV/c produced in the Alternating Gradient Synchrotron (AGS). Photographs in three different views were taken every time the π^+ beam entered the HBC and a total of 152,000 stereo triads were taken. These photographs were then scanned for four-prong scattering configurations in which the incident π^+ meson struck a stationary proton and four charged particles were produced in the final state. Neutral particles were produced as well, but these were not visible in the HBC photographs. Other configurations, such as two-prong or six-prong events (two or six charged particles in the final state), were not studied at this time. The focus of interest for the ND researchers lay in these four-prong events for a number of reasons, but the primary one had to do with the recent experimental success of other HEP groups, as well as their own, in studying resonance production in this four-prong configuration. The most recent experiment performed by the ND group, prior to this 18.5 GeV/c experiment, was a study (Cason et al. 1970) of π^- P scattering at 8 GeV/c and the focus of their research efforts was in the four-prong configuration with particular interest in the interactions analogous (same particles, but different charge combinations) to (1), (2), and (3) (see next paragraph).

About 57,000 four-prong events were identified and then measured for analysis. This entailed the measurement of the spatial coordinates of each charged-particle track in two of the three stereo views. With this information, computer analysis (Burren and Sparrow 1963) enabled the researchers to reconstruct these events in three-dimensional space. This geometric reconstruction enabled the researchers to calculate raw or unfitted values of energy and momentum for each of the charged-particle tracks in the final state by assuming a particular mass for each track. The next phase of the analysis was the kinematic fitting of the energy and momentum for each track. In this particular experiment three possible interactions were considered.

$$\pi^+ P \rightarrow P\, \pi^+\, \pi^+ \pi^- \pi^0 \qquad (1)$$
$$\pi^+ P \rightarrow P\, \pi^+\, \pi^+ \pi^- \qquad (2)$$
$$\pi^+ P \rightarrow N\, \pi^+\, \pi^+ \pi^+ \pi^- \qquad (3)$$

where the nucleons, P and N, are the proton and neutron respectively and the others are the various charge states of the π meson. The least-squares fitting procedure (Bock 1962) involved the assignment of a nucleon or π meson mass to each charged-particle track as well as the possible neutral-particle track (invisible). Different mass assignments resulted in different unfitted energy and momentum for that track. The conservation of energy and momentum was then imposed on the entire event for a specific set of mass assignments. The specific energy and momentum of each track was allowed to vary within a certain range. A fit to a particular interaction, such as one of the three above, occurred when energy and momentum conservation was maintained with a particular set of mass assignments. In the process of performing the kinematic fit, events of type (2) are referred to as four-constraint (4C) fits, while events of type (1) or (3) are referred to as one-constraint (1C) fits.[7] The final result of this fitting procedure for each event was a set of energy and momentum values for each possible fit to one of the above interactions, a χ^2 probability[8] for each fit, and a set of predicted bubble densities (see note 4) for each charged-particle track within a given fit.

Quite often more than one fit was obtained and an ambiguity between two or three fits to the above interactions resulted. This ambiguity was resolved in several ways. An ambiguity between a 4C and 1C fit was resolved by including the event in the 4C category (interaction (2)) since the χ^2 probability is generally greater for 4C fits. With a particular fit, the bubble density of each charged-particle track was calculated. This predicted bubble-density then was compared visually with the actual photograph of the event. Inconsistent predicted bubble densities eliminated one or more of the ambiguous fits. In addition to this, the so-called missing-mass-squared (MM^2) was calculated. The MM^2 is a measure of the mass of the neutral particle(s) that emerge from the scattering vertex. It is given by the expression

$$MM^2 = E^2 - P^2$$

Using unfitted energy (E) and momentum (P), of the measured charged-particle tracks, this quantity was calculated for the sample of fits to interaction (1). In this distribution[9], there is a peak at the square of the π^0 mass (0.0196 GeV^2). The shape of this distribution is very similar to those MM^2 distributions observed in earlier successful experiments that studied interaction (1) at lower beam momenta, such as the 8 GeV/c ND experiment. The ND experimentalists employed a MM^2 cut in the data by including only those events whose MM^2 was in the range from -0.21 (GeV)^2 to

0.18 $(\mathrm{GeV})^2$. Based upon their experience from earlier experiments they believed that this cut would remove badly measured events, multiple π^0 events, and neutron events from the sample. With this MM^2 cut the low χ^2 probability events were also eliminated. At this point in the analysis, any remaining ambiguous fits were removed from the sample for analysis. With these procedures the sample contained 4294 events of interaction (1).

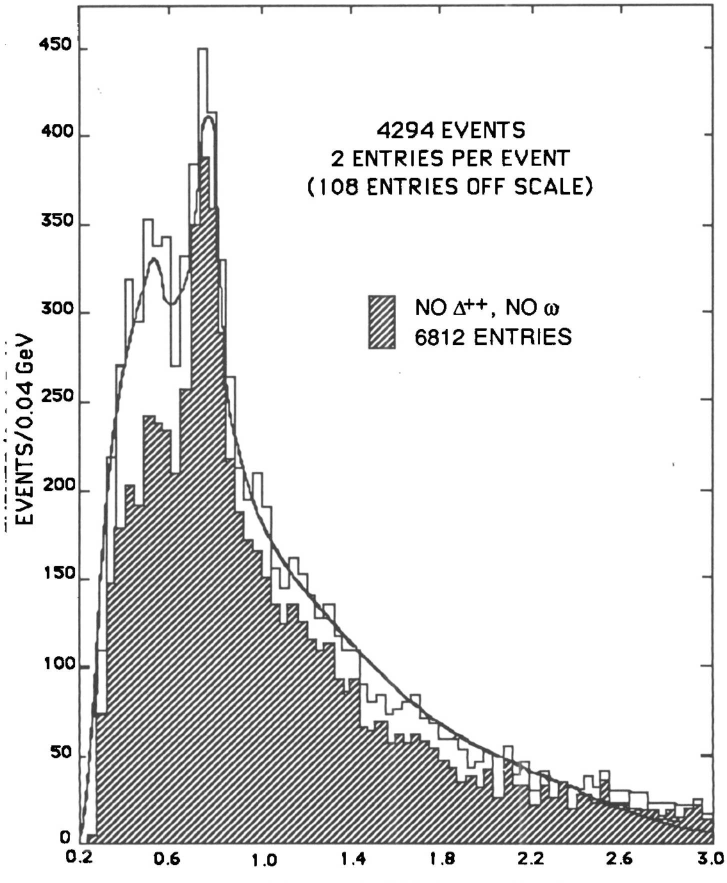

Figure 1. $M(\pi^+\pi^-)$ GeV

Figure 1a The effective-mass distribution for the $\pi^+\pi^-$ combination. The curve is described in the text.
Figure 1b (Shaded events) The effective-mass distribution for the $\pi^+\pi^-$ combination with ω and Δ^{++} events removed as described in the text.

The next phase of the experiment employed a computer program (Dalpiaz 1965) to calculate the various effective-mass distributions in order to study the physical properties of resonance production. In most of these cases the resonance states were al-

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ready well-established, but the measured properties of these states at this high momentum was of great interest as will be discussed shortly. The effective mass of a multi-particle system such as the $\pi^+\pi^-$ combination is defined as the square root of the following expression (see note 5)

$$(M_{\pi\pi})^2 = (E_{\pi\pi})^2 - (P_{\pi\pi})^2$$

where E and P are the energy and momentum of the $\pi\pi$ combination. This effective-mass distribution is shown in figure 1. In the figure the solid curve is a Breit-Wigner fit[10] superimposed upon a peripheral phase space background curve. From energy and momentum conservation, so-called kinematic considerations, the expected distribution of events may be calculated. This calculated curve is referred to as the kinematic phase space or background. In this particular case it has been modified to include the so-called highly peripheral nature of the π^+ P scattering. A typical peripheral phase space curve is shown in figure 3 for the $\pi^+ \pi^+ \pi^-$ effective-mass distribution. Any deviation from this expected background, as indicated by the pronounced peak at about 760 MeV in figure 1a or the broad enhancement at the low-mass end of the distribution in figure 3a, may be interpreted as a possible manifestation of the strong interaction that occurs between the π mesons. Thus, a detailed study of these phenomena will provide useful empirical information about the strong interaction at this high momentum.

In figure 1a there is a pronounced resonance peak at about 760 MeV as well as another enhancement at a lower energy of about 550 MeV. The distinction between these two is an important one and will be discussed shortly. The resonance peak at 760 MeV is the ρ meson resonance. Its physical parameters, such as mass, width, spin, parity, and isospin, are well-established. The measurement of these properties in this experiment was an important indication of the quality or purity of the 4294 events in the sample of events of interaction (1). The effective-mass distribution for the $\pi^+ \pi^- \pi^0$ and the π^+ P combinations exhibit the production of the ω (mass 780 MeV) meson resonance (figure 2) and the Δ^{++} (mass 1240 MeV) baryon resonance (not shown). These very pronounced resonance peaks are indications of the strong interaction occurring between the particles in these various combinations. Again their physi-

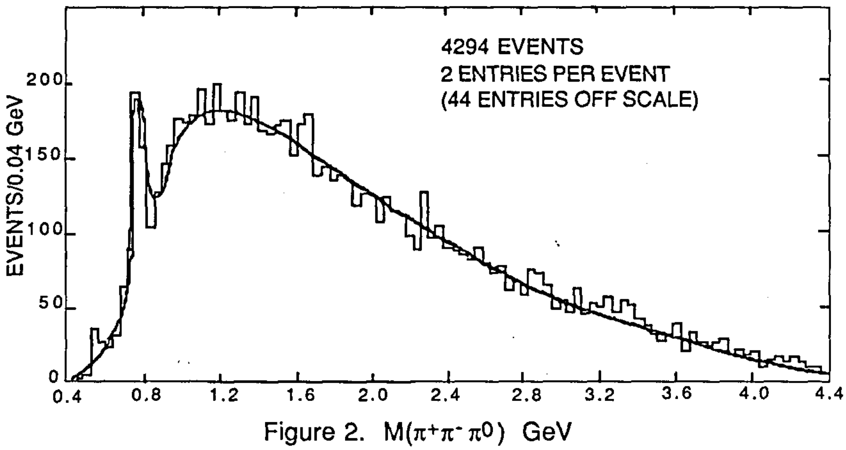

Figure 2 The $\pi^+ \pi^- \pi^0$ effective-mass distribution for all events of interaction (1). The curve is described in the text.

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cal parameters are well-known from earlier experimental work. In particular, in the case of the ω meson resonance, the observation of this resonance state is an important indication of the quality of the sample of events of interaction (1). This resonance state cannot be observed in either (2) or (3) and, furthermore, it involves the π^0 meson whose presence can only be inferred from the measurements of the other charged-particle tracks. The parameters of the π^0 can not be measured directly. If this resonance, as well as the ρ and the Δ^{++}, were not observed (reproduced) in the data of this 18.5 GeV/c scattering experiment, then in all probability the ND researchers would not have continued their study of resonance production in this interaction at this momentum.

In figure 1a, as mentioned earlier, there is a low-mass enhancement at about 550 MeV. This peak is a reflection of the decay of both the ω and the Δ^{++} resonance states. Very low-energy π mesons will result from these decays thereby producing $\pi^+\pi^-$ particle combinations that will have a low effective mass. These kinematic reflections, as they are called, can be removed by simply removing those events associated with the production of the ω and the Δ^{++}. Thus, those events with an effective mass in either of the following ranges will be excluded from the analysis of the production of the ρ resonance.

$$730 \text{ MeV} < M_{\pi\pi\pi} < 830 \text{ MeV} \quad \text{or} \quad 1140 \text{ MeV} < M_{p\pi} < 1340 \text{ MeV}$$

These mass cuts result in the distribution of shaded events shown in figure 1b. The ρ resonance peak remains very strong while the low-mass enhancement is removed. These kinematic enhancements or reflections from other resonance channels are important in the analysis of the properties of resonance production. These kine-

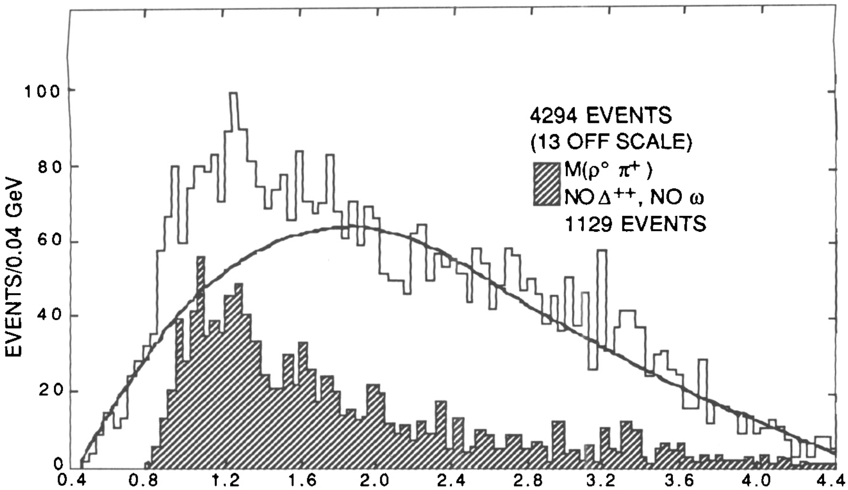

Figure 3. $M(\pi^+\pi^+\pi^-)$ GeV

Figure 3a The $\pi^+\pi^+\pi^-$ effective-mass distribution for all events of interaction (1). The curve is described in the text.
Figure 3b (Shaded events) The ρπ effective-mass distribution with ω and Δ^{++} events removed as described in the text.

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matic enhancements do not occur at the same mass nor do they occur with the same intensity as different experimental results are analyzed. Also the quantum numbers associated with these enhancements are not consistent from one experiment to the next. In sharp contrast to this, the physical properties of the resonance states, such as the ρ meson, are reproduced from one experiment to the next. As a result the HEP researchers must always determine if an enhancement above the expected kinematic background has properties that can be reproduced. If not, then these enhancements must be attributable to some additional kinematic effects, such as the reflections from other subchannels discussed above, and they must be removed from the study of the resonance production in that distribution. These kinematic enhancements have no direct bearing on the empirical study of the strong interaction through the analysis of resonance production. In figure 3a, the effective-mass distribution for the $\pi^+\pi^+\pi^-$ combination is shown along with the $\rho\,\pi$ distribution of shaded events in 3b. The latter distribution is an indication of the interaction

$$\pi^+ P \rightarrow P\,\rho\,\pi^+ \tag{4}$$

which is a subchannel of interaction (1). In both there is strong evidence for two enhancements, the so-called A_1 (mass 1080 MeV) and A_2 (mass 1320 MeV) mesons. At the time this experiment was performed there was a great deal of speculation as to whether or not these were legitimate resonance effects. The production of the A_2 was fairly reproducible from earlier experimental results whereas the A_1 production was not. In this experiment, because the number of events in interaction (4) was small (low statistics), the results were inconclusive, but seemed to indicate that the A_2 was a legitimate dynamic effect, whereas the A_1 was a kinematic effect analogous to that effect in the $\pi^+\pi^-$ effective-mass distribution. Additional studies were undertaken to examine the $\pi^+\pi^+\pi^-\pi^0$ effective-mass distribution and the $\rho\rho$ production in the interaction

$$\pi^+ P \rightarrow P\,\rho\,\rho \tag{5}$$

However, the initial published results (Hones et al. 1970 and Biswas et al. 1970) dealt primarily with the general characteristics of interaction (1) at 18.5 GeV/c and the experimental arguments in favor of performing a scattering experiment at this very high momentum while employing standard spectroscopy techniques. These included cross-section measurements of the total interaction, as well as that of other subchannels such as interactions (4) and (5). The physical parameters of the various well-known resonance states were reported along with any preliminary evidence for the A_1 and A_2 enhancements. Later papers (Cason et al. 1973 and Lichtman et al. 1974) dealt with more speculative phenomena and, for example, reported evidence for resonance production in interaction (5). The motivation for this study of interaction (5) came from the results of the ND scattering experiment at 8 GeV/c in which there were suggestions of possible enhancements in the 4π, $\rho\rho$ and $A\pi$ effective-mass distributions.

3. Reproducibility in this Scattering Experiment

As mentioned earlier, the ND researchers had a number of problems to resolve before they could begin to examine any new phenomena at this new very high momentum. The focus of the discussion in this section will be primarily on these preliminary efforts to insure the quality of the data and thereby place any new findings on a firm basis. Some discussion of the more speculative experimental results will also be given. One of the primary criteria or norms that the HEP physicists employed in this experiment was the reproducibility of results. This meant not only reproducing well-known phenomena, but employing data cuts, evaluative criteria, and calculational

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methods that were consistent with other experiments, and thereby gave results that were reproducible when compared with other experiments. This latter sense of reproducibility is more akin to the notion of consistency. The importance of including this notion of consistency in the formulation of this hypothetical imperative is that HEP experimentalists (and others as well) do not repeat experiments per se, but rather perform similar experiments that should yield results that reproduce earlier findings in a different context. These findings are often referred to as being consistent with other experimental results. Finally, this notion of reproducibility pertains to experimental findings of future experiments, performed in different circumstances (e.g. different beam particle, different beam momentum, different configuration, etc.).

In the preliminary analysis of the sample of events of interaction (1), the MM^2 and χ^2 cuts were performed in much the same manner as in earlier, lower momentum experiments. The ND researchers had used the specific ranges successfully in analyzing resonance production in interaction (1) at 8 GeV/c. The technique of comparing predicted bubble densities for various ambiguous fits to a single event employed the same criteria of identification as in earlier experiments. The cuts in the $\pi^+\pi^-$ distribution to remove the low-mass kinematic enhancement were the same. The basic argument employed by the researchers was that these techniques were yielding new results that reproduced the findings of earlier experiments. It should be noted that this reproduction was not a simple matter of repeating the same experiment. The crux of the experimental argument lies in the reproduction of results in different experiments. For example, the shapes of the MM^2 and the χ^2 distributions in the 18.5 GeV/c experiment were very similar to those in the 8 GeV/c experiment, even though different charged states of the π meson were used for the beam as well as a much higher beam momentum. As a result the cuts that were employed in the 18.5 GeV/c experiment were very similar to those of the 8 GeV/c experiment, and other results were also reproduced, as discussed in the previous section. This reproducibility works two ways in that it reaffirms the earlier results and lends weight to the arguments for accepting the new experimental findings.

However, it is in the examination of the effective-mass distributions that this notion of reproducibility is most clearly evident. The well-established resonance states, such as the ρ, the ω and the Δ^{++}, should be observed in any scattering experiment in which the appropriate particle combinations occur. All three are possible in interaction (1). The physical properties of these resonance states are well known. The ND researchers knew that if they did not observe these resonance states that the quality of their data was poor and that the remainder of their study of resonance production in interaction (1) at this momentum would be highly suspect. Furthermore, the mere observation of these enhancements in the various effective-mass distributions would not be a sufficiently strong enough argument for the quality of their sample. The specific physical properties of these resonances had to be measured as well. Thus the mass, width, spin, parity, and isospin all had to be measured. More importantly they had to be in agreement with those measurements in earlier experiments, performed under different conditions. This aspect of reproducibility is not just a check on the results of previous experiments, but more so a means of determining the quality of the experimental data in a current experiment. Thus, this aspect is a double-edged one. If these resonance states are observed and their measured physical properties are in agreement with earlier measurements then the current experiment offers additional information about these resonances at the new momentum, and at the same time this is strong evidence for the quality of the present experiment.

In contrast to this, the low-mass enhancement in the $\pi^+\pi^-$ effective-mass distribution is not a reproducible effect in the sense that it has no consistent set of physical properties. For example, measurements of the spin, parity, and isospin of this enhancement do not yield reproducible results. As mentioned earlier, one can show that this enhancement is directly associated with the low-energy π mesons from the decay of either the ω or the Δ^{++} resonance states. In other experiments where these strong resonance states (ω and Δ^{++}) are not produced, this low-mass enhancement is not observed whereas the ρ meson resonance is. In short, this enhancement is not reproducible, it is described solely by kinematic effects, and therefore is not a dynamic effect associated with the strong interaction.

So far this concept of reproducibility has past and present temporal connotations. Experimentalists refer to past experiments to check past results in terms of their present findings and use this reproducibility to argue for the quality of their present experimental results. However, this concept has very important connotations for future research. The current experiment becomes part of the chain of experimental argumentation to which the HEP researchers refer in their future research. In particular, new results, such as the observation of the A_1 and A_2 enhancements, must not only be consistent with previous findings, but must also be reproducible in any future experiment in which it is possible to observe these effects. In addition to this, any new findings of future experiments concerning these enhancements must be consistent with all previous experimental results, including the results of this particular experiment.

Finally, the more speculative studies in this ND experiment concerned possible resonance production in the $\pi^+\pi^+\pi^-\pi^0$ and in the $\rho\rho$ channels. Just as in the $\pi^+ \pi^-$ and the $\rho\pi$ distributions, certain cuts had to be made to remove kinematic effects that were not reproducible. The ω and the Δ^{++} events had to be removed from these distributions to examine the new effects. More importantly, the ND researchers were constrained from making any definite claims about the possibility of resonance production. Their findings were very limited by the number of events in this channel (interaction (5)) and they could not definitively reproduce the results of earlier experiments. They were forced to wait for additional experimental data. With these additional data, which they ultimately did obtain and publish (Cason et al. 1973), they would have enough data to draw conclusions and allow future experiments to evaluate their results by applying the reproducibility criterion.

At this point it must be made clear that, just as in the case of Kuhn's five scientific values or norms, the epistemic weight or significance that the experimentalist attributes to the norm of reproducibility will not be fixed for all time. Many experimental discoveries are made when certain results initially are not reproducible, but such discoveries are generally accompanied by great caution and respect for previous results. Laudan's (1984) discussion in *Science and Values* offers an excellent mechanism for the shifting and changing of scientific norms and values. The so-called "Reticulated Model of Scientific Rationality" describes the scientific endeavor in terms of a dynamic, triangular relationship between scientific facts, methods, and values or goals. In contrast to the Kuhnian (1970) picture of holistic scientific change in *The Structure of Scientific Revolutions*, Laudan argues that such change is piecemeal. A change in one aspect or level of scientific research, such as at the level of methodology, is not accompanied by wholesale change in facts and/or values. Rather, this change in one level is constrained and justified by reference to the other two aspects. However, it is not the purpose of this paper to discuss scientific change either in the theoretical or the experimental aspect of the practice of science. Suffice it to say that while experimental norms, such as reproducibility, may either shift in meaning or importance, it is done so in reference to the other levels of scientific practice. The norm does not change drastically from one experiment to the next. To detect such a change requires a more long-ranged analysis.

4. Conclusions

This notion of reproducibility has multiple applications and meanings, depending upon the specific goals of the experimental researchers. In the ND scattering experiment these are clearly exemplified at different phases of the experiment, as discussed in sections 2 and 3. In all cases, however, it must be emphasized that this methodological imperative does not place a great deal of importance upon the mere repetition of an experiment, but rather places great emphasis upon the reproduction of well-established results in different experimental contexts or situations. In other words, if the initial parameters of an experiment, such as beam momentum or target particle in this specific case, can be varied with the net results reproducing those results of other similar yet distinct experiments, then the current experiment is successful, at least in terms of this methodological imperative.

Reproducibility in its first sense refers to the reproduction in the current experiment of well-known results from earlier experiments. In particular, as discussed in the previous section, this pertains to the observation and measurement of the physical properties of the well-known resonance states. This sense of reproducibility was a very strong argument for the quality of the data and for the initial success of the experiment. Even though no new phenomena had yet been examined, the ND researchers were confident of the validity of this scattering experiment. The importance of this is evidenced by the fact that the initial publications were primarily concerned with a detailed presentation of fairly routine distributions and measurements. The more speculative findings were published later, after the validity of the experiment had been established. At the heart of this claim to validity lay the methodological norm of reproducibility. It should also be noted that the results of this experiment at 18.5 GeV/c and others (Cason et al. 1973 and Lichtman et al. 1974) later performed at these higher beam momenta, added further strength to the results of the earlier research. Additional, independent measurements of the physical parameters of the various resonance states served to further confirm the existence of these states.[11] Thus, reproducibility may be described as having a double-edged meaning in terms of the relationship between past and present experimental results. Both add to the credibility and acceptance of the other.

The second aspect of reproducibility pertains, as one might expect, to the relationship between present and future experimental results. Again this aspect is double-edged, with present results not only employed as a reproducibility check for the success of future experiments, but also future results serving as a confirmation of present findings. While these two aspects of reproducibility (past/present and present/future) may seem to be identical except for the temporal relationship, it is important to note that this temporal relationship is precisely what makes this methodological imperative of reproducibility so important. Experiments do not exist in isolation from other experiments. Rather, they function as an integral part of a chain of experimental argumentation that leads to a broader and deeper understanding of the physical world. Experimental research, when viewed in this fashion, is to be understood as an extremely dynamic and relatively independent process of acquiring knowledge of the physical world. (This strongly supports the discussion of Hacking (1983) as it pertains to his concept of experiment as intervention.)

In conclusion, the discussion of reproducibility in this HEP scattering experiment has not exhausted the meaning of this methodological imperative. The emphasis herein has been on the role of this norm in a more routine experimental context, and it is very important to understand the philosophical significance of these routine aspects. Other experimental situations, in which major experimental discoveries (expected or

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otherwise) have been made, would amplify other aspects of this norm. Thus, for example, a detailed examination of the discovery of the neutral-weak-currents, discussed by P. Galison (1987), would shed additional light on the importance of this methodological imperative. As mentioned in the introduction, one of the motivating factors for this paper is the epistemological project of normative naturalism. While this explication or test of the hypothetical imperative of reproducibility does establish its important role in this ND experiment, it also strongly suggests that this norm should be examined in other experimental contexts in order to more fully grasp the complexity of its meaning.

Notes

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[2]A meson is an intermediate mass particle, such as the π which has an integer value of its spin. A baryon is a heavier particle, such as the proton (P) or neutron (N), which has a half-integer value of its spin.

[3]Spectroscopy is a general field of inquiry in which the energy or frequency distribution of a particular sample is studied. In modern terms, because of the wave-particle dual nature of matter, one can relate the energy (E) of a particle to its frequency (f) by the relationship;

$$E = hf$$

where h is Planck's constant. Thus, in a typical HEP scattering experiment, the study of the energy (or frequency) distribution of various meson and baryon multi-particle combinations is referred to as meson and baryon spectroscopy.

[4]A liquid-hydrogen bubble chamber contains liquid hydrogen in a superheated state. The passage of a charged particle through the liquid hydrogen will cause ionization and thus leave a trail of bubbles. Higher-momentum particles will produce a lighter track in the HBC photograph than those with lower momentum. Neutral particles are not visible.

[5]The system of units employed in HEP research is based upon the electron-volt (eV), where 1 eV = 1.6×10^{-19} joules. Energy (E), rest mass (M_0), and momentum (P) are all measured in this system in HEP research and are related by the relativistic expression;

$$E^2 = (P)^2 + (M_0)^2$$

Typical units are 1 MeV = 10^6 eV for energy, MeV/c^2 for mass, and 1 GeV/c = 10^9 eV/c for momentum. HEP researchers often use mass, energy, and momentum interchangeably and will drop the factors of c, the speed of light.

[6]This term is used by HEP researchers in analogy to classical resonance phenomena, such as standing waves in a vibrating string or resonance in an alternating current circuit. For example, in the case of the vibrating string, only at certain fixed frequencies will the standing wave pattern occur. When the HEP experimentalists examine the energy distribution of a combination of particles (the effective-mass distribution as defined in the text), any enhancement above the expected distribution is interpreted as a resonance in that multi-particle system. This is based upon the relationship between energy and frequency as discussed in note 3. The lifetime of these resonance states is of the order of 10^{-23} seconds and thus not directly observable in the HBC.

[7]In the process of imposing energy and momentum conservation to a particular scattering event, a mass value must be assigned to each charged-particle track. This introduces four additional known quantities or constraints into the procedure of the simultaneous solution of a system of linear equations. If one assumes no neutral particles in the final state, such a fit is a four-constraint (4C) fit. In the case of a neutral particle in the final state, the three components of the momentum of the neutral particle can not be measured. This reduces the number of constraints by three and the result is a one constraint (1C) fit.

[8]The χ^2 probability is a measure of the quality or reliability of the least-squares fit. Low probability fits are simply not as reliable as high-probability fits. Refer to D. J. Hudson (1964) for an excellent discussion of this fitting procedure.

[9]See Hones et al. (1970) for the MM^2 and χ^2 distributions. Also figures 1, 2, and 3 are adapted from this (1970).

[10]The distribution of events in an effective-mass distribution is described by a Breit-Wigner shape, which was first developed in low-energy nuclear scattering experiments. The form is the following;

$$(dN/dM) = B.G + P.S.((\Gamma/2)^2/((M-M_0)^2 + (\Gamma/2)^2))$$

dN/dM is the number of events (dN) in a mass region of width dM.

B.G. and P.S. are the kinematic and peripheral phase space background. In this ND experiment these were generated by a computer program SFAKE (Lynch 1962), which employs a random-number-generator technique to describe the various background distributions.

Γ is the width of the resonance peak at half the maximum height.

M is the effective mass of one event and M_0 is the mass at which the resonance peak occurs.

The fitting process typically will vary the width and the resonance mass while using the other information as input.

[11]The collection of elementary particle data and information, annually published by the *Reviews of Modern Physics* (e.g. Wohl et al. 1984) usually lists a number of references to different experimental determinations of the physical parameters of the multi-particle resonance states. No single experiment is cited as the definitive determination of these parameters. In a very genuine sense, it is a type of experimental consensus that is reached over the values of these important parameters.

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