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UNDERSTANDING RAPID THEORETICAL CHANGE IN PARTICLE PHYSICS: A MONTH-BY-MONTH CO-CITATION ANALYSIS*

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While co-citation analysis nas proved a powerful tool in the study of changes in intellectual foci in science, the technique has never been used to study very rapid changes in the theoretical structure of a scientific field. In this paper we present month-by-month co-citation analyses of key phases in the weak-electromagnetic unification research program within particle physics and show that these analyses capture and illuminate very rapid intellectual changes. These data provide yet another illustration of the utility of co-citation analysis for understanding the history of science.

Introduction

The technique of co-citation analysis, developed by Henry *Small* and Belver *Griffith,*[1] has proven to be a powerful tool in understanding the intellectual structure of a scientific field at a given point in time. A sequence of annual co-citation analyses, produced from the references in a year's worth of scientific papers for a series of years, can be an extremely sensitive indicator of intellectual change. We have been heavy users of co-citation analysis to help us understand the intellectual history of a specialty within elementary particle physics, the physics of weak interactions, but until now our use of the technique has been conventional.[2] We have wanted for some time, however, to examine a period in the history of weak interactions where important intellectual changes occurred on a scale much smaller than a year's span of time to see if co-citation analysis would be sensitive to very rapid shifts in intellectual focus.

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Historical background

The period from early 1971 through 1975 is ideal for this purpose in the field of weak interactions because it was then that most of the physicists in the field turned their attention to the weak-electromagnetic unification research program.[3] Physicists have long wanted to find a theory which explains the four forces of nature (gravitational, electromagnetic, weak, and strong nuclear) as different manifestations of the same underlying phenomenon. In 1967 Steven *Weinberg*[4] and Abdus *Salam*[5] each proposed a theory for the unification of two of these four forces: the weak and electromagnetic. However, these two theories belonged to a class of gauge theories in which singularities occurred (i.e., the equations describing the process go to infinity at high energies), and it was thus impossible to use these theories to make necessary calculations. This problem was responsible for a lack of any theoretical interest in the *Weinberg – Salam* model in the first three years after it was proposed.[6]

In 1971 Gerhard *t'Hooft* showed how the singularities in gauge theories could be removed,[7] and interest in weak-electromagnetic unification grew dramatically. Almost immediately the original *Weinberg – Salam* model ran into trouble. One of its important predictions (that there should be strangeness-changing neutral current particle decays)[8] was disconfirmed by experiment. No strangeness-conserving neutral current decays had ever been seen either, but experiments of sufficient sensitivity had not yet been conducted.

Theorists reacted in two ways to these early difficulties of the *Weinberg – Salam* model. First, a number of theorists constructed alternative gauge theories without neutral currents, and two of these models (one by *Georgi* and *Glashow,*[9] and another by B. W. *Lee*[10] and *Prentki* and *Zumino*[11]) began to receive a lot of attention. Second, some theorists remained interested in the original *Weinberg – Salam* model, and they sought a mechanism whereby the *Weinberg – Salam* model could be adjusted so as to forbid strangeness-changing neutral currents.

The *Georgi – Glashow* model allowed no neutral weak currents whatsoever but required four new unobserved heavy leptons and five (or possibly even eight) quarks, rather than the three or four quarks required by most models prominent at the time. The B. W. *Lee* and *Prentki – Zumino* models, essentially identical, also excluded the kind of neutral current present in the *Weinberg – Salam* model (based on the existence of a heavy neutral transmitter of the weak force, the Z° in *Weinberg*'s model), but included a neutral current which "shows up only as a minute short-range parity violation in electromagnetism, and nowhere else." This latter characteristic of their model was crucial in keeping it in contention in the

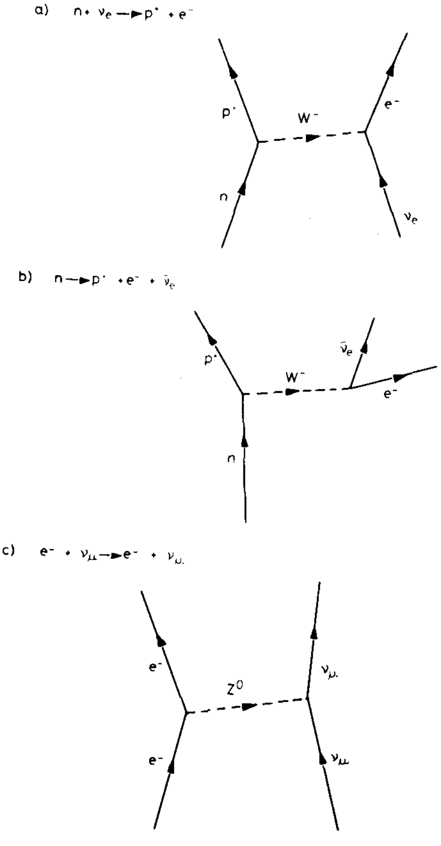

Fig. 1. Charged and neutral current weak interactions

face of the first series of experimental results which bore upon weak-electromagnetic unification, as we shall see.

Meanwhile, a way had been found to preserve the essentials of the *Weinberg – Salam* model (e.g., the existence of a Z^0) and, at the same time, explain the non-existence of strangeness-changing neutral current interactions: the so-called "GIM" mechanism. The original *Weinberg – Salam* model was a three quark model. In 1970 *Glashow, Iliopoulos* and *Maiani* (GIM)[12] proposed a four-quark model which, though it assumed only charged currents in the weak interactions, nicely forbade strangeness-changing neutral currents. The necessary modifications of the *Weinberg – Salam* model were reported in a paper by *Bouchiat* et al.[13] In addition, however, the new four-quark model (the fourth quark was called "charm") required that a whole new family of particles exist (charmed hadrons), and no candidates had ever been seen experimentally. So, in this rescue of the *Weinberg – Salam* model, a new set of phenomena were required: a fourth quark and the associated charmed hadrons. The strangeness-conserving neutral currents were left alone, although just then W. *Lee*[14] published a paper reporting the analysis of some old data in which their existence was questioned.

Analysis

The new innovation to be tested here has to do with the way we selected the articles whose references make up our co-citation activity plots. Instead of the usual practice of choosing all articles published within one calendar year (say 1973) in weak interactions as our citing article population, we created a long series of moving twelve-month periods from 1–12/72 to 6/74–5/75. In other words, a co-citation analysis was performed for a series of twelve month periods of article production where the next period begins with the articles published one month later than the beginning month of the previous period. A year's worth of citations were necessary for us to have enough data for precise analysis.

To produce the activity plots shown in Figs 2–9 we first did the usual co-citation analysis, where the co-citation matrix is transformed into a matrix of dissimilarities and this matrix serves as input to a multi-dimensional scaling program. This program produced a two-dimensional plot of the highly cited papers in each moving twelve-month time period such that the highly co-cited papers were placed near to each other and the little co-cited papers were placed farther apart. We infer that the relative distances between papers in the plane is an indication of their intellectual relatedness. Each paper was then treated as if it were a Gaussian hill whose height was the number of times it was cited overall in that time period (its visibility) and whose standard deviation was arbitrarily set so as to produce pictures at an appropriate level 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".

For lack of space we present only eight co-citation activity diagrams, chosen to show the points in time where crucial changes in the configuration took place. Fig. 2 shows the status of the field of weak interactions during the calendar year 1972. The left hill represents the remainder of the older theoretical research program in weak interactions which is being supplanted by weak-electromagnetic unification, represented by the hill labeled "*Weinberg – Salam* Model". The hill to the right is made up of the experimental papers which showed that strangeness-

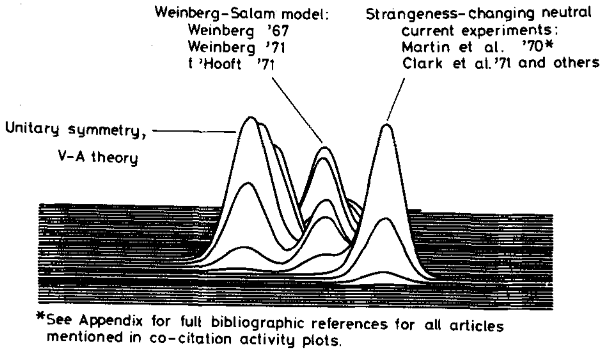

Fig. 2. Weak interactions co-citation activity plot for 1972

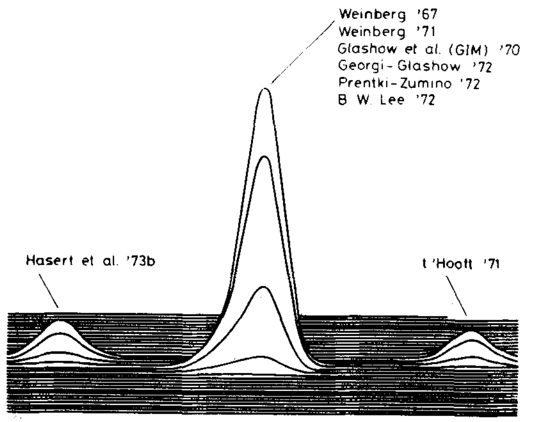

Fig. 3. Weak interactions co-citation activity plot for 6/73–5/74

changing neutral currents do not exist. These papers were the ones which caused the newly resurrected *Weinberg – Salam* model its first major difficulty, as outlined briefly above.

Shortly thereafter the activity plots change their structure dramatically to correspond essentially to the configuration of Fig. 3, where the center is dominated by a tall spike representing weak-electromagnetic unification. *t'Hooft*'s key paper is the small hill off to the right, and all three models *(Weinberg – Salam, Georgi – Glashow,* B.W. *Lee – Prentki – Zumino)* occupy center stage. What is new in Fig. 3 is the small hill to the left (*Hasert* et al.). *Hasert* et al. reported the first, tentative,

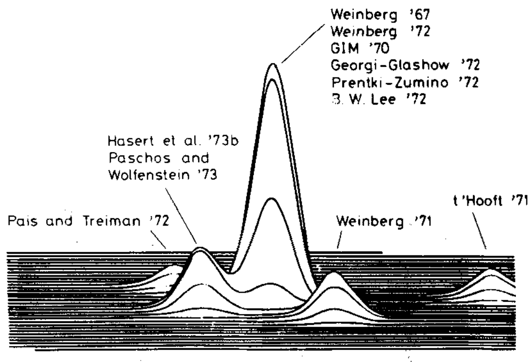

Fig. 4. Weak interactions co-citation activity plot for 7/73–6/74

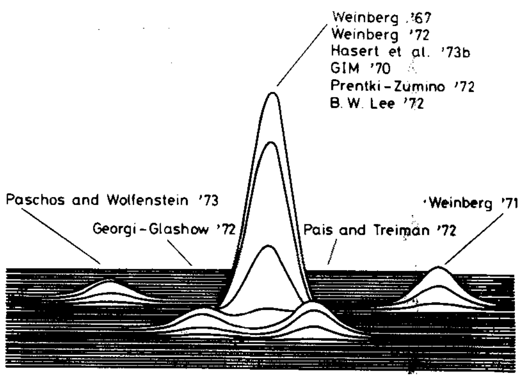

Fig. 5. Weak interactions co-citation activity plot for 8/73–7/74

evidence for the existence of strangeness-conserving neutral current particle decays. In Fig. 4 we see the *Hasert* et al. hill moving closer to the center of the picture (more highly co-cited with *Weinberg*) and getting larger (greater number of citations). The other new hills are crucial to a complete understanding of what is going on in the field at the time, but we cannot include all of the details here.

In Fig. 5 we see a dramatic change. *Hasert* et al. has joined *Weinberg – Salam* and B.W. *Lee–Prentki–Zumino* in the very center of the plot, while the *Georgi – Glashow* model has been shoved out of the center and remains as only a small hill to the lower left. The *Georgi – Glashow* model, remember, strictly forbade neutral current decays, while the B.W. *Lee* and *Prentki – Zumino* models allowed them, though not in a strong way. These latter two models could not strictly be elimin-

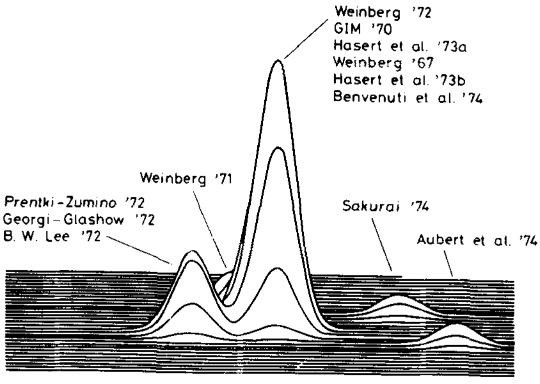

Fig. 6. Weak interactions co-citation activity plot for 2/74–1/75

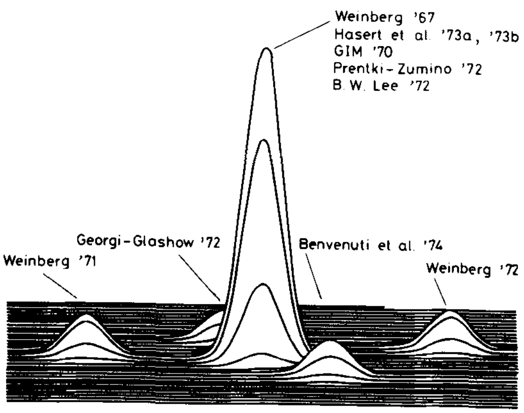

Fig. 7. Weak interactions co-citation activity plot for 3/74–2/75

ated by the neutral current experimental data, then, and they were not. Only *Georgi – Glashow* was pushed out of the center of the plot.

In Fig. 6 the major additions are three more experimental papers reporting neutral current events (another *Hasert* et al., *Benvenuti* et al., and *Aubert* et al.). At this time the *Georgi – Glashow* model is joined in the small hill lower-left by the B.W. *Lee* and *Prentki – Zumino* models. It is as if the weight of the neutral current evidence, not really favorable to B.W. *Lee* and *Prentki – Zumino* if it showed a broad range of neutral current processes, was also forcing the research community to place this model in disfavor. One month later, however, the B.W. *Lee – Prentki – Zumino* model is right back in the center as if, having decided that the neutral current evidence did not completely rule that model out, the physicists put it back in the center for additional consideration. (See Fig. 7).

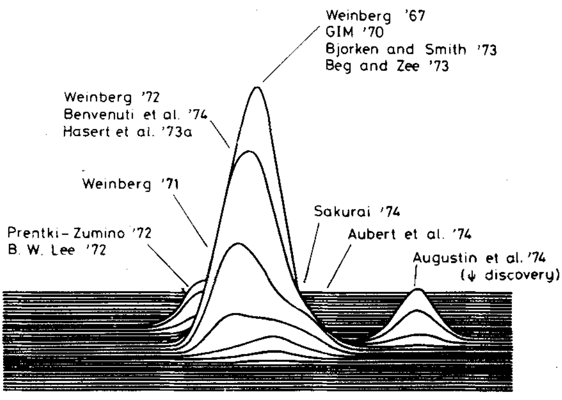

Fig. 8. Weak interactions co-citation activity plot for 7/74–6/75

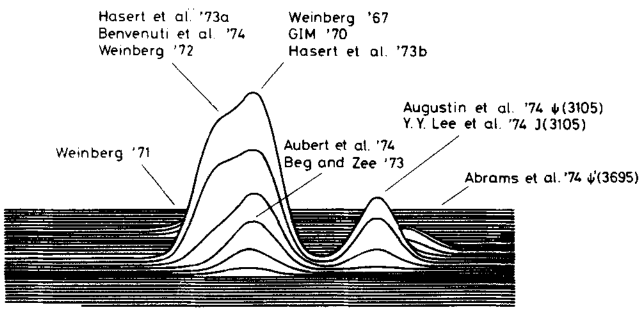

Fig. 9. Weak interactions co-citation activity plot for 9/74–8/75

With Fig. 8 a whole new kind of experimental evidence is shown emerging: the discovery of charmed hadrons (the so-called November 1974 Revolution – the discovery of the J/φ). These particles, which indicated the "charmed" or fourth quark, were required by the revised *Weinberg–Salam* model and were not a part of either *Georgi – Glashow* or B.W. *Lee – Prentki – Zumino*. With their discovery we see in Fig. 8 the elimination of the *Georgi – Glashow* model completely and the movement of B.W. *Lee – Prentki – Zumino* out of the center into a small hill behind and to the left. Two months later, Fig. 9, all of the competition to the *Weinberg–Salam* model has been eliminated, and *Weinberg–Salam* stands in the activity plot of Fig. 9 surrounded by its experimental confirmations.

Discussion

Based on extensive study of primary and secondary sources related to weak-electromagnetic unification, the sequence of events highlighted by the co-citation activity plots is a highly accurate rendition of the main features of what happened. It is interesting to note that the publication dates of new and important papers entering the plots were just about exactly the midpoints in the twelve-month periods from which we took citations. In other words, if one assigns the mid-point of the twelve-month period as the "real" time of the picture, one comes very close to the points in time at which at least the formal history of the field was taking place.

It is clear, in conclusion, that at least in very fast-moving fields like weak interactions annual co-citation plots necessarily obscure much of the dynamic of theory change. In particle physics, when things are "hot", changes of an important sort occur on a monthly time scale, and sometimes even faster than that. We have shown that co-citation analysis, suitably modified, is up to the task of aiding our attempts to understand such fast-moving intellectual change. This is certainly good news to researchers looking to exploit quantitative science indicators fully in the quest to understand the sociology and history of science.

References and notes

1. See, for example, H. G. SMALL, Co-Citation in the Scientific Litareture: 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, B. C. GRIFFITH, The Structure of Scientific Literatures I: Identifying and Graphing Specialties, *Science Studies,* 4 (1974) 17–40; B. C. GRIFFITH, H. G. SMALL, J. A. STONEHILL, S. DEY, The Structure of Scientific Literatures II: Toward a Macro- and Micro-Structure for Science, *Science Studies,* 4 (1974) 330–65; H. G. SMALL, A Co-Citation Model of a Scientific Speciality: A Longitudinal Study of Collagen Research, *Social Studies of Science,* 7 (May 1977) 139–66.
2. D. SULLIVAN, D. H. WHITE, E. J. BARBONI, Co-Citation Analyses of Science: An Evaluation, *Social Studies of Science,* 7 (1977) 223–40; D. SULLIVAN, D. H. WHITE, E. J. BARBONI, Problem Choice and the Sociology of Scientific Competition: An International Case Study in Particle Physics, *Research in the Sociology of Knowledge, Sciences, and Art,* Vol. III (1980), forthcoming; D. H. WHITE, D. SULLIVAN, Social Currents in the Weak Interactions, *Physics Today,* (April 1979), 40–7.
3. For a recent update and explanation of weak-electromagnetic unification suitable for the layman, see A. L. ROBINSON, Particle Theory: Stanford Electron Experiment Closes Options, *Science,* 201 (21 July 1978) 245; and S. COLEMAN, The 1979 Nobel Prize in Physics, *Science,* 206 (14 November 1979) 1290–2.
4. S. WEINBERG, A Model of Leptons, *Physical Review Letters,* 19 (1967) 1264–6.
5. A. SALAM, in *Elementary Particle Theory* N. SVARTHOLM (Ed.), Stocholm; Almquist and Forlag, 1968, p. 367.

6. See our "The Role of Experiment . . . ," *op. cit.*, note 1, for documentation.
7. G. t'HOOFT, Renormalizable Langrangians for Massive Yang-Mills Fields, *Nuclear Physics B*, 35 (1971) 167–88.
8. In particle theory the particles are thought to generate fields through which the particles interact. These fields are also thought to be particles, with the idea that one particle interacts with another by emitting a mediating particle, creating the field. This can be illustrated for the weak interaction by the diagram in Fig. 1a which shows the scattering of a neutrino by a neutron ($\nu_e + n \rightarrow e + p^+$). The ν_e "emits" a charged intermediate vector boson ($W\pm$), the as yet undiscovered but hypothesized particle which transmits the weak force, changing it into an electron. The neutron then absorbs the W^-, changing it into a proton. The W^- in that diagram is the charged current. An example of a particle *decay* that is mediated by the weak charged current is shown in Fig. 1b, neutron beta decay ($n \rightarrow p^+ + e + \nu_e$). An example of a neutral current interaction of a kind required by the WEINBERG–SALAM model is shown in Fig. 1c. WEINBERG proposed that, in addition to charged currents mediated by a $W\pm$, there must also be neutral currents, mediated by a massive neutral particle WEINBERG called the Z°.
9. H. GEORGI, S. L. GLASHOW, Unified Weak and Electromagnetic Interactions Without Neutral Currents, *Physical Review Letters*, 28 (1972) 1494–7.
10. B. W. LEE, Model of Weak and Electromagnetic Interactions, *Physical Review D*, 6 (1972) 1188–90.
11. J. PRENTKI, B. ZUMINO, Models of Weak and Electromagnetic Interactions, *Nuclear Physics B*, 47 (1972) 99–108.
12. S. L. GLASHOW, J. ILIOPOULOS, L. MAIANI, Weak Interactions with Lepton-Hadron Symmetry, *Physical Review D*, 2 (1970) 1285–92.
13. C. BOUCHIAT, J. ILIOPOULOS, PH. MEYER, An Anomaly-Free Version of Weinberg's Model, *Physics Letters*, 38B (1972) 519–23.
14. W. LEE, Experimental Limit on the Neutral Current in the Semi-leptonic Processes, *Physics Letters*, 40B (1972) 423–5.

Appendix
Papers cited in co-citation activity plots

ABRAMS, G. S., et al., Discovery of a Second Narrow Resonance in e^+e^- Annihilation, *Physical Review Letters*, 33 (1974) 1453–55.

AUBERT, B. et al., Further Observation of Muonless Neutrino-Induced Inelastic Interactions, *Physical Review Letters*, 32 (1974) 1454–7.

AUGUSTIN, J. E., Discovery of a Narrow Resonance in e^+e^- Annihilation, *Physical Review Letters*, 33 (1974) 1406–8.

BEG, M. A., ZEE, A., Hadron Structure and Weak Interactions in a Gauge Theory, *Physical Review Letters*, 30 (No. 14) (1973) 675–75.

BENVENUTI, A., et al., Observation of Muonless Neutrino-Induced Inelastic Interactions, *Physical Review Letters*, 32 (1974) 800–3.

BJORKEN, J. D., LLEWELLYN SMITH, C. H., Spontaneously Broken Gauge Theories of Weak Interactions and Heavy Leptons, *Physical Review D*, 7 (No. 3) (1973) 887–902.

BOUCHIAT, C., et al., An Anomaly-Free Version of Weinberg's Model, *Physics Letters*, 38B (1972) 519–23.

CLARK, A. R., et al., Experimental Limits on the Decays $K^0_L \rightarrow \mu^+\mu^-, e^+e^-$, and $\mu\pm e\mp$, *Physical Review Letters*, 36 (1971) 1667–71.

GEORGI, H., GLASHOW, S., Unified Weak and Electromagnetic Interactions Without Neutral Currents, *Physical Review Letters*, 28 (1972) 1494–7.

HASERT, F. J., et al., Search for Elastic Muon-Neutrino Electron Scattering, *Physics Letters*, 46B (1973) 121–4.

HASERT, F. J., et al., Observation of Neutrino-Like Interactions Without Muon or Electron in the Gargamelle Neutrino Experiment, *Physics Letters*, 46B (1973) 138–40.

LEE, B. W., Model of Weak and Electromagnetic Interactions, *Physical Review*, 6D (1972) 1188–90.

LEE, W., Experimental Limit on the Neutral Current in the Semileptonic Processes, *Physics Letters*, 40B (1972) 423–5.

LEE, Y. Y., et al., Experimental Observation of a Heavy Particle J. *Physical Review Letters*, 33 (1974) 1404–6.

MARTIN, B. R., et. al., Neutral Kaon Decays into Lepton Pairs, *Physical Review*, D2 (1970) 179–200.

PAIS, A., TREIMAN, S., Neutral-Current Effects in a Class of Gauge Field Theories, *Physical Review*, 6D (1972) 2700–3.

PASCHOS, E. A., WOLFENSTEIN, L., Tests for Neutral Currents in Neutrino Reactions, *Physical Review*, 7D (1973) 91–5.

PRENTKI, J., ZUMINO, B., Models of Weak and Electromagnetic Interactions, *Nuclear Physics*, B47 (1972) 99–108.

SAKURAI, J. J., Weak Interactions and the Baryonic Current, *Physical Review*, 9D (1974) 250–2.

t'HOOFT, G., Renormalizable Lagrangians for Massive Yang-Mills Fields, *Nuclear Physics*, 35B (1971) 167–88.

WEINBERG, S., Model of Leptons, *Physical Review Letters*, 19 (1967) 1264–6.

WEINBERG, S., Physical Processes in a Convergent Theory of the Weak and Electromagnetic Interactions, *Physical Review Letters*, 27 (1971) 1688–91.

WEINBERG, S., Effects of a Neutral Intermediate Boson in Semileptonic Processes, *Physical Review*, 5D (1972) 1412–7.