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THE WEAK INTERACTIONS FROM 1950-60:
A QUANTITATIVE BIBLIOMETRIC STUDY OF THE FORMATION OF A FIELD*

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THE WEAK INTERACTIONS FROM 1950-60:
A QUANTITATIVE BIBLIOMETRIC STUDY OF THE FORMATION OF A FIELD

When we were first asked if we might give a paper at this conference we were reticent because our active collaboration in a quantitative study of the history of that part of particle physics devoted to the weak interactions had ceased to involve new and original work several years ago when other duties began to be a more demanding claim on our time. However, upon reflection, we concluded that there were results which we could present for the period which is the focus of the conference which we had not called attention to before and which might illuminate the evolution of the field in a way different from the approach likely to be used by other presenters. Such a contribution might be thought valuable, and so we proceeded to develop what comes below.

We have not attempted to set our paper into the context of recent work in the sociology and history of particle physics. This must of course be seen as a liability because much exciting research has been published in the past several years, but this lack was unavoidable if we were to communicate at all with those attending the conference. We just did not have the time to do a complete job. This is, therefore, a report from our own empirical studies without reference to any other work. We apologize but believe that, on balance, there is benefit in sharing our data and analysis.

Background and Introduction

About ten years ago a group of sociologists and scientists gathered at Cornell University in a new program of research designed to discover and validate new methods of studying the evolution and health of scientific fields using quantitative measures. The interests of the group's founders lay both in finding ways to obtain a better basic understanding of how scientific fields develop--how, for example, the social and intellectual aspects of a scientific community interact--and in producing work that might have an influence on the way in which science policy is formulated by showing policy analysts better ways of monitoring the outputs of science and relating them to the inputs.

We believed that the best way to proceed with this program was to undertake several case studies of scientific specialties using teams of collaborators made up of sociologists and scientists familiar with the specialties in question. We believed, further, that one case study should focus on a field with a strong and highly developed theoretical basis which also involved major experimental work. That meant a field like particle physics, and we thought that within particle physics the study of the weak interactions might be a manageable specialty on which to focus.

A large and comprehensive data base was constructed comprised of all serial articles published in the specialty from 1950-1975 (N=5765), and our own weak interactions citation index was constructed from the references which appear at the end of the

serial articles. Over 80,000 references originating in one of the articles in our weak interactions bibliography citing articles both within our bibliography, and in other fields, make up our citation index. We have therefore been able to supplement the reading of important papers, reviews, proceedings and other documents with types of quantitative analysis of the development of the field of weak interactions that were developed especially for this purpose. These quantitative analyses have given us a view of trends and patterns for the specialty as a whole that is unavailable from traditional techniques of historical study.¹ We deal with the period from 1950-60 in this paper.

We will first give an overview of what the physicists working in weak interactions during this period were doing as indicated by

¹ The following papers are reports of our earlier analyses: Daniel Sullivan, D. Hywel White, and Edward J. Barboni, "The State of a Science: Indicators in the Specialty of Weak Interactions," Social Studies of Science, Vol. 7, (May, 1977), 167-200; _____, "Co-Citation Analyses of Science: An Evaluation," Social Studies of Science, Vol. 7 (May, 1977), 223-240; D. Hywel White, Daniel Sullivan, and Edward J. Barboni, "The Interdependence of Theory and Experiment in Revolutionary Science: The Case of Parity Violation," Social Studies of Science, Vol. 9, (November, 1979), 303-327; D. Hywel White and Daniel Sullivan, "Social Currents in the Weak Interactions," Physics Today, (April, 1979), 40-47; Daniel Sullivan, David Koester, D. Hywel White, and Rainer Kern, "Understanding Rapid Theoretical Change in Particle Physics: A Month-by-Month Co-Citation Analysis," Scientometrics, Vol. 2, No. 4, (1980), 309-319; Daniel Sullivan, David Koester, and D. Hywel White, "Survival in Particle Physics: An Analysis of Experimentalists' Persistence in Research," Scientia Yugoslavica, Vol. 6 (1980), 191-201; Daniel Sullivan, Edward J. Barboni and D. Hywel White, "Problem Choice and the Sociology of Scientific Competition: An International Case Study in Particle Physics," Knowledge and Society: Studies in the Sociology of Culture Past and Present, Vol. 3 (1981), 163-197; David Koester, Daniel Sullivan, and D. Hywel White, "Theory Selection in Particle Physics: A Quantitative Case Study in the Evolution of Weak-Electromagnetic Unification Theory," Social Studies of Science, Vol. 12 (May, 1982), 73-100.

an analysis of the subjects of their papers. The dominant problems and concerns are discussed. We will then focus on the events surrounding the emergence of the Tau/Theta puzzle, the discovery of parity nonconservation, and the resolution offered by the V-A Theory. For this latter analysis we take advantage of data from our citation index, displayed in some unusual ways which highlight the dominant issues of the period and the especially close relationship between theory and experiment in the latter half of the decade.

The Formation of a Field

The idea that weak interactions should form a separate field of study became well accepted only in the late 1940's when it emerged that a number of weak reactions, including Beta decay and muon decay, could be described by approximately the same coupling constant. By the beginning of the 1950's both the pion and muon were known, K mesons had been observed in cosmic rays, and it was appreciated that there exists a class of heavy strange particles, subsequently called hyperons, which also had been observed in cosmic rays. The attention of a rapidly increasing number of physicists began to be focused on this new field, though initially weak interactions drew many more experimentalists to work on its mysteries than theorists.² In Figures 1 and 2 we show the number

² All of the articles in our weak interactions bibliography were classified by a post-doctoral student in particle physics as theoretical or experimental from a reading of Nuclear Science Abstracts. A sample was checked by one of us (White) and agreement was about 95%. Later we acquired copies of all of the articles in our bibliography which allowed an additional check.

of different theorists and experimentalists (that is, an author was counted only once in a year in which he published) from all over the world who published in weak interactions each year from 1951-60. The rapid growth observed was due, we believe, to a combination of growth in the scientific community as a whole during this period and the relatively attractive character of weak interactions as a field which drew physicists to it from other fields. By 1957 nearly 400 physicists published at least once in weak interactions.

The patterns of theoretical and experimental article production are shown in Figures 3 and 4. The number of experimental articles published each year grew more rapidly than the number of theoretical articles until 1957 and 1958 when theorists published over 160 articles, almost four times the number published in 1956. The huge increase was due entirely to the discovery of parity nonconservation in 1956, about which we will have much more to say later. The bottom points shown in 1957 and 1958 in Figure 3 represent the number of articles published in those years exclusive of those concerned with parity. Such an outpouring of papers by theorists could occur because they did not have to design experiments, construct them, take data and analyze it before publishing, as do experimentalists. Their ability to change their research foci on short notice and get into print is much greater than is the case for experimentalists.

Figure 5 gives a capsule summary of what experimentalists were doing during this period. The analysis of π - μ decay dominates

the early years, since examples were plentiful in cosmic ray experiments and pions and muons could be made plentifully in the synchrocyclotrons then available. With the construction of larger accelerators (the Cosmotron came on line in 1952 and the Bevatron in 1955), the decays and characteristics of heavier particles involved in weak interactions could be studied and one saw a growing emphasis on experiments concerned with K decay and with the analysis of hyperons and their decays. The several experiments concerned with the "tau-theta puzzle", which began to capture the attention of more and more people in the field in the middle of the decade are included here in the K decay numbers.

Lee and Yang's paper on parity nonconservation transformed the field in 1956,³ and the effect is dramatically visible in Figure 5. Figure 6 is a comparable plot for theoretical papers, dominated almost entirely by the emergence of the "tau-theta puzzle", parity nonconservation, and V-A. We assume that with this audience we do not have to describe in detail the questions of physics involved during those exciting years. Most of the participants are here, and their recollections and remarks form much of the program of the conference. What is remarkable to us, however, is the extent to which first the "tau-theta puzzle," then parity nonconservation, and finally V-A theory dominated the publications in the field. We know of no parallels in other scientific fields where such a high fraction of the world's attention became focused so closely on a

³ T. D. Lee and C. N. Yang, "Question of Parity Conservation in Weak Interactions," Physical Review, Vol. 104 (1 October 1956), 254-58.

single set of issues. We are tempted to say that such concentration is only possible in fields where the central theoretical structure is both coherent and basic to all of the work that can be done.

There is a technique of analysis which we have used extensively in other contexts, and which we have had a role in refining,⁴ that helps illuminate the intellectual activities in a field and also gives a quantitative dimension. It is called co-citation analysis,⁵ and we will use it to focus in more detail on the period from 1956-60, which includes the discovery of parity nonconservation and the development and validation of V-A theory.

Parity and V-A

In a co-citation analysis one examines the referencing patterns in the papers published in a given year y to see what research questions defined by the content of the papers being cited were of common concern to the researchers publishing in that year. A start is made by identifying the papers cited most frequently by the weak interactions papers published in year y . In the analysis presented here, only papers cited ten or more times in papers

4 Op. cit., Sullivan, White and Barboni (1977), 223-40.

5 Credit for developing the technique of co-citation analysis must go primarily to Henry Small and Belver Griffith. See, for example, H. G. Small, "Co-Citation in the Scientific Literature: A New Measure of the Relationship Between Two Documents," Journal of the American Society for Information Science, 24 (July-August 1973) 265-9; H. G. Small and B. C. Griffith, "The Structure of Scientific Literatures I: Identifying and Graphing Specialties," Science Studies, 4 (1974), 17-40.

published in a given year were considered eligible for inclusion in a co-citation cluster. Then a count is made of the number of times these highly cited papers are cited together in papers published in year y. We infer that groups of earlier papers that are cited together frequently (in this case co-cited seven or more times) by papers published in year y defined a common focus for the papers published in y which made reference to them. Then, using a fitting technique called multi-dimensional scaling, one can produce a two-dimensional plot which arranges the papers in a plane such that their planar distances correspond as closely as possible to their relative co-citation levels.⁶

Figure 7 shows the kind of result the multi-dimensional scaling program produces. Nine papers (see appendix) were cited ten or more times by weak interactions papers published in 1956 and were co-cited seven or more times with at least one other paper.⁷ The multi-dimensional scaling program clustered them into four groups. The lower center group is made up of four papers, two by Dalitz, one by Fabri, and an experimental paper by Harris, Orear and Taylor. The Dalitz and Fabri papers define the "tau-theta

6 The two-dimensional plots were produced by a multi-dimensional scaling program called TORSCA. See V. R. Rao, "Computer Programs for Multidimensional Scaling," Cornell University Graduate School of Business and Public Administration, 1972.

7 These thresholds, by the way, were used to reduce the papers in the analysis to a manageable number. Our experience and the experience of others who have used co-citation analysis indicates that using such cutoffs, after suitable exploration of the effects on the plots of higher and lower cutoffs, highlights the core intellectual foci of the field. The less cited papers which are excluded do not tend to represent new clusters of activity which ought to become part of the analysis.

puzzle," and the Harris, et al. paper, concerned with the lifetimes of K^0 mesons in two and three body decays, presented data which those publishing in 1956 felt were crucial to discussions of the "tau-theta puzzle". The lower left cluster contains two papers, both experimental and coming a little later, which present data and analyses on the lifetimes of the K meson in two body decay modes, and which were only peripherally related to the "tau-theta puzzle". The lower right cluster has two papers devoted to the expected K^0 , - K^0_2 lifetime difference. Finally, the top center cluster is a single paper, by Konopinski and Mahmoud, in which the S/P or V/A character of the weak interaction is discussed together with implications of the particle-antiparticle assignments for the μ^+ .

We believe the contents of the four clusters of papers shown in Figure 7 represent pretty well those issues to which physicists working in weak interactions attended for much of 1956. To better indicate the relative degrees of emphasis those working in the field placed on each cluster of activity, we devised the plots shown in Figures 8-12. We begin with papers clustered as in Figure 7. Now imagine that associated with each paper on the plane there is a third dimension perpendicular to the plane which corresponds to the number of times each paper was cited. Each paper is then treated as if it were a cylindrically symmetric Gaussian hill whose height is the number of times it was cited overall (its visibility) and whose standard deviation is arbitrarily set so as to produce pictures at different levels of resolution. The Gaussians were then added together and the resulting plot of hills and valleys gives a sense of how much activity was going on in different parts

of what might be called the "subject space". In some of these plots we present simultaneously a picture with small standard deviations (so that the location of specific papers can be seen) and one with larger standard deviations which gives a good sense of the overall pattern.

The new information provided in Figure 8 is a clear indication of how important and dominant the concern with the "tau-theta puzzle" was. The hill representing the papers of Dalitz, Fabri, and Harris et al. is large and central.

The year 1957 yields the co-citation hill diagram shown in Figure 9. It is quite different from the picture of the previous year. Lee and Yang had asserted that parity must not be conserved (center hill), explaining the "tau-theta puzzle", and a major experimental effort was launched to determine if they were right (left hill). The papers verifying parity violation form that peak (Wu et al., Garwin, Lederman and Weinrich, and Friedman and Telegdi), along with several which extended the implications of parity violation (Salam, Landau, and a two-component neutrino theory by Lee and Yang). Lee, Dehne and Yang discuss the $K^0\bar{K}^0$ system in the light of parity violation.

To the right and right foreground are some of the older K decay lifetime measurements together with the K^0_2 discovery by Lande, et al., the differential absorption of $K^0\bar{K}^0$ by Pais and Piccioni, and an older paper by Takeda discussing the two body decay modes of the θ , and the paper by Gell-Mann and Pais on the θ_1 - θ_2 effect.

Figure 9 is a dramatic representation of the dominant concerns in weak interactions in 1957. It shows not only the clusters of activity, but also how important they were, relative to each other, in the eyes of those working in the field at the time. Parity had been found not to be conserved, but a general explanation for it, one which could form the basis for an ongoing theoretical and experimental research program, had not yet been developed.

However, in late 1957, as all at this conference are aware, a general theory of the weak interactions--the universal V-A theory--was proposed by Sudarshan and Marshak and by Feynman and Gell-Mann.⁶ Because only serial articles are included in our data base, the Sudarshan and Marshak paper from the Padua-Venice Conference is not included in the co-citation plot. However, its absence does not, we believe, alter the general structure that is revealed in Figure 10. It takes some time for new ideas to make their way into the published literature. That is why the large center hill is still dominated by parity nonconservation. The 1956 Lee and Yang paper, joined by their paper describing a two-component theory (which received the most citations in 1958), dominate the central region. They are joined there by the experimental papers verifying parity nonconservation, which are subsumed in the central region. Feynman and Gell-Mann on the theory of the Fermi Interaction (V-A),

B. E. C. G. Sudarshan and R. E. Marshak, Proceedings of the Padua-Venice Conference on Mesons and Newly Discovered Particles (September 1957), and "Chirality Invariance and the Universal Fermi Interaction," Physical Review, Vol. 109 (1958), 1860-62; and R. P. Feynman and M. Gell-Mann, "Theory of the Fermi Interaction," Physical Review, Vol. 109 (1958), 193-98.

with the Physical Review paper of Sudarshan and Marshak and the renormalisation paper of Tanikawa, form a closely related hill to the left. On the other side and in the foreground, analysis of decay processes by Kinoshita and Sirlin, Wyld and Treiman, and Pais and Treiman form lower peaks.

With the 1959 plot, a further interpretation of the 1958 data becomes possible. By 1959 V-A dominates the scene. One can think of the V-A hill in the 1958 plot as moving toward center stage and about to displace the hill concerned primarily with parity nonconservation. It is remarkable, even with the delays necessitated by publication, how quickly the content of the literature in this field changed in those years.

We present Figure 11 without the fine structure of the internal detail. In the central peak are Feynman and Gell-Mann, Sudarshan and Marshak, Tanikawa, Lee and Yang, Salam, Landau, and others. In the satellite peak to the left front is an experimental article by Crawford, et al. on Lambda beta-decay. All the other experiments are gone. The remaining satellites are theoretical articles exploiting (V-A) theory by Sakurai, Goldberger and Treiman, Okubo et al., Gell-Mann, and Berman.

One still senses great excitement in this field in 1959. The structure of the co-citation plot conveys focus and sense of purpose, and the height of the central hill shows a high level of activity. By 1966 the field appeared to pause intellectually. A paper by Zachariasen is the only new entry to the central hill, exploring K meson decay as a test of the universality of mu and e,

and the central hill is lower, which means that references in 1960 papers were less concentrated. Figures 13 and 14 provide dramatic indicators of this return to normal, and at the same time they show how stunning the discovery of parity nonconservation and the subsequent development of (V-A) theory were to the physicists working in the field.

In Figure 13 we display what is called a concentration ratio--the per cent of references in theoretical weak interactions articles published in a given year which go to the most highly cited 5% of all weak interactions articles cited by theory articles in that year--for the entire period from 1950-1971. In 1957, the first full year in which theory articles could cite Lee and Yang, almost 80% of all the references in the theory articles published went to the most highly cited 5%. That is a remarkable level of concentration on a tiny fraction of the literature in the field. By 1959, the concentration ratio dropped below 40% and continued to decline until 1963. We know from other analyses that the increase in 1963, and the even higher peak in 1965, were due, respectively, to the interest caused by the $\Delta S = \Delta Q$ selection rule controversy and CP violation, which came on the scene in 1962 and 1964.

Another indication of the degree to which almost everyone was focused on parity and V-A in the latter part of the decade may be had by examining Figure 14. There we show something we have called the reference half-life for theoretical weak interactions articles citing other theoretical weak interactions articles. The reference half-life is defined as the elapsed time (h) such that half the

references made in a given year are to papers less than n years old. The reference half-life is a measure of how dependent today's papers are on results from the immediate past. The shorter the reference half-life, the faster the field is moving. In 1957 half the references from theory articles were to other theory articles which were only a few months old. By 1960 the reference half-life had grown to about two years, which meant that most theorists were publishing papers whose focus still depended heavily on work published during and immediately after the parity and V-A papers. The data do seem to suggest that the field paused intellectually for a time. At least for the field of weak interactions the fact that this conference focused on the decade from 1950-60 was appropriate: 1960 was the end of one phase and the beginning of another.

From a situation at the start of the decade when new particles were being found and the first measurements of the weak interactions were being made, the field progressed through a major upset of the physical laws that were held to be appropriate to weak decays (parity nonconservation), to a theory that formed the foundation of the field for some time. It was striking how rapidly, once the possibilities for a new direction were sensed (parity nonconservation again), theorists and experimenters moved to develop implications and verify predictions. In many ways it fits our preconceptions of the way science should proceed.

It should not be overlooked that the progress of the experiments demanded the new accelerators that began producing

particle beams in this period. The "tau-theta puzzle" was only a puzzle until the precision of the experimental data forced an initially unpalatable position on the theorists and a basic review of the underlying concepts.

Conclusion

We have found that the quantitative techniques illustrated in this paper provide a reliable picture of the broad intellectual dynamics of a field. The field of weak interactions came into being at the beginning of the 1950's, and by the end of the decade it had provided the equivalent of a lifetime of excitement for many of the physicists here at this conference. We are glad to have been able to add our particular way of viewing things to the recollections of the participants.

FIGURE 1
NUMBER OF DIFFERENT THEORETICAL AUTHORS
WHO PUBLISHED EACH YEAR

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FIGURE 2
NUMBER OF DIFFERENT EXPERIMENTAL AUTHORS
WHO PUBLISHED EACH YEAR

0810775

FIGURE 3

NUMBER OF THEORETICAL ARTICLES PER YEAR

FIGURE 4

NUMBER OF EXPERIMENTAL ARTICLES PER YEAR

FIGURE 5
PER CENT OF EXPERIMENTAL ARTICLES
DEVOTED TO EACH TOPIC

FIGURE 6
PER CENT OF THEORETICAL ARTICLES
DEVOTED TO EACH TOPIC

FIGURE 7

CO-CITATION MULTI-DIMENSIONAL SCALING PLOT FOR
WEAK INTERACTIONS IN 1956

*Konopinski & Mahmoud, '53

Fitch &
Motley '56 *

Harris,
etal, '56 *

Gell-Mann &
* Pais, '55

Alvarez,
etal., '56 *

Dalitz, '53 * * Dalitz, '54

Fabri, '54 *

* Gell-Mann, '53

FIGURE 8

CO-CITATION HILL DIAGRAM - WEAK INTERACTIONS
1956

TAU-THETA PUZZLE

K DECAY

Fitch & Motley '56
Alvarez et al. '56

Dalitz '53
Dalitz '54
Harris, et al. '55
Fabri '54

Konopinski &
Mahmoud '53

MIXED STATES OF K^0

Gell-Mann '53
Gell-Mann & Pais '55

FIGURE 9

CO-CITATION HILL DIAGRAM - WEAK INTERACTIONS
1957

EXPERIMENTAL EVIDENCE &
IMPLICATIONS

Lee, Oehme & Yang '57
C. W. Wu et al. '57
Garwin et al. '57
Salam '57
Landau '57
Lee & Yang '57
Friedman & Telegdi '57

CLAIM: PARITY NOT CONSERVED

Lee & Yang '56

K DECAY

Fitch & Motley '56
Alvarez et al., '56

FIGURE 10

CO-CITATION HILL DIAGRAM - WEAK INTERACTIONS
1958

FIGURE 11

CO-CITATION HILL DIAGRAM - WEAK INTERACTIONS
1959

FIGURE 12

CO-CITATION HILL DIAGRAM - WEAK INTERACTIONS
1960

FIGURE 13

CONCENTRATION RATIO: PER CENT OF REFERENCES IN
THEORETICAL ARTICLES WHICH GO TO THE MOST HIGHLY CITED
5% OF ALL WEAK INTERACTIONS ARTICLES PUBLISHED THAT
YEAR

FIGURE 14

REFERENCE HALF-LIFE: THEORETICAL WEAK
INTERACTIONS ARTICLES TO THEORETICAL WEAK INTER-
ACTIONS ARTICLES

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APPENDIX

Articles in Co-Citation Plot for 1956

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- R. H. Dalitz, "On the Analysis of T-Meson Data and the Nature of the T-Meson," Phil. Mag., Vol. 44 (1953), 1068-80.
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- E. Fabri, "A Study of T-Meson Decay," Nuovo Cimento, Vol. 11 (1954), 479-91.
- V. Fitch and R. Motley, "Mean Life and K^+ Mesons," Physical Review, Vol. 101 (1956), 496-8.
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- M. Gell-Mann and A. Pais, "Behavior of Neutral Particles Under Charge Conjugation," Physical Review, Vol. 97 (1955), 1387-9.
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