Marietta Blau’s Work After World War II
Arnold Perlmutter
Department of Physics
University of Miami
Coral Gables, Florida 33124
completed, October 27, 2000

This paper has been translated into German and will be included, in a somewhat altered form, in a book *Sterne der Zertrümmerung, Marietta Blau, Wegbereiterin der Moderne Teilchenphysik*, Brigitte Strohmaier and Robert Rosner, eds., Boehlau Verlag, Wien.
A. Introduction

While it is clear that the seminal work of Dr. Marietta Blau was done in the 1920's and especially in the 1930's, it is also evident that her separation from the great research centers from 1938 to 1944 had a devastating effect on her productivity. It was during this period that Cecil F. Powell, at Bristol University, made use of Blau's earlier tutelage on the preparation and analysis of photographic emulsions. According to Blau's conversations with me (much later), she consulted with Ilford in the 1930's to improve emulsion sensitivity and uniformity, and presumably had also imparted crucial lore of the technique to Powell. C.F. Powell, who had been a student of C.T.R. Wilson, had employed cloud chambers in a wide variety of studies in vulcanology, mechanical engineering, and nuclear physics. In 1938 and 1939 Powell's experimental efforts turned to the use of photographic emulsions to investigate neutron interactions, and then to nuclear reactions\(^1\). With the coming of the war and then the British nuclear atomic bomb project, Powell established a formidable laboratory and collaboration for the analysis of emulsions and for their improvement by Ilford and Kodak. Thus it came about that Powell and his collaborators discovered the pion in emulsions, exposed in 1947 at high altitudes in the Bolivian Andes and Pyrenees. Powell then received the Nobel Prize for Physics in 1950 “for his development of the photographic method of studying nuclear processes and for the resulting discovery of the pion (pi-meson), a heavy subatomic particle.”

It stretches one’s credibility that Blau should not have shared in the first part of the citation, if not for the prejudices or narrowmindedness of the Swedish Academy, demonstrated on several other occasions (at least in the cases of Lise Meitner and C.S. Wu). The great Erwin Schrödinger himself twice nominated Blau for a Nobel Prize\(^2\). There certainly may have been other nominations. Consider, for example, this quote from the classic text on atomic physics by Max Born\(^3\):

“Another great advance was made by two Viennese ladies, Misses Blau and Wambacher (1937), who discovered a photographic method of recording tracks of particles. The grains of emulsion are sensitive not only to light but also to fast particles; if a plate exposed to a beam of particles is developed and fixed the tracks are seen under the microscope as chains of black spots. Their quality depends very much on the size of the grains, and special emulsions with very small and dense grains have been developed (Ilford, Kodak).

“The photographic tracks are some thousand times shorter than corresponding tracks in air, because of the higher stopping power of the solid material; they are of the order of
some microns. The advantages of this method are its extreme simplicity, the continuity of sensitiveness, and the great number of events recorded on one plate. On the other hand, high-quality tracks are observed and micro-photographed with oil-immersion objectives which have a narrow depth of focus; hence only a restricted part of a track appears sharp, and several photographs have to be taken with different focus.”

My own knowledge of Marietta Blau’s post war research is based somewhat on my personal contacts with her during 1956-1963 in Miami and Vienna (as well as with some of her earlier colleagues), but mainly from reading her papers written after 1945, and from several informative references. The incisive book by Peter Galison, *Image and Logic, A Material Culture of Microphysics*\(^1\), and a subsequent article in *Physics Today*\(^4\) contain much useful information on Blau’s life. Other sources include Leopold Halpern’s biographical sketch \(^5\), the internet web-page by Nina Byers, \(^6\) and the elaborate volume prepared by C.F. Powell, P.H. Fowler and D.H. Perkins. \(^7\)

As I stated above, Blau’s six year residence in Mexico effectively removed her from serious research. Galison states that she had to teach 24 hours a week, and in addition suffered the theft of materials that would have allowed her to establish a research laboratory.\(^1\) I do not know much about her years in Mexico, except for recalling that she worked hard to support her infirm mother, and that in the circle of European intellectuals that she frequented was also the famous exile, Leon Trotsky. In that group was also an erratic young man who was later identified as Trotsky’s assassin. Marietta said that she and her friends attempted to warn Trotsky of the man’s dangerousness, but that he dismissed their entreaties, and was murdered in 1940. The prevalent view is that the assassin was a Stalin agent, but I have no other information as to its veracity.

B. The First Scintillation Counter

I do not know of the circumstances that brought her to New York in 1944, when she first went to work for the International Rare Metals Refinery and later the Canadian Radium and Uranium Corporation. What is clear is that her frustration at being pent up in scientifically remote Mexico led to an explosion of creative activity, in spite of the fact that she at first found herself at the periphery of the American research establishment.

Blau’s first paper published after she came to the United States was in 1945, with B. Dreyfus \(^B46\). As far as I can tell, it was the first example to be published in the open literature on the use of the photomultiplier tube in conjunction with scintillating target, a ZnS screen to detect radioactive emissions. They actually measured the phototube current as a function of distance between the \(\alpha\)-particle source and the phototube, and observed a clear inverse square-law dependence. The paper is striking in its straightforwardness and simplicity.

According to the book by J.B. Birks\(^8\), the device was actually used as a dosimeter but it can be regarded as the first rudimentary scintillation counter, a great advance over
manual counting of light flashes by human observers, as pioneered by Rutherford and his collaborators. Actually, the first application of the photomultiplier to scintillation counting was done by Curran and Baker\textsuperscript{9}. The work was described in a classified report issued in 1944, but was only published in the open literature in 1948. In 1947-1948, Marshall, Coltman and collaborators published a series of papers\textsuperscript{10} describing the design and performance of a photomultiplier scintillation detector, with a well-designed optical system for reflecting the scintillation emission onto the photocathode. They reported the detection and counting of $\alpha$-particles, protons, fast electrons, $\alpha$-rays, $\gamma$-rays and neutrons.

At about the same time, in Germany, Hartmut Kallmann and his student I. Broser published papers on measurements on scintillations produced by $\alpha$-particles, $\beta$-rays and $\gamma$-rays in $ZnS$, $CaWO_4$, $ZnSO_4$ and naphthalene\textsuperscript{11}. That large transparent blocks of naphthalene, the first organic scintillator and first large volume scintillator, could produce the photons from $\beta$-rays and $\gamma$-rays and subsequently be registered by the photomultiplier tube, represented a major advance for the new technique. In 1948, Bell showed that crystalline anthracene is an even more suitable phosphor and that it gives scintillation pulses about five times the amplitude of those from naphthalene.\textsuperscript{12}

Robert Hofstadter discovered that $NaI$ crystals, activated with thallium, give higher pulses than anthracene, and because of the high photoelectric absorption of the heavier iodine constituent, such crystals can be used for $\gamma$-ray spectroscopy of very weak sources\textsuperscript{13}. Further developments, using liquid, plastic and crystal scintillators, soon made the scintillation counter a pre-eminent detector in nuclear and particle physics. In recent years, scintillation counting techniques have found a wide variety of important applications in biology, chemistry, geology, medicine, atmospheric science, and industry.

Thus, one can trace the evolution of the modern scintillation counter, using photomultiplier tubes, from the very humble device produced by Marietta Blau to its ubiquitous application in all science and technology.

As a personal footnote, it is interesting to note that the development of scintillation counters by Robert Hofstadter were critical components of his experiments on the scattering of (then) high energy electrons (600 MeV) from protons and heavy nuclei during the 1950’s, for which he received a Nobel Prize for Physics in 1961. When I was a graduate student under Hartmut Kallmann at New York University during 1951-1955, several of my colleagues and postdocs were working on the properties of organic phosphors for counting $\gamma$-rays and $\beta$-rays (I worked on the photoconductivity of $ZnS$ and $CdS$ phosphors). During that period, I recall several visits by a shy, polite, young man, Robert Hofstadter, who came from Princeton University to consult with Hartmut Kallmann on scintillation counters. A bit later, Hofstadter moved to Stanford University, where he continued his classic studies of nuclear structure using the high energy electrons.

It is a further somewhat remarkable confluence of trajectories that Robert Hofstadter and I became friends when he came frequently during the 1960’s, 1970’s and 1980’s to the
Center for Theoretical Studies at the University of Miami to visit my colleague, Behram Kursunoglu and me, and also to participate in a number of the Coral Gables Conferences on Symmetry Principles and High Energy Physics, and in several projects of the Center.

During my years in Kallmann’s laboratory, perhaps in 1953 and 1954, I recall that he received two of those middle-of-the-night phone calls from journalists in Stockholm, with the news that he was on a list of two or three finalists to receive the Nobel Prize for Physics. Though he was recognized as one of the principal architects of the scintillation counter, Kallmann shared the disappointment of not gaining this recognition with Marietta Blau, although for perhaps quite different reasons. Actually, no person received the Nobel Prize for the scintillation counter, a formidable device.

It is unfortunate that Blau did not further pursue the development of the scintillation counter. I would venture the explanation that because she was working for profit-making companies, she was not free to pursue her own inclinations, but had to follow the directives of management. In his biographical sketch, Leopold Halpern relates a conversation with Otto Frisch, who said that Blau’s method of using photomultipliers later became of great importance.

C. Research on Radioactivity

During the following two years Marietta Blau carried out a number of projects involving measurements on radioactivity. Given that at this time her employers were mining companies, i.e., International Rare Metals Refinery, Inc. and Canadian Radium and Uranium Corporation, it is not surprising that her work involved the studies of devices and procedures that make use of radioactive substances. This was certainly true of her work on the scintillation counter described in the previous section. In that paper she suggested the use of a radium preparation and the ZnS screen as a secondary standard in calibrating the intensity of any light source. One needs to know only the spectral sensitivity of the photomultiplier (expressed in amperes/lumen), and to find the efficiency of the fluorescent screen, defined as the ratio: energy of light emitted by the screen/energy of alpha particles absorbed by the screen. She concludes that article by suggesting that the device is not limited to alpha-or-beta-measurements, but suggested its application to measurements of strong neutron sources. However, this further work, which would surely have led to advances in her scintillation counter, did not appear, corroborating my surmise that the corporate leaders chose not to pursue this subject any further.

Her next publication, on “Radioactive Light Sources”, was co-authored with I. Feuer, and appeared in the Journal of the Optical Society. In this paper Blau examined further the use of radioactive preparations to produce light from fluorescent screens. She notes that fluorescent screens mixed with radioactive material, such as those used as paint for watch and instrument dials, change the luminescent emission because the continual bombardment by alpha particles changes the crystal structure of the phosphor. But separation of radioactive source from the fluorescent screen allows irradiation of the screen during
relatively short intervals, when the light output is quite constant. Certain phenomena of fatigue which occur after a somewhat longer or stronger irradiation are transitory, and the initial efficiency is restored after a short rest.

The most convenient radioactive preparations – if absolute constancy is required – is radium (half-life 1500 years) placed on a metal foil in such a manner that there is no escape of emanation and a minimum absorption of the emitted alpha-particles. The constants of these radium foils (number and energy of the alpha-particles emitted) can be tested very accurately. The only inconvenience of these preparations is the penetrating gamma radiation, which may be disturbing in case of radioactive light standards of great intensity and luminous surface, making necessary the use of stronger radium preparations. She suggests the use of polonium instead of radium. Polonium emits practically no penetrating radiation, and although its half-life is only 140 days, the intensity of the light source can be calculated exactly from the exponential decay law.

The paper goes on to discuss the experimental arrangements of radioactive sources (both radium and polonium) and fluorescent screens, showing the dependence of light intensity on distance of the sources from the screens, and on the absorption by aluminum foil.

Blau and Feuer now enumerate a number of applications and advantages of this arrangement. The radioactive light standards could be very useful for colorimetric measurements and similar purposes. They have the advantage of being easier to handle than ordinary light standards as they do not involve electric currents which must be kept constant. Besides, in the case of radioactive light standards, the light output can be varied by varying the intensity of the radioactive preparation or the absorption of the radiation, whereas in the case of light standards, an increase in current or absorption influences the spectral distribution of the source.

They emphasize that the advantage of radioactive light standards is even greater on cathode-ray screens (television, oscilloscopes or [now] computer) or of the luminous compound used for such screens. They compare the effects of α-particles and cathode rays, and say that the radioactive source can be directly introduced into the cathode-ray tube to control and measure the thickness of the screen. As this can be done before the tube is closed and evacuated, it might save time and work.

They conclude the article with designs where the radioactive standard is used to control and regulate the photoelectric section of an x-ray apparatus, and another where a device is used to control the maintenance of the level of a bar, disk, or plate. These are clearly industrial applications.

The next paper was co-authored during the same year (1946) with H. Sinason and O. Baudisch, on “Radioactivation of Colloidal Gamma Ferric Oxide” in Science$^B48$. This work clearly addresses important issues in medicine and cancer therapy.
Apparently, the lattice structure of $\gamma Fe_2O_3$ is incomplete, containing so-called “interstitial spaces” (atomic holes) which in the more stable lattice of $\alpha Fe_2O_3$, are filled up by ferric ions. Gamma ferric oxide in colloidal form may be injected directly into the blood stream. It had been noted that colloidal $\gamma Fe_2O_3$ has no toxic effects on living cells; the cells proliferate and, after some time, have eliminated and are entirely free of all the iron particles.

It is easily seen that the reticulo-endothelial cells in the body can be influenced and their antibody actions stimulated if the colloidal $\gamma Fe_2O_3$ particles are combined with some therapeutically acting material, such as certain radioactive substances.

After rejecting the use of radium and polonium, they finally chose the active deposits of radon $-RaA, RaB, RaC-$ as activators. Because of their lifetimes, the injections would decay with the lifetime of $RaB$ (26.8 minutes). After considering various methods of activation of metal disks, they adopted the method of Blau’s earlier mentor, H. Petterson$^{14}$. They conclude that there is no limit as to the charge of $RaB - RaC$ that may be applied with the $\gamma Fe_2O_3$. They remark that it may be even more advantageous to use, instead of $RaB - RaC$, the active deposit of thorium, Th B and Th C. Th B has a longer half-life (10.6 hours), and Th C is the last radioactive element produced in this series, as Th D is already a stable element.

Finally, they suggest that if we reduce by the radio therapeutic method the number of circulating lymphocytes, there is some hope to reduce also the growth and occurrence of tumors.

It is interesting to note that in this work, Blau made an apparently effortless transition from her early work on medical physics and polonium preparations$^{B15}$. I am not competent to judge the importance of this work for later developments in medical physics, but I am impressed by its motivation and erudition.

The next paper from this period was co-authored with J. Carlin, on “Ionization Currents from Extended Alpha-sources” in the Review of Scientific Instruments$^{B49}$. The work studies the ionization currents from extended two-dimensional radioactive alpha-particle sources, with immediate application to a device for measuring surface areas.

They first address the problem of the influence of the recombination of ions on the ionization current produced by the radiation. They study carefully the influence of voltages on the electrodes of the ionization chamber on the saturation ionization current. In general, the problem of predicting the saturation current or voltage by theoretical computations is a cumbersome and complex task, notably because of the constants involved, which have not yet been precisely determined and are usually derived from partially limited theories.

By choosing one particular geometrical arrangement of the experimental apparatus, however, the problems become considerably simplified and the relationships between satu-
ration current and voltage, if determined experimentally for one intensity, can be extended by calculations to any other source intensity.

They describe in some detail the experiments on a large parallel-plate condenser as the ionization chamber, contained in a cubic housing 30 cm on each side, with the plates of the chamber each possessing a diameter of 20 cm. The insulated electrode which led to an electrometer was protected by a guard-ring. The sensitivity of the instrument, a Compton electrometer, was recorded and followed during the experiments by measurements with a $U_3O_8$ standard.

The sources employed were circular brass or nickel disks uniformly plated with polonium (3.83 cm alpha-particle range). Both the disk area and polonium density were varied. The uniformity of plating on each disk was determined photographically and only the most uniform preparations, within 5 percent, were studied. The intensities of the more active disks were actually measured by the scintillation counter of Blau and Dreyfus described in Part B of this paper. They go on to study in great detail how the saturation current and saturation voltage are influenced by geometrical arrangements, and especially by the area of the source.

They finally apply their studies to describe a measuring instrument for the determination of plane areas, which they call a “polonium integrator”, where unknown areas interposed between the plates of the ionization chamber reduce the total ionization current by an amount proportional to the area. They actually show a model of the instrument, which can measure areas from 0 to 28 square inches (175 square cm) with an error not exceeding one percent.

During the same year, Blau and Sinason published a short paper “Routine Analysis of the Alpha Activity of Protactinium Samples” in Science. The classical method of measuring alpha activity of protactinium consists of the following procedure: Samples containing protactinium are painted uniformly on metal disks, as thin as possible in order to provide minimum absorption for the alpha-particles of protactinium. The current produced by the alpha-particles is measured by an electrometer or electroscope and compared with that of a uranium standard.

The current obtained by the protactinium sample, expressed in e.s.u., is used for the determination of the number of alpha-particles emitted/sec, $N$, $J_{esu} = N \cdot e \cdot n$, where $e$ is the electric charge of the ion; and $n$ is the number of ion pairs produced by an alpha along its path through the ionization chamber. Knowing the half-life of protactinium, the number of alpha-particles emitted by, for instance, 1 mg of protactinium can be calculated. One mg of protactinium emits (in all directions) $1.85 \times 10^6$ alpha-particles/sec.

The fraction $\frac{2N}{1.85 \times 10^6}$ gives the amount of protactinium (in mg) which the sample contains, provided that the absorption of the layer of foreign material can be neglected. But this can never be realized, and the maximum value of the above ratio corresponding to
zero absorption has to be determined by extrapolation, measuring samples of decreasing total weight. The ratio (current)/(sample weight) increases with decreasing layer thickness and, plotting these values versus sample weights, gives a curve whose intersection with the ordinate gives the actual value of the protactinium content per unit weight of the material.

It is evident that this method is time consuming and subject to various errors, especially if the sample is very dilute. Moreover, the method presents a great many difficulties in plants where other radioactive products are present. Blau and Sinanson decided to apply for routine measurements the method of measuring the samples in thick (alpha-saturated) layers, especially since it affords less handling of the material, which after suitable grinding, is fitted into special, strictly uncontaminated dishes. They proceeded by adding a known quantity of polonium to $\text{ZrP}_2\text{O}_7$ samples of low protactinium content. They were then able to calculate with considerable accuracy the fractional content of protactinium in their sample.

They recommend the same procedure in the case of other alpha emitters of appreciable half-life, e.g., plutonium and other transuranic elements, since the addition of polonium, due to its high specific activity, does not alter the absorption in the sample.

Finally, in 1948, Blau and Carlin published a paper, “Industrial Applications of Radioactivity” in the journal *Electronics*.\textsuperscript{51} If I am permitted a somewhat cynical comment, this paper does not describe new results, but serves as a kind of announcement of new radioactive devices to the engineering community. It makes use of the results of Blau and her collaborators over the previous three years, and cites as references six patent applications of Blau and collaborators, as well as two other patent applications, presumably also by other employees of her employers. Missing from the list of patents is the seminal work of Blau and Dreyfus\textsuperscript{46} on the scintillation counter, which I described in Section B and in the beginning of Section C. They give technical details of representative new devices based on radioactive sources, serving as resistors, electrostatic voltmeters, light sources, tube cathodes, area measurers, liquid level detectors, galvanometers, semimicrobalances, leveling systems, and micrometers.

This paper could be looked upon as the swansong of Blau’s work for industrial companies.

In the same year, Blau wrote a paper with J.E. Smith, still as a member of Canadian and Radium Corp., on “Beta-ray Measurements and Units”, which transcended her papers of the previous four years, although they made use of some of her earlier experiments\textsuperscript{53}. Here she attempted to establish a sensible unit to measure the ionizing power of beta-rays in condensed materials.

The authors discuss the introduction of a new unit proposed especially for medical research, “roentgen equivalent physical” or rep, by Evans\textsuperscript{15}. This unit later came to be called “roentgen equivalent man” or rem. [The modern SI unit for dose equivalent is
“sievert” (Sv), where 1Sv = 100 rem. Blau and Smith do not suggest the replacement of the roentgen unit as far as x- and gamma radiation are concerned, but in the case of beta radiation, it would appear that a more convenient unit is desirable.

They describe the difficulty of making definitive dosage measurements on beta rays. While the rep unit indicates the ionization density in the affected tissue, it does not take into account the amount of tissue which is actually affected, nor does it give any information about the total energy administered.

They suggest that a more convenient unit would be a quantity proportional to the total number of ions formed by the incident radiation. They propose a convenient and practical measurement which can be used by persons not very familiar with radioactive measurements. They propose the use of a photomultiplier tube and appropriate low persistence fluorescent screens, emitting light in the range of maximum sensitivity of the photocell. This is a clear application of the first scintillation counter developed by Blau and Dreyfus.

They go on to describe experiments with beta rays and various thicknesses of luminous screens and find good agreement between theory and experiment. There is a quite prescient statement where they propose that the method could be improved by the use of organic phosphors such as naphthalene, which are more transparent to their fluorescent light than inorganic phosphors. Here they quote Coltman and Marshall, among others since they presumably have not yet seen the reports of Kallmann and Broser on naphthalene.

Their method allows them to obtain one of the proposed units, either Q or Q/E or Q/R, where Q is the total number of ions, E the energy and R the range of the radiation.

They then describe their apparatus, which is a rather different upgrade of their first scintillation counter, and which permits them to examine ten fluorescent screens with a flick of a dial, and thus record the photoelectric current, for various measurements.

This paper is quite remarkable both in that it addresses fundamental questions of radioactive dosage, and proposes the use of a quite novel instrument to make radioactivity measurements. It reinforces my earlier conjecture that Blau made a fundamental contribution to the scintillation counter.

D. Marietta Blau at Columbia University

In 1948, the newly established Atomic Energy Commission set up Blau at Columbia University as a research physicist, and then two years later moved her to Brookhaven National Laboratory, which was just then turning to high energy research.

Her subsequent research at Columbia and Brookhaven represents a sharp departure
from that of her previous three years for the mining companies. Although I have no direct knowledge of the circumstances of this transition, it is clear from reviewing her papers of the following period that she exclusively returned to her primary research interest, the use of photographic emulsions, and their application, to study the phenomena of high energy physics, with exceptional dedication and energy. While it is true that she demonstrated enormous skill and loyalty in her studies of radioactivity for the mining companies during 1944-1947, she appears to have thrown herself totally into the emulsion work from which she had been separated for ten years, while she was effectively deprived of the recognition she should have had. Her output during this time is prodigious, in spite of the fact that she was effectively an outsider in the American research establishment.

In 1948, M. Blau, then at Columbia University, and J.A. Felice, then at Brookhaven National Laboratory, published a paper, “Development of Thick Emulsions by a Two-Bath Method”\(^{B52}\). Their proposal is alternative to the method of the so-called temperature development on Ilford, C2, 200 micron plates by Dilworth, Occhialini, and Payne\(^{16}\), and is probably applicable to thicker emulsions.

They adapted a method used by Crabtree\(^{17}\) et al, which was used for the uniform development of large quantities of motion picture film. The developer is divided into two baths. The first part contains the developing agent part of the sodium sulfite and potassium bromide, but no alkali. The second bath contains all the necessary constituents of an ordinary developer plus an additional amount of alkali. They then give an explicit recipe for the two baths.

Because the temperature is kept constant, the danger of reticulation is avoided. Proton tracks in the emulsion had their normal grain density while the background fog was very low, and the plates appeared to be uniformly developed throughout the emulsion. This method is discussed by Galison\(^1\), Rotblat\(^{18}\), and Powell et al\(^7\), and appears to be a significant contribution to the technique of emulsion development.

Thus, Blau’s first foray into the emulsion field, after ten years absence, led to an important advance, characteristic of her insight and meticulousness.

Blau’s next papers \(^{B54,B55}\) came out in the following year, and were on “Grain Density in Photographic Tracks of Heavy Particles”. Here she dealt with one of the three principal parameters of particle track measurements in emulsion, the other two being the energy-range relations and the scattering effect, in determining the energy and mass of nuclear particles. (It should be noted that grain density is the number of developed silver bromide grains per length of particle track, and generally increases as the ionization probability increases. It plays a role similar to ionization energy in work with cloud chambers or proportional counters.)

She refers first to an empirical relation between grain density and range which was established by workers in Powell’s laboratory and others \(^{19,20,21,22}\). She then describes
the development of theoretical formulas for the dependence of grain density on range and energy, based on the fundamental theory of Debye and Hückel\textsuperscript{23}, who solved the problem of highly ionized gaseous atmospheres or “strong electrolytes”, by assuming that the mobility of ions depends on the ion concentration. Comparing her formulas with the empirical results of the Bristol group\textsuperscript{19,20,21}, she found very good agreement.

It is quite striking that in this paper, and in the previous one on emulsion development, Blau methodically reeducated herself on the techniques of experimental emulsion work and acquainted herself with the principal technical developments since 1938. In both papers she made significant contributions to the field.

Blau’s following paper was done with M.M. Block and J.E. Nafe\textsuperscript{B56}, on “Heavy Particles in Cosmic Ray Stars”. This signalled the beginning of her particle studies at Columbia University, where she was apparently brought in to instruct the researchers on the techniques of using photographic emulsions at the Nevis cyclotron, which was then under construction. Apparently, for practice, they exposed some emulsions in balloons, and came upon a strange event in a cosmic ray star\textsuperscript{24}. In those years, as the “elementary particle zoo” was being assembled, each event was afforded special attention. In this case, the event was interpreted as the capture of a $\tau$-meson (now called a K-meson or kaon) by a bromine or silver nucleus in the emulsion.

The next paper, by Blau, Ruderman, and Czechowski, on “Photographic Methods of Measuring Slow Neutron Intensities” appeared in 1950\textsuperscript{B57}. The relative slow neutron sensitivities of $\beta$-sensitive emulsions, x-ray film-indium foil combinations, and boron-loaded plates were investigated. Since the detection efficiency depends upon the neutron energy, experiments were made with epithermal (0.3-10,000eV), thermal (.01 - 0.3eV) and cold (< .01eV) neutrons. $\beta$-sensitive emulsions and x-ray-indium combinations are about equally useful for the detection of epithermal neutrons. B\textsuperscript{10} loaded plates, which are best for detection of thermal and cold neutrons, have the following advantages: very low neutron intensities can be measured by counting of $\alpha$-tracks, neutrons can be counted in the presence of $\beta$- and $\gamma$-radiation, the number of $\alpha$-tracks is independent of the development conditions, and a wide range of intensities can be measured with a single plate.

Blau’s next publications, during the same year, were on a “Semi-Automatic Device for Analyzing Events in Nuclear Emulsions” in the Physical Review, with S. Lindenbaum and R. Rudin \textsuperscript{B59,B62}. This was a landmark work that led not only to future advances in analyzing emulsion tracks, but also portended much later developments in the analysis of bubble chamber, spark chamber, and streamer chamber photographs. The contributions of Marietta Blau to the Nevis Cyclotron experiments and to the semi-automatic device described in this paper are discussed cogently by Sam Lindenbaum in Appendix II of this paper\textsuperscript{25}. I must confess the sin of indolence in that I have not scoured the literature for references to this work in later developments of automatic devices for scanning and measuring visual tracks in detectors. (I am not a dedicated historian of science). When one considers the rudimentary level of computers and optical devices four decades ago, the
capabilities of this device are remarkable, and deserving of admiration.

The instrument is built around a microscope with a motor-driven stage, moved by selsyn motors in two dimensions. The accuracy of gears, feed screws etc., is such that dimensions can be measured to within 0.2 micron. These selsyn motors are fed from identical selsyn generators which are driven from a steering unit so that the photographic plate can be moved in any direction and with any desired speed up to 25 microns per second. For convenience, the arrangement is controlled by a steering wheel and the speed is controlled by a foot pedal. There is also a recording chart that moves at a speed of 2000 times that of the stage. The image of the plate is observed by the operator through the eyepiece and at the same time is projected on a small slit before a photomultiplier tube.

The measurements are done quite rapidly and easily. For example, a conservative estimate of the driving time for the grain density record of a 2000 micron track is about 10 minutes. The system is adaptable to the measurement of high Z tracks \((3 \leq Z \leq 26)\), especially by the measurements of \(\delta\)-rays (electron tracks emanating from the main track). They compare their measurements with those of Bradt and Peters on large Z nuclei and P. Freier, and find good agreement. The paper is notable for its completeness and erudition.

A brief paper, “Dependence of High Altitude Star and Meson Production Rates on Absorbers” written by Blau, Nafe and Bramson was given as an abstract in the Physical Review in 1950. They studied the effects of copper and lead absorbers on the rate of star and meson production. Comparing star and meson production in the different sets of plates under varying thickness of absorbers, they observed distinct transition effects.

E. Marietta Blau at Brookhaven National Laboratory

After her move to Brookhaven National Laboratory in 1950, Marietta Blau published her first paper, an abstract, “Stars Induced by High Energy Neutrons in the Light Elements of the Photographic Emulsions” in the 1952 Physical Review, with A.R. Oliver. They irradiated emulsions with the 300 MeV neutron beam of the Columbia cyclotron and determined the ratio of stars induced in the light elements to those induced in the heavy elements of the emulsion. Assuming the cross section is a linear function of \(A^{2/3}\) (where \(A\) is the atomic mass), the ratio \(N\)-light/\(N\)-heavy should be 0.27. Counting all stars with \(\geq 2\) prongs in both emulsion and gelatin layers, they obtain a value for this ratio of \(0.179 \pm 0.024\). Because of the uncertainty connected with the recognition of 2-prong stars only 2-prong stars showing a distinct recoil fragment were considered. On the other hand, they accepted all 2-prong gelatin stars assuming that in all cases an additional short prong may have been lost in the gelatin. Even though these conditions favor a higher ratio \(N\)-light/\(N\)-heavy = \(0.213 \pm 0.026\) it is still lower than the calculated value, showing increased transparency of light nuclei. If one takes into account the 0-, 1-, and 2-prong stars, \(N\)-light/\(N\)-heavy would still be further decreased since for the light elements 3- and 4- prong stars are probably favored.
In the following year, 1953, Blau, Oliver and Smith expanded on the previous abstract with a longer paper on “Neutron and meson stars induced in the light elements of the emulsion” in the Physical Review B65.

Again, they made use of G5 emulsions, laminated with gelatin layers of 5-8 microns. They followed the ideas of Harding28, Menon, Muirhead and Rochat,29 and Hodgson30 of introducing very thin layers of gelatin between photographic emulsion pellicles in order to separate the light and heavy emulsion elements in experiments investigating the cross section of disintegration processes of particles incident on the emulsion.

They expand somewhat on the results of the previous paper on 300 MeV neutrons, finding that the mean prong number in stars from light nuclei is greater than in heavy nuclei. The $\alpha/p$ ratio for light nuclei is approximately 0.75, and $25\pm5$ percent of all stars have a recoil with charge $\geq 3$. From the angular distribution of black tracks in light element stars, and the forward excess of black prongs in heavy elements, they conclude that, at most, 70 percent of black prongs in heavy elements are due to nuclear evaporation.

The second part of the paper discusses the results of exposing the same configuration of emulsion pellicles and gelatin layers to the positive pion ($\pi^+$-mesons) beams of 70-80 MeV and $60\pm5$ MeV from the Columbia cyclotron. They conclude that 24-30 percent of emulsion stars originate in the light nuclei of the emulsion, and find a lower limit of the opacity of light nuclei of 0.64. In most cases, absorption of the incoming meson takes place, and the absorption occurs mainly on nucleon pairs. Absorption by more than two nucleons is less than 30 percent.

In an interesting Appendix to this article, the authors describe the absorption of x-rays by the emulsions used in these experiments. They finally determined that the ratio of light elements in emulsion to light elements in the gelatin layers is $2.95\pm0.3$.

In 1952, Blau and Salant published a letter in the Physical Review B64 on “T-tracks in Nuclear Emulsions.” This paper presents evidence of so called “T-tracks”, which seemed to be heavy particles produced in the cosmic radiation and stopping in the emulsion, with the apparent release of other particles, including fast (minimum-ionizing) particles. The eleven cases they observed seem to represent some kind of enigma. They cannot decide whether the T-tracks and their products are coincidences of observation or not. Since I have not seen any further reference to this phenomenon, I would have to conclude that the observations were not valid. I do recollect that Blau was not fond of Salant, and that he may have been a cause for her eventually leaving Brookhaven.

The next two papers were produced from work at Brookhaven National Laboratory on the interactions of 500 MeV negative pions ($\pi^-$-mesons) produced with emulsion nuclei. The first was a letter with M. Caulton and J.E. Smith in Physical Review in 1953B66 and then a longer article with M. Caulton in the Physical Review in 1954B67. These papers signalled the complete return of Blau to nuclear physics research with the technique she
had essentially invented, and in which she kept pace with the widening application of photographic emulsions to high energy subnuclear phenomena. According to Galison\textsuperscript{1}, she was the first to demonstrate that meson interactions with nuclei could produce additional mesons\textsuperscript{B66}. Actually, in that letter, Blau, Caulton and Smith give credit to the Bristol group\textsuperscript{31} for finding a meson production event in plates exposed to cosmic rays and one event found in the 220 MeV negative pion beam of the Chicago cyclotron\textsuperscript{32}. However, since the authors identified six events in which two mesons leave an emulsion nucleus and a seventh in which two mesons appear to emerge from a hydrogen nucleus (a proton), it gives unequivocal evidence of meson production. In addition to the six events, eight more are consistent with additional meson production, although the tracks are too short for unmistakable identification.

Hence, it may be stated with considerable justification, that Blau's was the first definitive report of additional meson production by high energy mesons, an important, if not unexpected, observation.

They estimate that the number of two meson events reported in the paper constitute at most 25 percent of all events in which a charged meson – observed or absorbed – is produced. The above figure would then represent 5.2 percent to 12 percent of all interactions. From this experiment nothing can be learned about the production of neutral mesons ($\pi^0$-mesons) and therefore the actual cross section of meson-meson production at 500 MeV meson energy cannot be compared with theoretical data. They quote, however, C.N. Yang and E. Fermi (a private communication), who estimate that the fraction of events leading to two charged mesons is 16 percent to 18 percent (the second number includes events with two charged and one neutral meson). This figure is twice the value calculated by Blau, Caulton and Smith from the experimental data, but considering the meager statistics and the simplified assumptions, the disagreement is probably not too serious.

In this paper, I can recognize the total modesty, honesty, and commitment of Marietta Blau, who ventured no claims beyond the experimental evidence and conservative conjecture.

The second, longer paper, “Inelastic Scattering of 500-MeV Negative Pions in Emulsion Nuclei”\textsuperscript{B67} was on an expansion of the results given in the shorter letter \textsuperscript{B66}. It goes into considerable detail on the exposure of the emulsions to two different beams of the Brookhaven Cosmotron, namely (1) the 500 MeV meson beam and (2) particles emitted from the Cosmotron target (beryllium) at an angle of 32° with the 3 GeV proton beam direction. They also describe the methods on the search for interactions in the pellicles, and on the measurements made on incoming meson tracks and on outgoing particles.

They discuss, in succession and in some detail, the observations of stars with no mesons, stars with one meson and events with two mesons, i.e., additional meson production. They perform a careful analysis of meson interactions in nuclear matter, and also some data on the production of neutral pions ($\pi^0$-meson). They finally conclude that
the cross section for the production of charged mesons per nucleon is 3.5 millibarns or 14 percent of the total meson – nucleon cross section at 500 MeV. They believe that they underestimate this cross section, and that it could be as high as 10 millibarns, probably an overestimate. They note that C.N. Yang and E. Fermi (a private communication) expect the cross section for meson production by mesons to be 12 percent of the total cross section, which is estimated by Lindenbaum and Yuan\textsuperscript{33} to be 610 millibarns.

They conclude the paper with a comparison of the results with those of cosmic ray mesons, where the mean shower energy is 640 MeV\textsuperscript{34}. There appears to be a considerable discrepancy with the results between shower mesons and single artificial mesons, which they are at a loss to explain.

Blau resumed her collaboration with A.R. Oliver and continued her studies of high energy pion interactions, publishing a paper on “Interaction of 750-MeV $\pi^-$-mesons with Emulsion Nuclei” in the Physical Review \textsuperscript{B68} in 1956.

The pions were selected by an analyzing magnet from secondary particles emitted from a beryllium target at 32° to the direction of the proton beam of the Brookhaven Cosmotron. They scanned 132.8 meter of meson track under high magnification and found 322 interaction events. Subtracting from the path length (6.5 ± .02)\% for probable muon contamination, the mean free path in emulsion is (38.5±2.2)cm, while the geometric mean free path (for $r_0 = 1.38 \times 10^{-13} \text{cm}$) is 27 cm. This is in fair agreement with a value expected from the $\pi^- - p$ cross section of 42 millibarns and $\pi^- - n$ cross section of 17.5 millibarns found by Lindenbaum and Yuan\textsuperscript{33} in the same energy interval. Accepting these cross sections and integrating over the emulsion nuclei (number of neutrons = 1.2×number of protons) leads to a mean free path of 34.7 cm.

They then analyze the results according to the type of interaction. They find 5 elastic scattering events on free protons and 6 near elastic scatterings on protons near the edge of nuclei. From the 5 events, they find a mean free path for elastic $\pi^- + p$ interactions of 24.8 ± 11.4 meters, while the mean free path for all $\pi^- + p$ interactions (cross section 42 millibarns) is expected to be 7 meters; the elastic cross section without charge exchange is 12±5.4 millibarns or about one third of the total cross section. If one assumes the relation

$$(\pi^- + p \rightarrow \pi^- + p)/(\pi^- + p \rightarrow n + \pi^0) = \frac{5}{4} \text{ (equal weight for states } \frac{3}{2} \text{ and } \frac{1}{2}),$$

then about 60 percent of all interactions should be elastic.

They then turn their attention to 15 events that can be called inelastic scattering by free protons or protons at the periphery of the nucleus, according to the schemes

$$\pi^- + p \rightarrow \pi^- + \pi^+ + n \text{ or } \pi^- + p \rightarrow \pi^- + \pi^0 + p.$$ 

They show the angular distributions (in the center of mass system), of emitted nucleons, fast mesons and slow mesons. Nucleons in the backward direction is preferred (12:3), and
for fast mesons the forward direction is preferred. They calculate the Q-value for the nucleon and the slower meson, assuming they form an “excited state,” and find Q-values spread over an interval of 30-170 MeV, and there is, at least within small statistics, no indication of a maximum value.

In the study of charge-exchange scattering and a possible $\pi^- + p \rightarrow \pi^0 + \pi^0 + n$ reaction, they find two events in which electron pairs (Dalitz pairs) give direct evidence for $\pi^0$ production. They find 15 events where the meson stops in the emulsion and another 16 where there is a small recoil or blob. The number of stoppings observed (15), plus the two cases with electron pairs, is unexpectedly high in comparison to the cases leading to charged meson production, even within the meager statistics$^{35}$.

Finally, they find fifteen events of meson scattering through angles $\geq 10$ degrees without visible nuclear interaction and 17 other cases where the meson scattering is accompanied by recoil or slow-electron emission. The first 15 events could represent elastic scattering on peripheral neutrons or scattering with $\pi^0$ production; but some of these could be scattering on protons in nuclei where the emission of the slow proton has been suppressed by the exclusion principle. There is one case observed of $\pi^- + n \rightarrow p + \pi^- + \pi^-$. The total number of $\pi^- + p$ collisions is 41, taking 11 as the number of elastic scatterings observed. The mean free path in the emulsion is $3 \pm 0.5$ meter or about one-half of the mean free path for $\pi^-$ collisions on free protons, calculated with a cross section of 42 millibarns. Therefore, one-half of all observed collisions must have occurred on bound protons on the nuclear periphery.

The find the ratio

$$\frac{\pi^- + p \rightarrow \pi^- + p}{(\pi^- + p \rightarrow \pi^0 + \pi^- + p) + (\pi^- + p \rightarrow \pi^+ + \pi^- + n)} = \frac{11}{13}. $$

Judging from this ratio and assuming again equal weights for the 3/2 and 1/2 state in Fermi’s theory, 44% of all $\pi^- + p$ collisions are inelastic.

Finally, the ratio of $\pi^- + p$ to $\pi^- + n$ scattering (considering in both cases events without evaporation tracks or recoils) is 41:16=2.6, while the ratio found in this energy interval by Lindenbaum and Yuan$^{36}$ is 42:17.5=2.4.

They then turn their attention to interactions of the $\pi^-$-mesons with nuclei. In addition to 266 nuclear events (233 stars, 17 meson scatterings with recoils or electron interactions), they found also 500 stars in area scanning. They find $(40 \pm 4\%)$ of all stars have 1 emitted meson and only $(3 \pm 1\%)$ have 2 emitted mesons, quite similar to the results obtained for 500MeV $\pi^-$-mesons$^{367}$. They explain this by the higher interaction cross-section of 750MeV mesons and by an increased meson production leading to mesons in an energy interval of 100-300 MeV which have small mean free path in matter. They also discuss the angular distribution of the mesons in the laboratory system.
Noting that if the π- meson is completely absorbed, the total excitation energy is nearly 900 MeV; and in heavy elements (which are responsible for all stars), stars with 9-15 prongs would be expected. On the other hand, it can be anticipated that stars with fast forward-scattered mesons are small, consisting of a few short prongs in light elements and 1-2 prongs in heavy elements. As already mentioned, 60% all stars have no charged meson; 62% of these have no fast proton $\geq 60$MeV, and a mean prong number of only $4 \pm 0.4$. Only 2% have a prong number $\geq 9$. This suggests that a great amount of energy is carried away by fast neutral particles for which the nucleus is rather transparent. Finally, the great number of observed $\pi^-$ stopping raises the question of a possibly greater proportion of collisions leading to charge exchange than is calculated with the Fermi statistical theory.

They conclude the paper with a description of prong distribution in all types of stars, and the appearance of stable fragments in $\pi^-$ meson stars.

Blau’s last work published from research at Brookhaven National Laboratory was on “Hyperfragments and Slow K-mesons in Stars Produced by 3-BeV Protons” in the Physical Review $B^{69}$. This work was done about a year after the first example of a hyperfragment (a $\Lambda^0$ hyperon bound to an ordinary nucleus) was found by Danysz and Pniewsky$^{37}$, and then shortly after the first systematic investigation of hyperfragments produced by the 3 GeV proton beam at the Brookhaven Cosmotron by Fry, Schneps and Swami$^{37}$. A systematic search for hyperfragments in particle beams of well-defined energy gives information on data related to particle physics, $\Lambda^0$-production cross section, particle nature of the $\Lambda^0$ (associated production, etc.), as well as to physics of the nucleus (formation of the hyperfragment, binding energy, etc.).

The stack of emulsions was exposed to about 30,000 protons/cm$^2$ and then the individual emulsions were scanned at fairly low (300X) magnification, since she was searching for fairly prominent stars. She describes in some detail the measurement procedures followed for the determination of mass, charge, and energy determination of the hyperfragments themselves and of the outgoing decay particles or nuclear fragments.

Of the 14,480 stars investigated, she found 14 events which are believed to be spontaneous disintegrations of hyperfragments coming to rest in the emulsion, with the possible exception of one event where decay in flight is suspected. In addition, she found two stars with double centers which may represent disintegration of slow and probably heavy hyperfragments. Both cases occurred in large stars and it was impossible to disentangle the prongs belonging to each center.

Only a few of the events could be analyzed; however all of them, with one exception are compatible with a $\Lambda^0$ hyperon bound to the nucleus. All the observed hypernuclei, with one exception, are isotopic spin singlets, $I = 0$ for nuclei with odd atomic number, and doublets, $I = \frac{1}{2}$ for nuclei with even atomic number. The exception could be explained as a decay in flight of a $\Lambda Li^8$, the first decay of a hypernucleus in a $I=1$ state.
She goes on to discuss the likely identity of the other hypernuclei, $\Lambda Be^8$ and $\Lambda Be^9$, a $\Lambda H^4$, a $\Lambda Li^6$, $\Lambda B^9 - \Lambda B^{10}$ or $\Lambda C^{10} - \Lambda C^{13}$, $\Lambda B^9$, or $\Lambda C^{11} - \Lambda C^{12}$, a $\Lambda O^{16}$ or higher atomic number, $\Lambda Be^9$, $\Lambda H^4$ or $\Lambda H^5$.

The number of hyperfragments per star is $14/14,480 \approx 1 \times 10^{-3}$, in good agreement with Fry’s results$^{37}$, who found 21 hyperfragments in 20,000 stars. Since all hyperfragments originate in heavy elements, which are responsible for only about 75% of all stars, the frequency is actually somewhat higher, about $1.3 \times 10^{-3}$.

Blau also has found four $K^{\pm}$ mesons emitted from stars, all of them of low energy, since the probability of finding particles of range $\geq 2.5$ cm is small in a stack of the size used in the experiment. She finds no examples of associated production of other unstable particles.

In summary, from Blau’s work at Brookhaven National Laboratory, it is clear that Marietta Blau stepped authoritatively into the main stream of particle research, in spite of the fact that she was not in command of large research groups. In particular, she quantified the interaction of (then) high energy pion interactions including finding the first examples of additional pion production. She also contributed significantly to the observations of hyperfragments at an early stage. Although the improvement of statistics came several years later with the exploration of hydrogen, deuterium and helium bubble chambers, the path of further research was made clear by the emulsion results.

F. Marietta Blau at the University of Miami (Coral Gables)

i) A Personal Memoir

To the best of my recollection, Marietta Blau came to Coral Gables as an Associate Professor in Autumn, 1956. I had arrived in February, 1956 to take up the position of Assistant Professor, and continued my interests in solid state physics by then investigating the optical properties of the semiconductor GaAs.

Because I do not have a very good memory for detail, I cannot recount the specifics of my meeting with Blau, but I do recall that we had a nearly instant rapport, and that I responded without hesitation to her invitation to collaborate with her on photographic emulsion research in high energy physics. She also recruited three other colleagues, including Claude F. Carter. The other two did not remain with the group.

I feel that I must depart here, at least temporarily from simply summarizing her papers, and interject my own impressions and experiences. It was not simply on a whim that I answered her call, because in the previous few years, before and after my Ph.D. in 1955 in solid state physics, I had seriously attempted to independently study theoretical physics, particularly nuclear physics, with some guidance from a former teacher at New York University. Before I made any substantial progress on my own, the idea of an opportunity to do high energy experimental physics with such a distinguished mentor excited
Marietta Blau was a rather small person, perhaps 5 feet 2 inches tall (158 cm) and quite slender, with a sweet kindly expression. Her head was barely visible over the steering wheel of her little Plymouth coupe, and she was not a very skilled driver, yet she negotiated the trip from New York to Miami several times, before the days of interstate roads. The initial impression she made was that of a fragile person who could be blown over by a breeze. I would say that she was quite good looking, but presented herself in a very modest, self-effacing manner. She spoke deliberately, slowly, and softly, and her English, if slightly accented, was polished. She was well-versed in the classics, literature, and the arts. We attended many musical events together, especially visiting chamber music groups. I recall that we once attended a presentation of Verdi’s “Requiem”, by the Miami Symphony (then the University of Miami Symphony), and that we were so overwhelmed, that we jointly sent a warm letter of appreciation to the conductor, John Bitter (a brother of the well-known authority on high-field magnets, Francis Bitter). It was my first hearing of the “Requiem”.

When she arrived in Miami, she found several former students and colleagues from Vienna, namely Fritz Koczy and Elizabeth Rona, both of them at the Institute of Marine Sciences at the University of Miami. Koczy later became Director of the Marine Institute, and he and I became great friends until his untimely death, I believe in the 1970’s.

My oldest son, Bernard, was three years old when we arrived in Miami, and Joseph was born in 1957, just after Marietta arrived. She became a close family member, showering the children and my first wife, Ruth, with gifts. My older son reminds me that she presented them with a sleep-out Indian tent when he was about six years old. We often entertained each other in our homes. She met my parents on their visits to Miami, and they all enjoyed each other greatly. She grieved compassionately when my mother died in 1960, shortly after Marietta’s return to Vienna.

I cannot recall the details of how she built up our laboratory, but she did have generous funding from the Air Force Office of Scientific Research (AFOSR). Actually, Claude Carter assisted her ably in fiscal and procurement affairs, in which I played just a peripheral role. We obtained about six or seven precision Leitz binocular microscopes with magnifications up to 2000X, for which we had designed enlarged movable stages, built for us by local instrument makers.

Initially, we were housed in cramped quarters of the Physics Department, at that time in wooden shacks which were used during World War II for the training of Air Force pilots. The University of Miami then rented space for us on the ground floor of an old apartment building in Coral Gables, about two miles away from the Main Campus. The upper floor was occupied by the Institute for Molecular Evolution directed by Sidney W. Fox, a distinguished biochemist from Florida State University. We had about eight or ten rooms, mostly devoted to scanning microscopes, equipment room, and of course the
ubiquitous coffee lounge. One large room was reserved for a multiple scattering microscope, whose large foundation and massive stage were designed by a master instrument maker, Brouwer, from a town near Berkeley, California. Brouwer was famous for designing and building these instruments for emulsion laboratories around the world, for the purpose of measuring the momentum of fast, minimum ionizing tracks in the emulsion, and an essential parameter in the determination of particle properties. I cannot recall the exact specifications of this marvelous stage, but I seem to recall that it could measure deviations of a micrometer in longitudinal movements of several centimeters (some tens of thousands micrometers). It was the massive base of concrete blocks for this microscope that required our laboratory to be placed on the ground floor of the building. An interesting dividend of our needs (the microscopes and the fragile emulsions) was that the entire facility had to be air conditioned (at that time by window coolers), an unusual luxury in those years in Miami, which suffers sweltering temperatures for half of the year.

Marietta Blau was a most effective teacher, giving courses in electromagnetism and nuclear physics, among others, to advanced undergraduates and graduate students. At that time, we did not have a Ph.D. program, but gave a Master of Science degree. I believe, that because of her slight stature and her gender, she was not afforded the respect to which she was entitled. She fought with the administration and the Chairman of the Physics Department about the use of overhead from her federal grants. After one complaint to another colleague, the theorist Behram Kursunoglu, I recall that the latter called the chairman an idiot. She answered, in her soft plaintive voice, “Is that all he is?”.

I really cannot recall how I learned the emulsion craft, but I do know that Marietta Blau was a wonderful teacher in the laboratory. We recruited housewives and students, in the tradition of Cecil Powell, to be scanners of the emulsion pellicles, and in the cases of the more gifted assistants, to allow them to make precision measurements. She of course schooled me in the theory of ionization measurements, multiple scattering, and range-energy relations, and I had to study these problems on my own, but after about three years I emerged as fairly competent researcher. All of the faculty scanned, supervised the scanners, and made precision measurements as needed. The tedium of emulsion work cannot be overestimated. Constant checking of the efficiency and accuracy of observations was necessary. It is not a simple matter to describe the amount of work that went into the experiments discussed in Parts C and D of this memoir, nor that which is described below.

As the bubble chamber, spark chamber, streamer chamber, and digitized chambers evolved in the 1960’s and 1970’s, emulsion research regressed in importance in the accumulation of statistics. One of the reasons is that the bubble chambers and spark chambers could be composed of elemental substances, such as hydrogen, deuterium, helium, or other interesting substances, and that the measurements could be automated to the extent that made the accumulation of data far more rapid and efficient. In modern applications, electronics, solid state detectors, and other devices further increase the effectiveness of detectors. However, emulsions remain an interesting detector in special situations, especially
where spatial resolution and continual exposure are needed.

(ii) Marietta Blau’s Research at Miami

Sometime during 1957, when the laboratory was established, we began to scan a small stack of Ilford G5 emulsions which had been exposed by Gus Zorn to the negative pion beam at the Brookhaven Cosmotron. The results were reported in Il Nuovo Cimento, in 1959, by M. Blau, C.F. Carter and A. Perlmutter, “Negative Pion Interactions at 1.3 GeV/c”\(^{69}\).

Since the energy of the incident pions was not precisely known, the momentum was determined by multiple scattering measurements to be \((1.3 \pm 0.1)\text{GeV/c}\), which was corroborated by kinematic considerations of elastic scattering on protons. The plates were scanned by following incident pions from the lead edge. The track length scanned was 380 meters, and the number of interactions found was 811. After correcting for scanning efficiency and for the contamination of the beam by muons and electrons, the corrected track length was 340 meters, giving a total cross section in agreement, within statistical limits, with the results obtained by other investigators.

There are tables which summarize the interactions with free or nuclear edge nucleons. There are 10 elastic collisions with free protons, \(\pi^- + p \rightarrow \pi^- + p\), and (7) with peripheral protons (matched by Fermi momentum) (type I); 11 inelastic collisions with free protons, \(\pi^- + p \rightarrow \pi^- + p + \pi^0\) and (15) with peripheral protons (type II); and 5 inelastic collisions, \(\pi^- + p \rightarrow n + \pi^+ + \pi^-\), and (1) with peripheral protons (type III). Other collisions with peripheral protons which could not be analyzed total (38). As for collisions with peripheral neutrons there are (8) quasi-elastic ones \((\pi^- + n \rightarrow \pi^- + n)\) (type VIII), another (29), elastic or inelastic which could not be analyzed, and another handful of inelastic events. A comparison of these events with those of Walker and Crussard\(^{35}\) at a somewhat higher energy does not indicate any significant disagreement.

It is of interest, in view of the results to be presented later, to substantiate that the clean \((\pi^- + p)\) events of types I, II and III represent free proton interactions; this supposition could be verified in part by calculating the total free proton cross section. But to do so one needs to know the relative contributions of multiple pion production and events of type VI with zero prongs \((\pi^- + p \rightarrow n + \pi^0\) or \(\pi^- + p \rightarrow n + \pi^0 + \pi^0\)) to the total free proton cross section. Although these contributions could not be found directly from this data, they could be estimated from the hydrogen cloud chamber results of Eisberg et al\(^{38}\) and from the curves derived from bubble chamber experiments of the Wisconsin group\(^{39}\). Both groups find a total cross section of 34 millibarns.

The cloud chamber results\(^{38}\) seem to indicate that one should expect double production events to amount to about 25% of those of types (II and III) and that the number of zero prong stars should be about 15% of all visible proton events, including double production. Applying these corrections to our data, we obtained a mean free path for
free proton collisions of 9.7 meters (30 millibarns). The contribution of zero prong stars could also be estimated from the bubble chamber data, yielding a charge exchange cross section (elastic and inelastic) at 1.2 GeV of 30\% of the visible proton interactions. This leads to a mean free path of 8.7 meters (34 millibarns) for this emulsion data.

Although the size of this sample is small, if it is combined with the cloud chamber data at a similar energy, some of the features seem to suggest a regularity which warrants further investigations on much larger samples. The combined results (for types II and III) are plotted as function of nucleon momentum in the center of mass system, with a pronounced peak at about 550 MeV/c, in qualitative agreement with both the statistical and isobar models of pion production, and as function of their angle in the center of mass system, with the distribution strongly peaked in backward direction, in agreement with the isobar model. In both cases it is evident that events which require Fermi momentum to be added to the target protons cause an apparent broadening of the distributions, as might be expected. Further figures give momentum distribution in the center of mass system of protons from reaction of type II plus similar data from the cloud chamber experiment, and the angular distribution of the same protons in the center of mass system. Similar plots are given for the neutrons of reaction of type III. Further plots of the momentum distribution and angular distribution in the center of mass system of both emergent pions in reaction II, and nuclear interactions are given.

Finally, a histogram of the Q-values in the rest frame of the nucleon-pion isobar for reactions II and III, is given. Although the sample is not large, the Q-value does show a bunching near 150 MeV, while the range of values is from 0 to 300 MeV.

The remainder of the paper discusses the nuclear interactions of the pions. the total number of interactions with nuclei is 725 (not free proton collisions). In addition to 263 stars without emitted charged mesons, we find 41\% of all events have no emitted mesons. The number of 1 meson: 2 meson: 3 meson stars is 317:94:14. In plotting the angular distribution and energy distribution of emitted mesons, a comparison is made with the Monte Carlo calculations in Los Alamos by the MANIAC and shows only fair agreement.

The paper concludes with a listing of events producing $K$ mesons, hyperons and hyperfragments, a total of ten events.

During Blau’s stay in Miami she vigorously attacked the problems of ionization in nuclear emulsions, the results of which were given in an article in The Review of Scientific Instruments in 1960. This was a problem which she had addressed earlier in articles at Columbia University and which justifiably obsessed her. During the course of this investigation, in which measurements were made on known tracks for the purpose of particle investigation, it was found that a single parameter, namely mean blob length, could be related to the probability of ionization over the entire energy range.
We discussed first the probability of development of any single crystal, \( p \), where
\[
p = 1 - \exp(q x \nu),
\] (1)
where \( q \) is a parameter that depends only on development conditions, \( x \) is the path length of the ionizing particle through the crystal, and \( \nu \) is the number of ionization acts per unit length. One could then write an expression relating the average probability of development \( \bar{p} \) taken over all crystals in the path under consideration, to the value of the ionization. By definition, \( \bar{p} = n_g / n_t \), where \( n_g \) (the grain density) and \( n_t \) are the number of developed AgBr crystals per unit path length and the total number of AgBr crystals per unit path length, respectively. If all the grains are assumed to be of equal diameter \( x \) with their centers aligned, then the average value of the probability is
\[
\bar{p} = 1 - \exp(-y),
\] (2)
where \( y = q \bar{x} \nu \). If one then assumes with Demers\(^44\), that the AgBr crystals are of equal diameter \( \frac{3}{2} \bar{x} \), distributed at random about the particle, then
\[
\bar{p} = 1 - \frac{8}{9} y^2 \left[ 1 - (\frac{3y}{2} + 1) \exp(-\frac{3y}{2}) \right].
\] (3)
A further refinement of the crystal distribution consists of replacing the assumption of equal grain size by the supposition that all values of crystal diameter between 0 and \( 2 \bar{x} \) are equally probable.\(^45\) In this case, the mean probability becomes
\[
\bar{p} = 1 - \frac{3}{2} y^2 \left[ (1 - \frac{1}{y}) + (1 + \frac{1}{y}) \exp(-2y) \right].
\] (4)
We plot the three curves in Fig. 1, and see that they are nearly linear for small values of \( \bar{p} \), but differ as \( \bar{p} \to 1 \); which of the three curves best represents the ionization accurately is not known as yet.

We then go on to discuss the blob density, \( B \), or the number of AgBr single grains or clusters per unit length of track, and introduce \( B^* = B / B_0 \), where \( B_0 \) is the blob density for minimum ionizing tracks, related to \( n_g^* = n_g / n_0 \) by applying appropriate corrections \(^46\). Some authors \(^47\) recommend the use of total gap length, \( L_H \), while others recommend the use of mean gap length, \( \lambda \).\(^47,48,49\).

We go on to describe the experimental apparatus, which was inspired by the earlier device of Blau, Rudin, and Lindenbaum\(^62\) and first reported by S.C. Bloch\(^50\). Sylvan Bloch was a graduate student at the University of Miami who designed the apparatus to be used with a photomultiplier or phototransistor. His recollections of Marietta Blau are given in Appendix III of this paper.\(^51\). The remainder of the paper is devoted to comparisons of experimental results of 1.3\( GeV/c \) pions and 680 MeV/c antiprotons, and their reaction products, giving good agreement with the blob density parameter.
In July, 1957, we made an exposure of photographic plates to the 620 MeV/c K$^+$−meson beam at the Berkeley Bevatron. This exposure was unsuccessful because of the fogging of the emulsions from unknown radiation. An exposure of a stack of emulsions to the 670 MeV/c antiproton beam of the Berkeley Bevatron was made in January 1958. The results of this study were reported in TN60-461. Unfortunately, I do not have a copy of this report, and have not been able to obtain one. It was not published in the open literature.

Finally, an exposure to the 450 MeV/c K$^-$-meson beam at the Bevatron was made in January, 1959. The interactions of the K$^-$-mesons, brought to rest in the emulsion, were observed and analyzed. This work was presented in a report submitted to the AFOSR and later a part of this work was published in Nuovo Cimento. We had accumulated a substantial number of stopping K$^-$ in emulsion, but because of the huge statistics accumulated by the European K$^-$ Collaboration, we restricted ourselves only to describing some unusual interactions of hyperons.

One event was the likely decay of a hyperfragment in an unusual mode, i.e., via a π$^+$-meson, rather than the customary π$^-$-meson. The most likely interpretation is a $\Lambda H^{3,4} \rightarrow \pi^+ + (3,4)n$. There had been two previous π$^+$-decay events observed by Schneps et al. We quote Deloff et al and Ferrari et al, who estimate that on the basis of $\Lambda^0 \rightarrow \Sigma^+$ exchange inside the hyperfragment, the branching ratio into the π$^+$ mode is of order 1% of the π$^-$ mode in the case of $\Lambda H^{3,4}$. We discuss also other possible mechanisms for this phenomenon.

Another unusual event is the possible production and decay of a (Σ$^+p$) hyperfragment. The fast π$^+$ meson (about 90MeV) emitted from the apparent hyperfragment indicates that the short connecting track is probably a (Σ$^+p$) → π$^+$ + p + n, leading to a Q value not incompatible with that expected for such a decay, and that the binding energy is less than 1 MeV. Previous observations of such a decay give no more conclusive results than this one.

We also found several examples of stopping K$^-$ interactions with two nucleons, which are generally difficult to detect. We found one example of $K^- + (pn) \rightarrow \Sigma^- + n + \pi^+$ and another example of $K^- + (nn) \rightarrow \Sigma^- + \pi^- + p$.

There was likely one, and three other possible examples, of the exotic decay $\Sigma^+ \rightarrow p + \gamma$, compatible with a branching ratio of $1.4 \times 10^{-4}$ to $2 \times 10^{-2}$ to the normal decay mode, $\Sigma^+ \rightarrow p + \pi^0$, but by no means certain.

There are several apparent events in which the Σ$^-$ produced by the stopping K$^-$ seems to release a large amount of visible energy, compatible with the decay of a hyperfragment through the interaction $\Sigma^- + p \rightarrow \Lambda^0 + n$.

There is an unusual apparent decay of a Σ$^-$, but the kinematics strongly suggests the
parent particle, with the decay scheme \((\Sigma^- n) \rightarrow \pi^- + n + n\), again an exotic hyperfragment.\(^{57}\)

Finally, a sample of four scatterings by \(\Sigma^-\) or \(\Sigma^+\) interactions in emulsion are added to those found by other groups, giving a total of ten events. The total mean free path in emulsion is then about 38 cm in the energy range from 0 to 200 MeV. The only systematic study of the scattering of \(\Sigma\)-hyperons in bubble chambers was that of Stannard\(^{58}\), who found cross-sections of 38 mb and 10 mb for the elastic scattering of \(\Sigma^+\) and \(\Sigma^-\), respectively, on protons.

Clearly, our work was a significant contribution to the early knowledge of hyperon interactions.

G. Other Writings by Marietta Blau

During her years in the United States, Marietta Blau published four more works, in addition to the research articles I have described above.

The first of these, “Bericht über die Entdeckung der durch kosmische Strahlung ‘Sterne’ in photographischen Emulsionen”, was written while she was at Columbia University\(^{58}\), and published in Sitzungsber. 159, 53-57, (1950). Blau gives a brief history of her work with photographic emulsions in the 1920’s, her collaboration with H.Wambacher, and through the friendly support of V.R. Hess (the Nobel Laureate) and R. Steinmaurer, exposure of plates at an altitude of 2300 m in 1936. She describes the cosmic ray stars found in the emulsions, some with as many as twelve heavy prongs. They found that in about 10% of the cases, the primary energy was greater than 200 MeV. They were encouraged by these results, and obtained a grant from the Academy of Sciences through the efforts of Stefan Meyer for new high altitude exposure. In a classic bit of understatement, she says that all this work was interrupted by the political conditions in Austria. She concludes the article with a remark that seems somehow tinged with envy: “Meanwhile, this work was carried out in England and America with improved methods, and the progress of recent years in theoretical and experimental areas have not only nearly completely solved the problem of “Stars”, but have led also to important knowledge in the fields of cosmic rays and nuclear physics.”

In the same year, Blau published an article in an apparent festschrift in honor of Karl Przibram’s 70th birthday, entitled, “Möglichkeiten und Grenzen der photographischen Methode in Kernphysik und Kosmischer Strahlung,” in Acta Phys. Austriaca 3, 384-395 (1950)\(^{61}\).

This paper, like the previous one but longer, is also a review of the evolution of the photographic emulsion method in particle and nuclear physics. She discusses first the observation of protons in emulsion and then the observation of neutrons through the recording of their knock-on protons up to 13 MeV. She describes the work of M. Goldhaber, who impregnated emulsions with various elements and observed nuclear reactions. Emul-
sions of lower sensitivity, impregnated with uranium salts or the salts of other radioactive elements, are well suited for the study of decay processes, and certain important contributions were made with the emulsion technique. In 1947, Demers and Wottan observed alpha particle decay, and in the same year, using the methods of Green and Livesey and of Tsien-Sam-Tsiang, found threefold and fourfold splitting of uranium atoms from neutron bombardment. She goes on to credit first Ilford Ltd., London and then a short time later Eastman-Kodak, Rochester with providing a larger content of AgBr and relatively small grains, in pellicle thickness up to 600 microns. The development methods were worked out by Occhialini, Powell and Lattes, who also standardized the photographic material. (She singles out also the efforts of P.Demers, N.A.Perfilov, M.M. Shapiro, H. Yagoda and A. Zhdanov among the other important contributors to the development of this process).

Blau goes on to discuss the importance of new methods and refined measuring devices in leading to new discoveries in physics generally, but especially in the area of nuclear physics. In the meanwhile, the predicted particle – meson – with about 200 times the electron mass was confirmed with the Wilson cloud chamber and Geiger-Müller counter. Corresponding to the previously mentioned sensitivity of the new emulsions, it appeared possible to obtain meson tracks up to about 1000 microns to their stopping point.

¿From this point on, it is only possible to describe the advances in the photographic method in connection with the theory of mesons. Both developed with each other; the new theoretical knowledge called for newly refined measuring techniques and, furthermore, emulsions of greater sensitivity.

In January 1947, Perkins exposed Ilford (B1)-emulsions for some hours in an aircraft at an altitude of about 10km. He found in his plates a new, until then unfamiliar phenomenon – multiple nuclear disruption by mesons: in one star, consisting of four prongs, one of the tracks corresponded to the slowing down incoming particle with increasing grain density. It was determined by measurements that the particle had a mass substantially less than that of the proton. Further searches by Perkins and the physicists of the Bristol group in the cosmic radiation confirmed the first example, slowing down charged particles of small mass, present in the cosmic radiation, can disrupt atomic nuclei with the emission of heavier particles.

Are these light particles identical to the mesons found in the Wilson chamber? To decide this question, one must make grain density and scattering measurements, leading to a mass of about 300 electron masses. She compliments the group of Perkins, Lattes, Occhialini and Powell for pursuing, and finding in the cosmic rays the spontaneous decay of a π-meson into a secondary µ-meson. From the fact that the µ-mesons had equal lengths, one could determine the masses of the π- and µ-meson, the latter accompanied by a neutrino. The ratio of masses of the π- and µ-meson was found to be \( \frac{m_\pi}{m_\mu} = 1.32 \), in agreement with the values found in California from magnetic measurements on artificial mesons produced by their cyclotron.
She discusses the further increase of sensitivity of emulsions to fast $\beta$-particles obtained by Eastman-Kodak at the end of 1948 and their exposure of the Bristol group in the Jungfraujoch. They found interesting cases of $\mu$-meson to $\beta$-particle decays and showers of $\beta$-particles accompanied by heavy particles.

But besides these discoveries, other researchers in cloud chambers demonstrated the existence of a charged particle with a mass equal to half that of a proton. In the new emulsions the existence of this meson–$\tau$-meson–with a mass of about 1000 electron masses was established, and at the end of its track produces a star consisting of three prongs. One track is a $\pi$-meson, while although the other two do not end in the emulsion, they are also identified as $\pi$-mesons, and, furthermore, all three tracks were coplanar. Another fortunate case was observed by Leprince-Ringuet, who observed a stopping $\tau$-meson that showed it produced in its decay, a mass of more than 700 electron masses.

Before closing the chapter on “Pioneering Work of the Photographic Method”, she devotes several pages to the research of Bradt and Peters in Rochester, and Frier, Lofgren, Ney, and Oppenheimer in Minnesota, who exposed plates in balloons at 30 km and found extraordinarily thick and long tracks. Using new techniques for analyzing these tracks, they found them to be the nuclei of various atoms: iron, sodium, magnesium, silicon, potassium, calcium. The energy of observed particles is extraordinarily large, often greater than a GeV.

The paper concludes with a discussion of grain density and the range-energy relation. This portion is clearly based on her paper on “Grain Density in Photographic Tracks of Heavy Particles”$^{B54}$, which was done at about the time she was preparing the present article.

The third paper in this group was written by Marietta Blau in 1959 while she was at the University of Miami, and is titled “Ionisationmessungen in photographischen Emulsionen” and published in Acta Phys. Austriae$^{B70}$. Like the previous paper in this section, it was for Karl Przibram’s festschrift, but this time for his 80th birthday. This paper is based in part on our paper discussed above on “Studies of Ionization Parameters in Nuclear Emulsions”$^{B72}$ and probably on another series of articles she was writing at that time for the volume edited by Luke C.L. Yuan and Chen-Shiung Wu, Methods of Experimental Physics, Vols. 5A and 5B, Nuclear Physics,$^{B74}$ which I will discuss below in the last part of this section. Hence, I will not elaborate further on this publication, which is presumably covered in references (B72) and (B74).

The contributions of Marietta Blau to the volumes of Yuan and Wu on Methods of Experimental Physics, Nuclear Physics$^{B74}$, Vols. (5A and 5B) are a masterful discussion of the photographic emulsion technique in nuclear and particle physics by the person who is most responsible for its discovery and for much of its evolution and application.

The contributions are in five parts. The first in Vol. 5A, Section 1.7, is the longest,
and starts with a historical introduction (1.7.1), some of which was discussed earlier, and which I will not repeat. As in reference (B61), she attributes the discovery of the $\pi^-$-meson to Perkins\(^{59}\) and the positive counterpart to Lattes et al\(^{60}\). The first heavy meson was the $\tau$-meson discovered by Brown et al\(^{61}\) in nuclear emulsions. She notes that the method also has been successfully applied in the field of slow neutrons, photo-disintegrations, and in problems connected with fission.

In the following sections she discusses questions that are clearly addressed to the concerns of emulsion practitioners, namely (1.7.2) on Sensitivity of Nuclear Emulsions, (1.7.3.1) on Processing Techniques of Nuclear Emulsions, with clear recipes for research workers, (1.7.3.2) on Water Content of Emulsions, and (1.7.4) on Optical Equipment and Microscopes.

In (1.7.5) Blau discusses in some detail the Range of Particles in Nuclear Emulsions, beginning with (1.7.5.1), Measurement of the Residual Range of Particles in Nuclear Emulsions, and then (1.7.5.2), Range-Energy Relations in Nuclear Emulsions, where she introduces the Bethe-Bloch equation, the fundamental relation describing the energy loss of particles as function of velocity\(^{62}\). In (1.7.5.3) she discusses Range Straggling and in (1.7.5.4) the Range-Energy Relations for Multiply Charged Particles, quoting the seminal work by Barkas\(^{63}\). In (1.7.6) she discusses Ionization Measurement in Emulsions, basing it on Sternheimer’s\(^{64}\) adaptation of the Bethe-Bloch equation to photographic emulsions. This section and the following one (1.7.7), Ionization Parameters: Blob Density, Gap Density, Mean Gap Length and Total Gap Length, include many of the results of our 1960 paper on Ionization Parameters\(^{B72}\).

In section (2.1.1.3) Blau discusses the Charge Determination of Particles in Photographic Emulsions. There are two magnetic methods, namely the “sandwich method” and the magnetic deflection in the emulsion itself. In the “sandwich method”, the measurement is made of deflections of particles traversing the air gap between two parallel emulsion sheets. The curvature of the trajectory of the particle in the magnetic field existing in this gap is determined by the angle between the particle’s exit and entrance directions in the two adjacent emulsions. Although the accuracy of this method could be increased by using wider gaps, the maximum separation is limited by the fact that it becomes increasingly difficult to follow a track. Distortion may also impede the usefulness by causing large errors, especially for tracks with dip angles exceeding 10°. However, the method can be used to obtain at least the sign of the charge.

The other method of magnetic deflection requires distortion free emulsions. It yields an accurate value of the charge only if the magnetic field is large, the path in the field long, and the mean scattering angle $\alpha_{sc}$ is small compared to the magnetic deviation angle $\alpha_m$, where $\alpha_m = (t/\rho)$, where $\rho$ is the radius of curvature of a trajectory which describes a path of circular arc $t$ in a region of field $H$. Then $\alpha_m = (tHz/p)$, where $z$ is the charge of the particle and $p$ is its momentum. The authors in this field have adopted, as a general rule, that the sign of charge of particles in energy range 200-2000MeV can be determined

\[29\]
with 80% probability if the path length is 2 cm and the applied magnetic field is 30,000 gauss. I tried myself to apply this method in 1960 with Derek Prowse at U.C.L.A., but we were met by disappointing results.

¿From the previous discussions on ionization, it was seen that the grain density was expressed by the relation \( g = f(z^2\beta) \). Thus the grain density alone gives no information on \( z \) or \( \beta \) separately. One must then supplement such observations with an independent method, such as scattering, which is a measure of momentum and charge.

Another important parameter for the magnitude of charge determination is the production of \( \delta \) rays. These arise from collisions with atomic electrons in the emulsion when the energy transfer is greater than the average energy given to grains forming the particle trajectory. Thus, the atomic electrons acquire considerable velocities, and hence are able to render several grains developable, thereby forming short trajectories which protrude from the original trace. \( \delta \)-ray measurements were first used to discriminate among charges of energetic heavy primaries which were discovered in the cosmic radiation by Bradt and Peters, and by Freier et al\(^{26}\). Blau then gives an extensive discussion of the application of the \( \delta \)-ray technique.

In Section (2.2.1.1.5) Blau discusses Momentum Measurement in Nuclear Emulsions. This portion of the paper, about twenty pages long, is about as definitive a treatment as I have seen in the literature on the subject of multiple scattering of charged particles through matter, giving an estimate of \( (p\beta) \), where \( p \) is the momentum and \( \beta \) is the velocity. She quotes all the important references in the literature, and also goes into experimental details.

In (2.2.3.8) Blau discusses the Detection and Measurement of Gamma Rays in Photographic Emulsions. She points out that gamma radiation generally causes a general blackening of the emulsions, similar to that of visible light, and is applied qualitatively to biological problems. In physics it becomes more interesting for high energy radiation when electron pair production sets in and electromagnetic cascades start to develop. The study of these cascades, their multiplication, and the energy of individual electron pairs are used for the determination, or at least, estimate of the primary photon energy causing these phenomena. She discusses the opening angle of electron pairs, their energy measurement, the ionization method, and finally the problem of \( \pi^0 \)-meson production and its short decay time, about the limit that can be determined by visual measurements. It was an early great achievement of the emulsion technique.

Finally, in (2.3.5), in volume 5B of the Yuan and Wu, Methods of Experimental Physics, Blau discusses Determination of the Mass of Nucleons in Emulsions. She describes, in some detail, the application of the constant sagitta method, then the Lund photometric method, the so-called mean track width method, and then the mass measurement of particles which do not end in the emulsion.
Had Blau been in better health, it is clear that her last contribution in Yuan and Wu’s book could have become a classic exposition of the emulsion technique in high energy physics as a book of its own. As it stands, even with the passage of about forty years, it remains an important contribution to the literature of experimental particle physics.

A Russian translation of Blau’s contributions was apparently issued in 1965.\textsuperscript{B75}

H. Epilogue

In April 1960, Marietta left by train from Miami, to New York, and then on to Vienna. My family and the Carters bade her an emotional farewell.

I continued to work on our K\textsuperscript{−}-interactions results, and then obtained a grant from the Research Corporation to expose a stack of Ilford K5 emulsion plates to the 800 MeV/c K\textsuperscript{−}-meson beam at the Bevatron in Berkeley. I left Miami in the Summer of 1961 for the University of Trieste, where I had hoped to collaborate with Carlo Franzinetti. Unfortunately, he had just left for the University of Pisa, so I was left to work on the emulsions by myself, and to collaborate with the bubble chamber group at Trieste which was scanning photographs of the antiproton beam at CERN. Since the scanning and measuring devices for the bubble chamber photographs were still in development, I collaborated with a young colleague at Trieste, Mario Ceschia, to perform phenomenological computations on antiproton-proton interactions at laboratory energies from 30 to 180 MeV. We based our analysis on a refinement of the Ball and Chew model\textsuperscript{65} and on the adaptation of modifications of the p−p potential to the \bar{p}−p potential, and found decent agreement with the experimental results then available,\textsuperscript{66} also making predictions on differential cross sections and polarization.

With the help of three scanners, I also found two heavy hyperfragment decays produced by the fast K\textsuperscript{−}-beam\textsuperscript{67}. My stay in Trieste was supported by I.N.F.N. (Istituto Nazionale Fisica Nucleare).

In the Spring of 1962, my family and I traveled from Trieste to Vienna where we met with Marietta Blau at her apartment. She was, of course, a gracious hostess, but the main purpose was to finish our hyperon paper\textsuperscript{B75}. She expressed great displeasure at her treatment by the faculty at the Institut für Radiumforschung, and her inability to engage in productive work. She was clearly not in the best of physical health.

I extended my leave from the University of Miami, by going to the Weizmann Institute of Science in Rehovoth, Israel, in August 1962, with a grant from the Israel Atomic Energy Commission. There I collaborated with a group that had been studying the interactions of K\textsuperscript{−}-mesons with emulsion nuclei with the production of (Σ\textsuperscript{±}+π\textsuperscript{±}). We combined their results with ours from Miami and carried out a detailed analysis of the results. We found that the coulomb effect on the energies of the charged Σ-hyperons and charged π-mesons
was observable, and had an effect on the $\Lambda(1405)$ resonance\textsuperscript{68}.

In 1963 I returned to the University of Miami, where I collaborated with Joseph Cox on a phenomenological treatment of particle scattering\textsuperscript{69}. In the late 1960’s, I collaborated with a group from Northwestern University on experiments using spark chambers designed to measure the magnetic moment of the $\Sigma^+$-hyperon at Argonne National Laboratory. In the 1970’s and early 1980’s I collaborated with a group at the University of Michigan which carried out experiments on high energy polarized proton-proton scattering at Argonne National Laboratory and Brookhaven National Laboratory, where the particle detectors were scintillation counters.

I mention these endeavors mainly to emphasize my debt to the influence and legacy of Marietta Blau over the rest of my life. When I first read the article by Peter Galison in Physics Today in 1997\textsuperscript{4}, I was prompted to send a short letter to Physics Today in 1998\textsuperscript{70}. In it I wrote that my several years of working with Marietta had changed my life. After rereading the present article, I can emphatically reaffirm that remark and express gratitude for my association with that wonderful person. She led me into particle physics, and even if I am dissatisfied with the quality of my achievements, I am grateful for being a participant in interesting experiments, and in having established a world-wide circle of friends and associates in this exciting field.

Actually, these associations were greatly amplified after 1964, when my colleague at the University of Miami, the theorist, Behram Kursunoglu, with my help, established the Center for Theoretical Studies and the now-famous Coral Gables Conferences on Symmetry Principles at High Energy, and which have persisted, with some name changes, to this day. The Center was host to some of the great scientists of our time, including P.A.M. Dirac, R. Feynman, Lars Onsager, J.R. Oppenheimer, E. Wigner, H. Bethe, F. Crick, E. Teller, R. Hofstadter, M. Gell Mann, W. Lamb, J. Schwinger, A. Salam, S. Weinberg, V. Zworykin, among others, and also to a number of gifted post doctoral fellows. After Kursunoglu’s retirement in 1992, we have continued these activities under the auspices of the Global Foundation, and I continue to collaborate with him on problems of unified field theory and astrophysics.

I return now to the subject that must have been the source of great pain and frustration in Marietta Blau’s professional life, namely the official neglect of her role in the discovery of the pion that I mentioned at the beginning of this article. She was too proud and private to reveal this disappointment to me openly, but I do recall that she had great disdain for C.F. Powell. This is corroborated by reading her Acta Phys.Austriaca article\textsuperscript{61} and her article in Yuan and Wu’s book\textsuperscript{74}, where she actually attributed the discovery of the $\pi^-$-meson to Perkins\textsuperscript{59} and that of the $\pi^+$-meson to Lattes, Occhialini and Powell\textsuperscript{60}. I now remember that she thought more highly of Perkins, Lattes and Occhialini than she did of Powell, and felt that the latter was rewarded more for his public posture than for his achievements or abilities.
I think that it is clear from some of the work described in this paper and the summary in Appendix IV, that the pion was the central discovery in nuclear physics after the war. It is interesting to recount briefly the history leading up to this discovery.

In 1935, Hideki Yukawa, the great Japanese theorist, attributed the finite range (≈10^{-15} m) of nuclear forces between nucleons to the existence of a massive field quantum or carrier of integral spin$^{71}$. This has turned out to be a fundamental concept in the theory of fields, and has led to further application in weak interactions. The estimate of the mass of this carrier was about 300 electron masses. There ensued then one of the great nasty tricks that nature plays on the mortal explorers of its secrets. In 1937, C.D. Anderson$^{72}$ observed what was called the $\mu$-meson, or muon, in cloud chambers exposed to the cosmic rays. Anderson, incidentally, had first also observed the positron, or the antielectron, several years earlier, after it had been postulated by P.A.M. Dirac$^{73}$. The muon was found to have a mass of about 206 electron masses, and furthermore it did not interact strongly in nuclear matter as should the Yukawa particle. Hence, the nuclear physicists were faced with the conundrum. The muon was actually also a lepton, or, a “heavy electron”. Thus it was that in 1947, with the discovery of the pion by Perkins, Lattes, et al that the dilemma was resolved. It was suggested first by Marshak and Bethe$^{74}$ that two particles were involved, and indeed the experiments showed that $\pi^+ \rightarrow \mu^+ + \nu_\mu$ and $\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$, and that the pion has a mass of about 274 electron masses, as I have mentioned in Appendix IV. Thus the pion was the “prize plum” that ushered in the great era of high energy physics of the last half of the 20th century.

Marietta Blau’s contributions were central to this discovery, but as I said in the early part of this paper, after the end of the war she was no longer in a position to forge new roads, but still made contributions at a modest level. It is my fervent belief, that had Blau been able to expose her photographic plates in 1938, in the high Alps, with Stefan Meyer’s sponsorship, that she would have been able to detect a $\pi$-meson. This is a poignant example of how social and political upheaval can thwart the purest quest for new knowledge.

As an aside, it is truly remarkable how quickly new devices and techniques are developed. As I mentioned earlier, emulsions were largely supplanted by bubble chambers in the 1960’s, those in turn by spark chambers, then streamer chambers, and now whole new classes of detectors. It is a further irony that at present, high energy physics is again turning toward outer space, with the advent of new detectors in space and on earth. I feel privileged to be a witness to these events.
Acknowledgements

I am grateful to my wife, Lynn Meyer, for her encouragement and for her skillful criticism of this manuscript.

I would also like to thank Judy Mallery for her help in typing this manuscript.
Indeed, I did work with Marietta Blau at Columbia, in the late 40’s. I was a graduate student and she was a Research Associate. As a graduate student, I was in charge of the nuclear emulsions section. Of course, none of us knew anything about emulsions—it took Blau to teach us the techniques of developing, scanning, etc. In this, she was indispensable...We were still building the Nevis Cyclotron (in those days, grad students really built the equipment, tested it, etc., since we had no engineers or post-docs), and for practice, exposed some nuclear emulsions in balloons. We came across a strange event, which we published in ’49. It took until 1999 for me to work again in cosmic rays—I just published a paper in PRL on Dec. 13 (TODAY). I can’t tell you anything about her Brookhaven work. I do know that she was treated rather shabbily at Columbia—but who wasn’t during that era.
Appendix II
My Interactions with Marietta Blau
by S.J. Lindenbaum, Brookhaven National Laboratory
Upton, NY.

After the war I simultaneously was employed as a full time staff member of the “Nevis Cyclotron Laboratories” of Columbia University (1946-1951) and was pursuing my Ph.D. in Physics at Columbia.

I was initially assisting Professor Rainwater (in effect a Deputy Director) under Professor Booth (the Director) in developing the Radio Frequency System for the Nevis approximately 400 MeV Cyclotron design and construction project. However, my duties were soon broadened in this small scientific staff to include most aspects of the Cyclotron Project including planning elements of the future research program.

Marietta Blau was a senior staff member brought in to prepare an emulsion program for the Cyclotron, as she was the well known outstanding pioneer in the emulsion technique and its application to studying Nuclear Stars.

I was asked to look into her program and help where I could. I found Marietta to be almost unbelievably well versed in every aspect of the emulsion techniques even though my expectations were high, considering her reputation as the outstanding pioneer that she was.

She set up a very complete emulsion laboratory, with scanners that she trained herself. Marietta also taught me the emulsion technique at a sophisticated level which was unattainable through reading the literature, which I did.

It was obvious to her that the high data rates an FM Cyclotron would generate in a long program would overwhelm human scanners, and she felt that as much automation as possible should be developed for the scanning and analysis programs, and this would also eliminate most of the biases introduced by human scanning. I totally shared her conclusion, and since I guessed that the first Nevis Cyclotron experiment would be most rapidly done with emulsions, and I had a thesis topic in mind— namely to solve a great uncertainty of the times— what was the process or processes which lead to Cosmic Ray stars.

Thus I began to collaborate extensively with Marietta and an engineer R. Rudin, on the development of a semi-automatic device for analyzing events in nuclear emulsions. This program was successfully completed and published [Rudin, R., Blau, M., Lindenbaum, S.J., Semi-Automatic Device for Analyzing Events in Nuclear Emulsions. Rev. Sci Instr.21,978-985 (1950), and Phys Rev. 78, 319A (1950)].
I believe if emphasis had not quickly shifted to the bubble chamber, and soon thereafter to the electronic "bubble chambers", which I later pioneered, that this semi-automatic device would have become quite important. In any event, it was the first idea which was successfully developed to automate visually observed events, and likely influenced future developments. Marietta Blau, in addition to being an outstanding scientist, was a warm and caring individual whose company was always very much enjoyed by myself, and her colleagues, and although a quiet individual, she certainly stimulated me and other colleagues greatly.

I went on to do my thesis–the first Nevis experiment - by exposing minimum ionization track sensitive emulsions to internal 350-400 MeV proton beam and demonstrated, that contrary to the most popular belief at the time–that the Fermi Statistical Theory explained the major mechanism of Nuclear Star Formation – that actually a cascade of individual nucleons was the major element in Star production, and that the only role of the Fermi Statistical theory was to cause a thermodynamic evaporation due to rearrangement of the holes in the Fermi sea produced by the nucleonic cascade [Bernardini G. Booth E.T. Lindenbaum S.J., Phys. Rev. 80, 905 (1950), Phys. Rev. 83, 669-671, (1951), Phys. Rev. 82, 307 (1951), Phys. Rev. 85, 826-834, (1952), Phys. Rev. 88, 1017-1026 (1952).

Although Marietta Blau did not participate in this extensive important program, it was the laboratory she developed which was used for it.
I was privileged to be one of Professor Blau’s graduate students – perhaps her last one. Under her direction, I earned a Master’s degree while participating in her research project at the University of Miami, funded by the Air Force Office of Scientific Research. The research was based on the use of nuclear emulsions to study fundamental particle interactions. This work resulted in one of my first publications, which was one of Professor Blau’s last publications:

“Studies of Ionization Parameters in Nuclear Emulsions” in Review of Scientific Instruments 31, 289-297 (1960), M. Blau, S.C. Bloch, C.F. Carter, and A. Perlmutter.

I was also a student in Professor Blau’s course in nuclear physics. She was an excellent teacher, very demanding, and respected by her students. As in her research, she had high standards and expected the best from students.

Professor Blau was no less demanding from her colleagues. I was in her office one day when she was berating another professor, saying, “You know nothing about fundamental particles!”
A Brief Tutorial on Units and Nomenclature in Particle Physics.

The masses and charges of elementary particles have been established by a variety of methods over the course of the past century. For example, the mass of the electron is about \( m_e = 9.11 \times 10^{-31} \text{kg} \) and its charge is \( q_e = -e \), where \( e = 1.60 \times 10^{-19} \text{coulomb} \). The mass of the proton is \( m_p = 1.67 \times 10^{-27} \text{kg} \) and its charge is \( q_p = +e \). As far as we know, these are the only stable elementary particles, and are, along with the neutron, which has no charge and a mass slightly larger than that of the proton, the principal constituents of the atom. All other known particles have charges which are either neutral \((q = 0)\) or are positive or negative multiples of \( e \), with the exception of quarks, which I will discuss later.

As for masses, it is much more convenient to make use of Einstein’s famous relation, \( E_0 = mc^2 \), where \( E_0 \) is called the rest energy, \( m \) is the mass of the particle in kg, and \( c = 3.00 \times 10^8 \text{m/s} \) is the approximate speed of light. This allows one to introduce another energy unit, the electron volt (eV), where \( 1 \text{eV} = 1.60 \times 10^{-19} \text{Joules} \). Then, the electron has a rest energy of about \( E_{oe} = 0.511 \times 10^6 \text{eV} = 0.511 \text{MeV} \), and the proton a rest energy of about \( E_{op} = 938.3 \text{MeV} \), or about 1840 times that of the former. The free neutron has a rest energy of about \( E_{on} = 939.6 \text{MeV} \) and decays (weakly) in about 14.8 minutes to a proton, an electron and an anti-electron neutrino, i.e., \( n \rightarrow p + e^- + \bar{\nu}_e \). The neutron is stable only when it is bound in an atomic nucleus.

The principal units utilized in giving energies or mass energies, are \( \text{KeV}(10^3 \text{eV}) \), \( \text{MeV}(10^6 \text{eV}) \), \( \text{GeV}(10^9 \text{eV}) \) and \( \text{TeV}(10^{12} \text{eV}) \). Prior to the 1960’s \( \text{BeV} \), was used for \( 10^9 \text{eV} \), but since the \( B \) stood for “billion” in the U.S.A., and “billion” in Britain meant \( 10^{12} \), it was decided to represent \( 10^9 \) by the prefix Giga, hence GeV.

The total energy of a particle is given by \( E = K + E_0 \), where \( K \) is the kinetic energy. The relation \( E = \sqrt{p^2 c^2 + E_0^2} \), where \( p \) is the momentum, is very useful. Here, it is seen that the unit for \( p \) is conveniently \( (\text{eV}/c) \) where \( c \) is the speed of light.

The terminology used to identify various particles, radioactive nuclei and radiation has undergone some changes over the years. But the early designation by E. Rutherford at the beginning of the last century of the various radiations emanating from radioactive nuclei as \( \alpha, \beta, \gamma \) are still in use. \( \alpha \)-radiation refers to the nuclei of helium atoms, with charge \(+2e\) and a mass nearly four times that of a proton. Hence, \( \alpha \)-particle is synonymous with helium nucleus \( ^4_2 \text{He} \). \( \beta \)-radiation refers to electrons, of charge \((-e)\) and mass \( m_e \), emitted from nuclei—identical with the electrons in the outer regions of the atom. Since the discovery of the electron’s antiparticle, the positron, \( (e^+) \) whose charge is \(+e\) and mass \( m_e \), the term \( \beta \) is generic for both \( e^- \) and \( e^+ \). The third kind of radiation, \( \gamma \), refers to gamma radiation, high energy photons, of no mass or charge, and with energies from a few KeV up to many TeV. Actually, \( \gamma \) is a generic term for photon, which can also refer to radio, microwave or visible light. In nuclear and particle physics, gamma rays emanate
from nuclei, as contrasted with x-rays, which are produced by transitions of closely bound atomic electrons. Generally speaking, gamma rays are more energetic than x-rays.

Here, it might be useful to consider some of the principle elementary particles. The $\pi$-meson, or pion, comes in a family of three, $\pi^+, \pi^-, \pi^0$, where the rest energies are about $m_{\pi^\pm} = 139.6\text{MeV}$ and $m_{\pi^0} = 135.0\text{MeV}$, and decays according to the schemes, $\pi^+ \rightarrow \mu^+ + \nu_\mu$, and $\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$, both in about $2.6 \times 10^{-8}$ seconds, and $\pi^0 \rightarrow \gamma + \gamma$ in about $8.4 \times 10^{-16}$ seconds ($\gamma$ is the symbol for massless photon). The $\mu^\pm$-lepton (originally called $\mu$-meson, and now muon) is some times called the “heavy electron”, has a mass of about $105.7\text{MeV}$, and decays in about $2.2 \times 10^{-6}$ seconds, according to the schemes $\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$ and $\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$, where $\nu_e$ and $\nu_\mu$ stand for two kinds of neutrinos, both of which were considered to be massless until the past few years, when underground experiments at Kamiokande in Japan, and elsewhere, indicate that neutrinos have a very small rest energy of about or less than $1\text{eV}$, thus supplanting the electron as the lightest particle (photons, of course, have zero rest energy, or at best $1\text{eV}$).

There is another lepton, discovered only in the 1970’s, $\tau$-lepton, with a rest energy of about $1777.1\text{MeV}$ and which decays via many modes, in about $2.96 \times 10^{-13}$ seconds, all involving a $\nu_\tau$ or $\bar{\nu}_\tau$, to muons, and to various combinations of pions and kaons. It also comes with positive or negative charge $\pm e$.

The kaon (or K-meson) called a “strange” particle, discovered shortly after the pion in 1948, comes in several varieties, $K^+, K^-, K^0, \bar{K}^0$, and has rest energies of about $E_{0K^\pm} = 493.7\text{MeV}$ and $E_{0K^0} = 497.7\text{MeV}$. The lifetime of $K^\pm$ is about $1.24 \times 10^{-8}$ seconds and has many decay schemes, including $K^+ \rightarrow \mu^+ + \nu_\mu$, $K^- \rightarrow \mu^- + \bar{\nu}_\mu$, and also $K^\pm \rightarrow (3\pi)$ (originally called a $\tau^\pm$-meson) and $K^\pm \rightarrow (2\pi)$ (originally called a $\theta$-meson). The $K^0$ comes in two principal varieties, $K^0_s$($K^0$-short) and $K^0_L$($K^0$-long), with lifetimes of about $0.89 \times 10^{-10}$ seconds and about $5.2 \times 10^{-8}$ seconds. They oscillate between each other, and are responsible for the observation of time reversal non-invariance.

The hyperons, which first appeared in the late 1940’s, 1950’s and 1960’s, are also called strange particles and all have rest energies larger than that of the proton. The lightest of these is the $\Lambda^0$(1115MeV), then a family called $\Sigma$ comprised of $\Sigma^+$(1189MeV), $\Sigma^-$($1197\text{MeV}$), $\Sigma^0$(1192MeV). The $\Sigma^+$ and $\Sigma^-$ decay mainly into nucleon (n or p) and pion ($\pi^+, \pi^-$, or $\pi^0$) in a time less than $10^{-10}$ seconds, while the $\Sigma^0$ decays in about $10^{-19}$ seconds into a $\Lambda^0$-hyperon and a photon. The heaviest of these hyperons is the $\Xi$, which appears in two charge states, the $\Xi^0$(1315MeV) and $\Xi^-$($1321\text{MeV}$), and decay mainly into $\Lambda^0$ and $\pi^0$ or $\pi^-$ in times of about $10^{-10}$ seconds. The six hyperons named here, and the two nucleons, proton ($p$) and neutron ($n$) form an octet of particles in one of the early classification schemes established by M. Gell Mann in 1961. In the same spirit, the mesons $\pi^+, \pi^-, \pi^0, \eta, K^-, \bar{K}^0, K^+, K^0$, form the lowest octet in this scheme, where the $\eta$ is a neutral meson resonance of rest energy $547\text{MeV}$, decaying mainly into three pions or two photons in about $3.4 \times 10^{-18}$ seconds.

These classification schemes were obtained by introduction of quarks, by M. Gell
Mann and G. Zweig. They postulated that there are three quarks \( u \) (up), \( d \) (down), and \( s \) (strange) of charges \(-1/3e, 2/3e, \) and \(-1/3e\), respectively and their antiparticles, which are the constituents of mesons (2 quarks) and baryons (3 quarks). In the 1970’s and 1980’s and 1990’s there were postulated and confirmed three more quarks, \( c \) (charm), \( b \) (bottom), and \( t \) (top), which generated an explosion of information and theoretical progress. For the purposes of this paper it is necessary only to mention that the first decuplet of baryon resonances, which we discussed in section E\( E_{69} \), could be understood as a grouping of \( u, d \) and \( s \) quarks.

There is a related way of describing particle groupings that preceded these schemes, introduced by W. Heisenberg to describe atomic nuclei, namely isospin (I). This quantity can take on values \( I = 0 \) (singlets, such as \( \Lambda^0 \), \( I = 1/2 \) (doublets, such as \( n \) and \( p \) ), \( I=1 \) (triplets, such as \( (\Sigma^+, \Sigma^0, \Sigma^-) \) and \( I = 3/2 \) (quartets, such as \( (\Delta^-, \Delta^0, \Delta^+, \Delta^{++}) \), etc.

While quarks have not been seen in a free state, since they are confined to elementary particles by strong forces involving also gluons, they can be detected only indirectly, but their utility in bringing an order to hundreds of particle states has been of inestimable value.

Originally, mesons were so named because they had masses intermediate between electron and proton. Now, with the discovery of heavier mesons arising from the heavier quarks, \( c, b \) and \( t \), mesons may be much heavier than protons. More fundamental is the fact that because mesons are composed of two spin 1/2 quarks, they must have integer spin, i.e., 0, 1, 2, 3... and they are designated as Bose-Einstein particles, or bosons. They obey quite different statistics from Fermi-Dirac particles, or fermions, which have half-integer spin, i.e. \( \frac{1}{2}, \frac{3}{2}, \frac{5}{2}, \ldots \). Baryons, which are composed of three spin 1/2 quarks, are therefore fermions, as are also electrons, muons, tauons, and neutrinos.

For the reader who wishes to go beyond the early results discussed in this paper, I can recommend several of many good publications. One is the Physical Review, Review of Particle Properties, \( D_{50}, \) No. 3, (1 August 1994). This one is the more or less official compendium and probably contains more information than most people need. A new update of this should appear shortly. A more accessible source is “Introduction to High Energy Physics”, by Donald H. Perkins, 3rd Edition, Addison-Wesley Publishing Company, Inc. 1987.
Footnotes

1 Peter Galison, *Image and Logic: A Material Culture of Microphysics*, University of Chicago Press (Chicago and London) 1997.

2 Walter Moore, *Schrödinger, life and thought* (Cambridge University Press) 1989, pp. 479-480.

3 Max Born, *Atomic Physics*, Blackie and Son Ltd., the (Glasgow) 1969, pp. 36-37.

4 Peter Galison, *Physics Today* 50, 42, Nov. 1997.

5 Leopold Halpern in *Women in Chemistry and Physics; a Bibliographical Sourcebook* Edited by L.S. Grinstein, R.K. Rose, and M.H. Rafaelovich, Greenwood Press (Westport, Connecticut and London), 1993, pp. 50-56.

6 Nina Byers, *Contributions of 20th Century Women to Physics* ([http://www.physics.ucla.edu/~cwp/phase2/Blau/Marietta@843727247.html](http://www.physics.ucla.edu/~cwp/phase2/Blau/Marietta@843727247.html)).

7 C.F. Powell, P.H. Fowler and D. Perkins, *The Study of Elementary Particles by the Photographic Method*, Pergamon Press (New York, London, Paris, Los Angeles) 1959.

8 J.B. Birks, *The Theory and Practice of Scintillation Counting*, The MacMillan Company in (New York) 1964.

9 S.C. Curran and W.R. Baker, U.S. Atomic Energy Report MDDC, 1296, 17th Nov (1944); Rev. Sci. Instr. 19, 116 (1948).

10 J.W. Coltman and F.H. Marshall, Nucleonics 1, 358 (1947); F.H. Marshall and J.W. Coltman, Phys. Rev. 72, 528 (1947); F.H. Marshall, J. Coltman and A.I. Bennett, Rev. Sci. Instr. 19, 744 (1948); F.H. Marshall, J.W. Coltman and L.P. Hunter, Rev. Sci. Instr. 18, 504 (1947).

11 I. Broser and H. Kallmann, Z. Naturforsch. 29, 439, 642 (1947); H. Kallmann, Natur und Technik (July, 1947); Phys. Rev. 78, 621 (1950).

12 P.R. Bell, Phys. Rev. 73, 1405 (1948).

13 R. Hofstadter, Phys. Rev. 74, 100 (1948).

14 H. Petterson, BerIIa, Wien 132, 55 (1923).

15 R.D. Evans, Nucleonics 1, no. 2, 32 (1947).

16 C.C. Dilworth, G.P.S. Occhialini, and R.H. Payne, Nature 162, 102 (1948).

17 Crabtree, Parker, and Russel, Soc. Mot. Pic. ENO, VO RR 21, 21 (1933).

18 J. Rotblat “Photographic Emulsion Technique”, Prog. in Nucl. Phys., 1, 37-72 (1950).

19 C.M.G. Lattes, P.M. Fowler, and P. Cuer, Proc. Phys. Soc. London 59, 883 (1947).

20 C.M.G. Lattes, G.P.S. Occhialini, and C.F. Powell, Nature 160, 486 (1947).

21 J.H. Webb, Phys. Rev. 74, 511 (1948).

22 D.H. Perkins, Nature 159, 126 (1947).

23 P. Debye and E. Hückel, Physik. Zeits. 24, 185 (1923).

24 See Appendix I, “Recollections of Marietta M. Blau”, Martin M. Block (Dec. 13, 1999).

25 See Appendix II, “My Interactions with Marietta Blau”, S.J. Lindenbaum (Feb 21, 2000).

26 H.L. Bradt and B. Peters, Phys. Rev. 74, 1828 (1948); P. Frier et al, Phys. Rev. 74, 413 (1948).

27 S.J. Lindenbaum, Columbia University thesis 1951.

28 J.B. Harding, Nature 163, 440 (1949); Phil. Mag. 42, 63 (1951).
This leads to a nominal mass of the isobar state to be $m_p + m_\pi + Q = (940 + 140 + 150)\text{MeV} = 1230 \text{MeV}$, remarkably close to the mass of the $\Delta$ resonance of 1232 MeV. Remember that this was several years before the advent of the quark model and the identification of the lowest lying decuplet composed of an $I = 3/2$, $\Delta(1232)$; $I = 1$, $\Sigma(1385)$; $I = \frac{1}{2}$, $\Xi(1530)$; $I = 0$, $\Omega^-(1672)$. The numbers in parentheses are the approximate rest energies of the $\Delta$ resonances in MeV. The width of the $\Delta$ resonance is 120 MeV, in agreement with the paper’s result. As far as I know, this was the first evidence for the $\Delta$ resonance, in this case a $\Delta^0$, allegedly composed of an up- and two down- quarks. Hence, although we were disappointed not to match the predictions of the isobar model, it is gratifying, in retrospect, to give early evidence for the $\Delta$ resonance.

43 N. Metropolis, R. Bivins, M. Storm, J.M. Millerr, G. Friedlander and A. Turkevich, Phys. Rev., 110, 204 (1958).
44 P. Demers, Can. J. Research A25, 223 (1947).
45 P.H. Fowler and D.H. Perkins, Phil. Mag. 46, 587 (1955).
46 G. Alexander and R.H. W. Johnston, Nuovo Cimento 5, 363 (1957).
47 Castagnoli, Cortini, and Manfredini, Nuovo Cimento 2, 301 (1955).
48 C. O’Ceallaigh, Nuovo Cimento, Suppl. 12, 412 (1954).
49 M.G. Menon and C.O’Ceallaigh, Proc. Roy. Soc. (London) A221, 292 (1954).
50 S.C. Bloch, Rev. Sci. Instr. 29, 789 (1958).
51 See Appendix III, “Recollections of Marietta Blau at Miami”, S.C. Bloch, (April 3, 2000).
52 K$^-$ Collaboration, Nuovo Cimento 13, 690 (1959); 14, 315(1959); 15, 873 (1960).
53 J. Schneps, Phys. Rev. 112, 1335(1958); Y.W. Kang, N. Kwak, J. Schneps and P.A. Smith, Nuovo Cimento 22, 1297 (1961).
54 A. Deloff, J. Szymanski and J. Wrzeconko, Polish Academy of Sciences, Institute of Nuclear Research, Report no. 95/VII, (June 1959).
55 F. Ferrari and L. Fonda, Nuovo Cimento 7, 320 (1958); N. Dallaporta and F. Ferrari, Nuovo Cimento, 5, 111 (1957).
56 M. Baldo-Ceolin, W.F. Fry, W.D. B. Greening, H. Huzita and S. Limentani, Nuovo Cimento 6, 144(1957); R.C. Kumar and F.R. Stannard, Nuovo Cimento 14, 250 (1959).
57 E. Gandolfi, J. Hengheboart and E. Quercigh, Nuovo Cimento 13, 864 (1959).
58 F.R. Stannard, Phys. Rev. 121, 1513 (1961).
59 D.H. Perkins, Nature 159, 126 (1947).
60 C.M. G. Lattes, G.P.S. Occhialini and C.F. Powell, Nature 160, 486 (1947).
61 R.H. Brown, V. Camerini, P.H. Fowler, H. Muirhead, C.F. Powell and D.M. Ritson, Nature, 163, 82 (1949).
62 F. Bloch, Z. Physik 81, 363 (1933).
63 W.H. Barkas, Phys.Rev. 89, 1019 (1953); W. H. Barkas, F.M. Smith and W. Birnbaum, Phys. Rev. 98, 605 (1955).
64 R.M. Sternheimer, Phys.Rev. 88, 851 (1952); Phys.Rev. 91, 256 (1953).
65 J.S. Ball and G.F. Chew, Phys.Rev. 109, 1385 (1958); J.S. Ball and J.K. Fulco, Phys.Rev. 113, 647 (1959).
66 M. Ceschia and A. Perlmutter, Nuovo Cimento 33, 578 (1964).
67 A. Perlmutter, Phys.Lett. 4, 336 (1963).
68 M. Friedmann, D. Kessler, A. Levy, A. Perlmutter, Nuovo Cimento 35, 355 (1965).
69 J. Cox and A. Perlmutter, Nuovo Cimento 37, 761 (1965).
70 A. Perlmutter, Physics Today, 49, 84, August 1998.
71 H. Yukawa, Proc.Phys. Math. Soc. Japan 17, 48 (1935).
72 C.D. Anderson and S. Neddermeyer, Phys.Rev. 51, 884 (1937); 54, 99 (1938).
73 P.A.M. Dirac, Proc. Roy. Soc. A117, 610 (1928).
74 R. Marshak and H. Bethe, Phys.Rev. 72, 506 (1947).
75 M. Gell Mann, Phy. Lett. 8, 214 (1964); G. Zweig, CERN Report 8419/Th 412, 1964.
76 W. Heisenberg, Z. Physik 77, 1 (1932).