Weisskopf Tribute: Speeches/CERN Courier special issue, December 2002

Research highlights by J D Jackson

I describe some highlights in Viki's career as a physicist. My coverage is restricted to his research and publications in peer-reviewed professional journals, with a brief mention of his personal circumstances along the way. I leave to others the many other contributions in his multifaceted career – as conscience of our profession, as administrator, as international statesman,
as essayist and popularizer of science. Viki's research career divides itself rather naturally into three phases: radiation and matter; quantum electrodynamics (QED) and quantum field theory; and nuclear physics, with some leakage of QED into phase 3.

Viki was born Victor Frederick Weisskopf in Vienna on 19 September 1908. He died at his home in Newton, Massachusetts on 22 April 2002. In his teens he attended a gymnasium and then the University of Vienna for two years, before going to Göttingen on the recommendation of Hans Thirring, professor of theoretical physics in Vienna.

First research and publication

Now, many of you are thinking: "Ah, yes, Weisskopf-Wigner". However, Viki's career as a scientist did not begin in Göttingen in 1928, but five years earlier, and not as a physicist. The location and date of Viki's first research can be pinpointed exactly. The Weisskopf family had a summer home at a small resort village, Altaussee, about 80 km east-south-east of Salzburg in a region of lakes and modest mountains. On the night of 10 August 1923, when Viki was not yet 15, he and a friend, George Winter, spent several hours on top of "Loser", an 1800 m peak, 2 km from Altausser See. They observed a total of 98 shooting stars of the annual Perseid shower that they classified as to colour and appearance. The results of their investigation were published in Astronomische Nachrichten in March 1924 (Winter and Weisskopf, 1924). Viki's first research was as an astronomer! It is not many of us who can claim a first research publication at age 15.

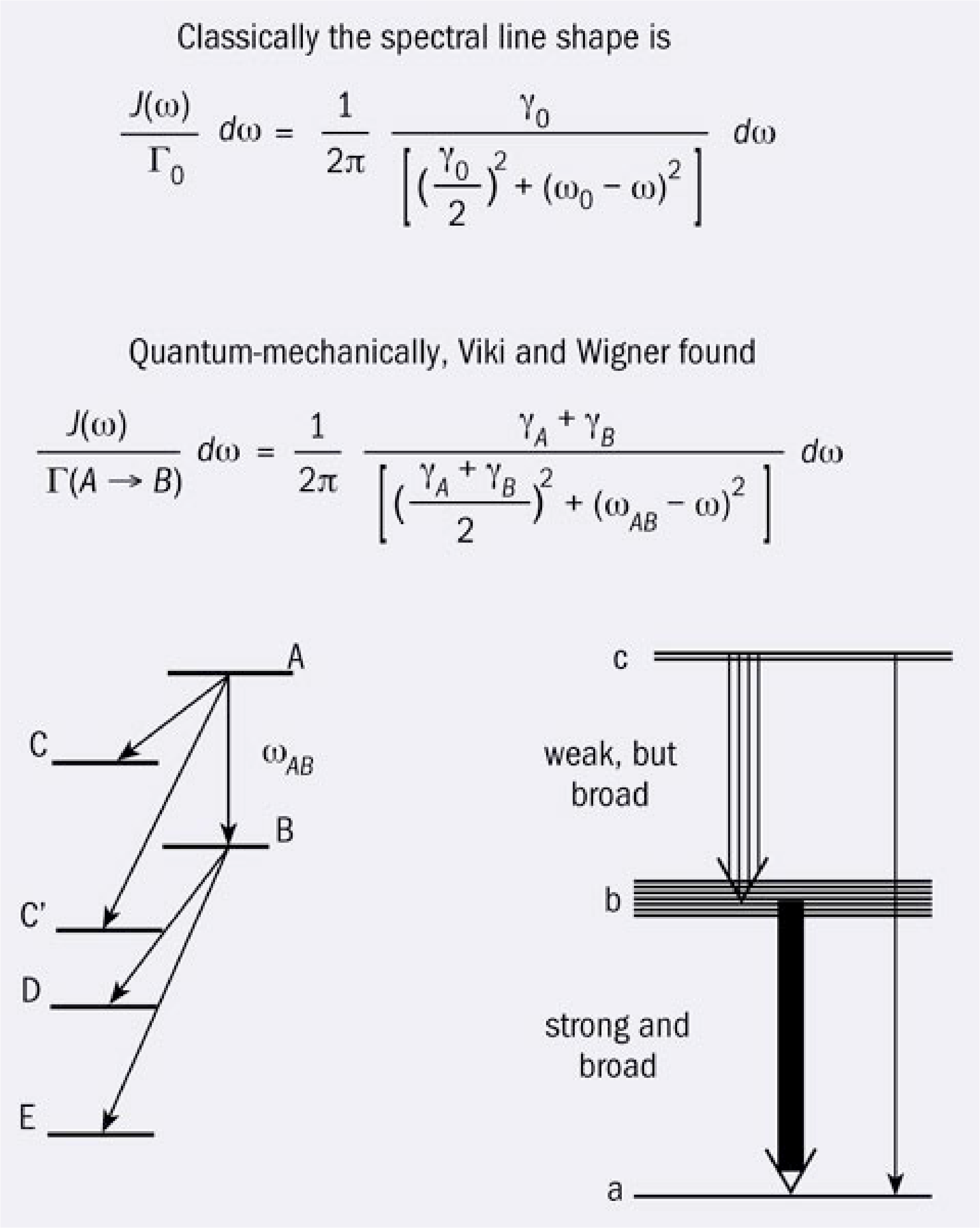
Figure 1
Weisskopf at age 20, about to begin his studies at Göttingen. (Courtesy of the Weisskopf family.)

PHASE 1: RADIATION AND MATTER

Now back to the chronology. In the autumn of 1928 at age 20, Viki began his studies towards his PhD in Göttingen. Max Born was the professor of theoretical physics; Walter Heitler, Lothar Nordheim, and Gerhard Herzberg were junior faculty. Herzberg taught Viki quantum mechanics. Viki's research was nominally under Born, but Born was not well. Viki was left on his own. He began the first phase of his physics research career - the interaction of radiation with matter.

Weisskopf-Wigner

He began to investigate the problem of emission of radiation by atoms. He was able to make progress on a two-level quantum system, but not beyond. He sought help from Eugene Wigner, who was then in Berlin, but came back to Göttingen for regular visits. Wigner became Viki's mentor and the collaboration led to two papers published in 1930 (Weisskopf and Wigner, 1930a, 1930b). The first, and most important, paper covers the exponential decay of excited atomic states and the natural breadth of the associated spectral lines. Their technique was to solve the time-dependent amplitude equations exactly, but to limit the number of matter states involved. In contrast to the semiclassical result, where an intense line was necessarily broad and a weak line narrow, the quantum theory accommodated broad, but weak, lines, as indicated in figure 2. The Weisskopf-Wigner approach has found wide applicability.



Classically the spectral line shape is

$$\frac{J(\omega)}{\Gamma_0}\,d\omega = \frac{1}{2\pi}\,\frac{\gamma_0}{\left[\left(\frac{\gamma_0}{2}\right)^2 + (\omega_0 - \omega)^2\right]}\,d\omega$$

Quantum-mechanically, Viki and Wigner found

$$\frac{J(\omega)}{\Gamma(A \rightarrow B)}\,d\omega = \frac{1}{2\pi}\,\frac{\gamma_A + \gamma_B}{\left[\left(\frac{\gamma_A + \gamma_B}{2}\right)^2 + (\omega_{AB} - \omega)^2\right]}\,d\omega$$

Figure 2

Classical and quantum expressions for line breadth (bottom). The explanation of weak but broad spectral lines.

PhD thesis - resonance fluorescence

Because Wigner had collaborated with him, Viki could not use the line-breadth work for his thesis. Instead, he worked out the theory of resonance fluorescence, that is, the absorption and re-emission of light by atoms, especially with the frequency of the incident beam near that of a difference frequency between two energy levels of the atom. He took his PhD examination in April 1931. Viki's thesis was published later that year (Weisskopf, 1931). In it he thanks his official thesis supervisor, Born, the experimenter James Franck, and Wigner for effective assistance and discussions.

As a new PhD, Viki went first to Leipzig, joining Yoshio Nishina, Felix Bloch and George Placzek, to work with Werner Heisenberg. Christmas 1931 he was invited to Berlin for the spring term by Erwin Schrödinger, to be Schrödinger's assistant in Fritz London's temporary absence. During the term, Schrödinger arranged a one-year Rockefeller fellowship for Viki to begin in autumn 1932. For the long summer period, Viki and his then girlfriend went to Kharkov in the Soviet Union where Lev Landau was. During this period Viki continued working on the interaction of radiation and matter - Doppler and collisional broadening of spectral lines, scattering of radiation by excited atoms and lifetimes of excited states.

Viki's plan for his Rockefeller grant was to spend six months in Copenhagen with Niels Bohr and six months in Cambridge with Paul Dirac. In the event, because of his stimulating time at the Bohr Institute and Ellen Tvede (whom he met on his second day in Copenhagen), he stayed eight months, going to Cambridge in May 1933. There he had the well-known difficulty in interaction with Dirac, but found instead Rudolf Peierls, there on a Rockefeller grant for the whole year. Peierls taught Viki some quantum field theory and how to do the "alpha gymnastics" of computations with the Dirac equation. During his time in Cambridge he received an invitation to work as Wolfgang Pauli's assistant in Zurich, succeeding Hendrik Casimir.

PHASE 2: QUANTUM ELECTRODYNAMICS AND QUANTUM FIELD THEORY

Viki's two years with Pauli were very fruitful. I will not repeat the self-deprecating stories that Viki told of Pauli's put-downs. He recounts some of them in his autobiography (Weisskopf, 1991 pp75-83).

Self-energy

Pauli set Viki the problem of calculating the electromagnetic self-energy of an electron in the framework of Dirac's hole theory - spin 1/2 electrons and their antiparticles (positrons) - rather than the single-particle Dirac theory. The self-energy diverges linearly (with inverse size) classically and quadratically in the single-particle Dirac theory. Viki unfortunately made an error of sign and found an incorrect result - the same degree of divergence as in the one-electron theory (Weisskopf, 1934a). With the help of Wendell Furry he soon corrected the error (Weisskopf, 1934b). The divergence in hole theory (QED) was less, only logarithmic instead of the quadratic divergence of the one-electron theory. Viki said: "My calculation resulted in one of the darker moments of my professional life. I made one of those minor errors that can have a big effect. Somehow I confused a plus sign with a minus sign, and the self-energy I came up with turned out to be very large. Field theory seemed to make things even worse," (Weisskopf, 1991 p80). With Furry's help he recovered. They were the first to show that QED helps to lower the degree of divergence appreciably. Viki returned to this problem five years later, as we see below.

The other important paper of the Zurich years is the Pauli-Weisskopf paper on the field theory of charged scalar particles (Pauli and Weisskopf, 1934). Dirac's hole theory was conceptually bizarre and repugnant to Pauli. The single-particle Dirac equation has both positive energy and negative energy solutions, with a gap in energy -mc2 < E < mc^2. Dirac postulated that all of the states below -mc2, called the negative-energy sea, were filled according to the Pauli exclusion principle for spin 1/2 particles and not directly observable. If energy greater than $2mc^2$ is supplied, one of the negative-energy electrons in the sea can be knocked out into the positive-energy region. The result is a positive-energy electron, plus a "hole" in the sea. The hole can be identified with an antiparticle that has a charge that is opposite to the electron: that is, a positron. A particle-antiparticle pair is produced. Despite its rather ugly nature, Dirac's hole theory was successful. Phenomena such as relativistic bremsstrahlung and pair production were calculated by Hans Bethe and Heitler.

The Klein-Gordon equation and scalar particles

Now, there is another relativistic single-particle equation, the Klein-Gordon equation, describing particles without spin (scalar particles). It too has both positive- and negative-energy solutions. But because the hypothesized particles have zero spin, one could not imagine a Dirac-like sea of filled negative-energy states - there is no Pauli principle for spinless particles. It appeared that the idea of particles and antiparticles was unique to spin 1/2 particles described by the Dirac equation. Nevertheless, Viki began to investigate the quantum field theory of scalar particles in interaction with the electromagnetic field. He found with Pauli's help that the field theory contained charged particles of the same mass and equal and opposite electric charges. A field theory of scalar particles has particles and antiparticles, too. Pauli asked Viki to calculate photoproduction of particle-antiparticle pairs to compare with the Bethe-Heitler calculation for spin 1/2. The spin-zero result is essentially the same as the spin 1/2 expression, which differed only by having some relatively small additional terms coming from the magnetic-moment interactions of the spin 1/2 particles. While the paper might be viewed merely as a theoretical exercise in the absence of any fundamental scalar charged particles in nature, it was important at the time. It clarified minds by showing that particles and their antiparticles were not unique to Dirac's theory of electrons and positrons, and that scalar QED gave results similar to spin 1/2 QED.

Marriage and a second year and a half in Zurich

Viki had been very productive during his first year in Zurich, perhaps in part because he was alone. Ellen and he had agreed to test their love with a one-year separation. The test proved successful and they were married in Copenhagen on 4 September 1934. During his second year he continued on topics in electrodynamics, beginning to investigate the properties of the vacuum in QED. This line of study reached fruition in Copenhagen in 1936.

Copenhagen II (1936-1937)

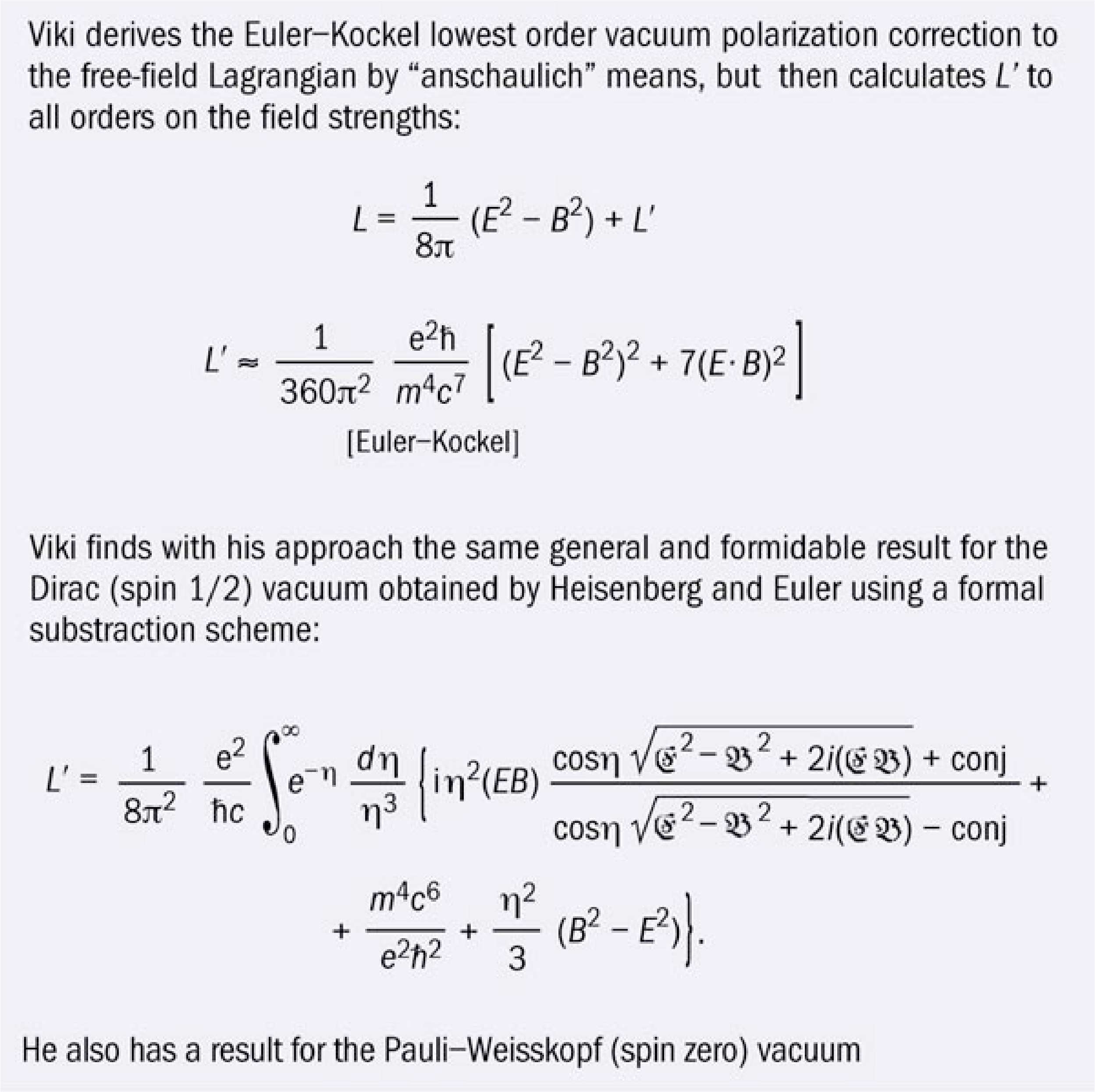
As his term with Pauli was ending, Viki received from Bohr a fellowship to work in Copenhagen where he spent the next two years. At the Bohr Institute, nuclear physics was beginning to be emphasized in addition to basic problems in quantum mechanics and field theory. Of the stimulating atmosphere at the institute, Viki said: “Influenced by this remarkable group, I wrote two of my best papers during that time.” (Weisskopf, 1991 p95).

Vacuum polarization

The first paper is on “polarization of the vacuum”, that is, the properties of the vacuum in the presence of virtual electron-positron pairs and their interaction with electromagnetic fields. This paper (Weisskopf, 1936) is perhaps the most technically sophisticated of Viki’s papers. It is a tour de force not repeated until Julian Schwinger’s 1950 paper on the same topic. The subject had been discussed by Heisenberg and Euler within the framework of a formal subtraction scheme of Heisenberg’s, but Viki addressed it comprehensively in a transparent way with the physical assumptions made very clear. After presenting an anschaulich derivation of the Euler-Kockel first correction to the Lagrangian of the free electromagnetic field, he extended the results to full generality. The preliminaries had yielded three infinite quantities in field-free space – the total energy of the vacuum electrons, their charge and current densities, and the constant field-independent electric and magnetic polarizabilities of the vacuum. He asserted that these properties were unobservable and physically meaningless. They could therefore be subtracted to leave a finite, meaningful description of electromagnetic field interactions in the vacuum. He then said:

“It should also be added that the polarizability could in no way be observed, but would only multiply all charges and field strengths by a constant factor.”

This is a prescient statement of the charge and wave-function renormalization of modern theory. Figure 3 displays the Euler-Kockel approximation and Weisskopf’s more complete result, in agreement with Heisenberg and Euler and thereby lending support to their subtraction methods.



Viki derives the Euler–Kockel lowest order vacuum polarization correction to the free-field Lagrangian by “anschaulich” means, but then calculates L' to all orders on the field strengths:

$$L = \frac{1}{8\pi}(E^2 - B^2) + L'$$

$$L' \approx \frac{1}{360\pi^2}\,\frac{e^2\hbar}{m^4c^7}\left[(E^2 - B^2)^2 + 7(E\cdot B)^2\right]$$

[Euler–Kockel]

Viki finds with his approach the same general and formidable result for the Dirac (spin 1/2) vacuum obtained by Heisenberg and Euler using a formal substraction scheme:

$$L' = \frac{1}{8\pi^2}\,\frac{e^2}{\hbar c}\int_0^\infty e^{-\eta}\,\frac{d\eta}{\eta^3}\left\{i\eta^2(EB)\,\frac{\cos\eta\sqrt{\mathfrak{E}^2 - \mathfrak{B}^2 + 2i(\mathfrak{E}\mathfrak{B})} + \text{conj}}{\cos\eta\sqrt{\mathfrak{E}^2 - \mathfrak{B}^2 + 2i(\mathfrak{E}\mathfrak{B})} - \text{conj}} + \right.$$
$$\left. + \frac{m^4c^6}{e^2\hbar^2} + \frac{\eta^2}{3}(B^2 - E^2)\right\}.$$

He also has a result for the Pauli–Weisskopf (spin zero) vacuum

Figure 3
Euler-Kockel approximation to L´, the correction to the classical Lagrangian for free fields, and the formidable complete expression.

Evaporation model of particle emission from nuclei

The second paper (Weisskopf, 1937) showed Viki joining Bohr and others in exploring Bohr’s picture of the compound nucleus in nuclear reactions. Bohr’s idea was that an incident particle captured by a heavy nucleus rapidly loses its identity and transfers its energy to the general excitation of the system. In a second independent stage the excitation energy is given up, most frequently by emission of one or more particles. Viki addressed this second stage via statistical methods. He masterfully marshalled the fragments of theory and experiment to give formulae that describe fast neutron emission and neutron widths of highly excited nuclear states. Detailed balance and nuclear-level densities expressed in terms of entropies were important ingredients. These results became known as the “evaporation model” for nuclear reactions. I am not sure how many post-war nuclear physicists know that Weisskopf was the first to do more than hand-wave.

PHASE 3: NUCLEAR PHYSICS (WITH A LITTLE QED)

When in Berlin in 1932, Viki had witnessed Nazi brutality towards Jews and other minorities. By 1936 he and Ellen had decided to emigrate. As we just saw, he began publishing in English and in a US journal. In the autumn of 1936 he was offered attractive positions in Kiev and in Moscow. He and Ellen visited the Soviet Union at the end of the year. What they saw and felt led Viki to decline both jobs. Instead, with Bohr’s recommendation, Viki was offered and accepted a position at the University of Rochester. They sailed to the US in September 1937. The third phase of Viki’s career now beganwith a new country, a new language and a largely new field.

Rochester (1937-1943)

Viki spent five and a half years at Rochester. He taught, did research on his own and with students, went to Stanford twice and Michigan once to teach in the summers. He worked on nuclear reactions and on the electron self-energy problem again. His nuclear-physics papers include one that is an early treatment of coulomb excitation (Weisskopf, 1938), one on yields of reactions in heavy nuclei (Weisskopf and Ewing, 1940) to help the Rochester experimenters who were constructing a cyclotron, and one on radiation properties of heavy nuclei (Weisskopf, 1941) in which he defined what became known as “Weisskopf units” for the rates of radiative transitions.

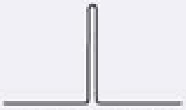


Fig 1a: schematic charge distributions of the electrons

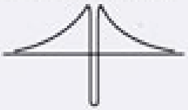


Fig 1b: schematic charge distributions of the vacuum electrons in the neighbourhood of an electron

one-electron theory	**hole theory**
from charge	from charge
$W_{\text{static}} = \frac{e^2}{a}$	$W_{\text{static}} = \frac{\alpha}{\pi}\ mc^2\ ln\,(\hbar/mca)$
from spin	from spin
$U_{mag} = \frac{\alpha}{6\pi}\ mc^2\ (\hbar/mca)^3$	$U_{mag} = \frac{\alpha}{2\pi}\ mc^2\ (\hbar/mca)^2 - \frac{\alpha}{4\pi}\ mc^2\ ln(\hbar/mca)$
$U_{el} = U_{mag}$	$U_{el} = -U_{mag}$ (note sign diff.)
$W_{spin} = U_{el} - U_{mag} = 0$	$W_{spin} = -\frac{\alpha}{\pi}\ mc^2\ (\hbar/mca)^2 + \frac{\alpha}{2\pi}\ mc^2\ ln(\hbar/mca)$
from vacuum fluctuations	from vacuum fluctuations
$W_{fluct} = \frac{\alpha}{\pi}\ mc^2\ (\hbar/mca)^2$	$W_{fluct} = \frac{\alpha}{\pi}\ mc^2\ (\hbar/mca)^2$
total self-energy	total self-energy
$W_{total} = \frac{e^2}{a} + \frac{\alpha}{\pi}\ mc^2\ (\hbar/mca)^2$	$W_{total} = \frac{3\alpha}{2\pi}\ mc^2\ ln(\hbar/mca)$

in n$^{\text{th}}$ order

$$W^{(n)}_{total} = A_n\ mc^2 \cdot \alpha^n\ (ln(\hbar/mca))^n$$

Figure 4

Summary of the various contributions to the self-energy of the electron in one-particle theory (left column) and hole theory or QED (right column). At the bottom is Weisskopf's result for the divergence of the self energy in arbitrary order of approximation.

In 1938-1939 Viki revisited the self-energy of the electron (Weisskopf, 1939). He had two purposes - the first was to explain as much as possible in physical terms the differences between the self energy in hole theory and one-electron theory. The second was to prove the logarithmic divergence to all orders in perturbation theory. That Viki proved the latter result is still not appreciated. In figure 4, I summarize Viki's careful parsing of the self-energy in single-particle Dirac theory and in hole theory (QED). The polarization of the vacuum in hole theory (indicated in the tiny sketch in the upper right-hand corner) leads to reduction in the singularity of the energy from the charge and a crucial difference in sign within the contributions from the spin, yielding the logarithmic divergence of the total self energy in QED found in 1934.

Los Alamos (March 1943 - autumn 1945)

In early 1943, J Robert Oppenheimer and Hans Bethe recruited Viki to come to Los Alamos. In April, Viki and Ellen, soon to be naturalized US citizens, moved to Los Alamos for the remainder of the war. Viki served as Bethe's deputy in the theoretical division. (In my lecture I marked this important period in Viki's life, with only a picture - a seemingly carefree group of skiers, Viki with Emilio Segrè and his wife, Enrico Fermi, Bethe, and Hans Staub and his wife.)

MIT - return to civilian life (1946 -)

In early 1946 Viki joined the faculty at MIT and that autumn began teaching and doing research again. His research was in both nuclear physics and QED.

Lamb shift

With graduate student Bruce French, Viki began in October 1946 – before knowing of Willis Lamb's result - to investigate the possibility of making sense of the higher order radiative corrections in electrodynamics in spite of the infinity in the self-energy of the electron. The idea was to exploit the difference between quantities calculated for bound and free electrons, an idea developed before the war with the help of Hendrik Kramers. Viki's demonstration that the divergence is only logarithmic made it plausible that differences would be finite and meaningful. The Shelter Island Conference in spring 1947, where Lamb announced his observation of the tiny "Lamb shift," spurred on this research.

By early 1948, French and Weisskopf had the first fully convergent QED answer for the Lamb shift. The problem was that it differed by a tiny amount from a calculation by Richard Feynman using his diagrammatic techniques and finished at about the same time. Schwinger initially had another answer, but soon agreed with Feynman. Viki was in awe of the brilliance of both Feynman and Schwinger and so assumed that French had made a mistake. He was sent back to the drawing board and for six agonizing months searched for an error. French eventually proved that Feynman and Schwinger had both made the same mistake in matching the relativistic end of the logarithmic integral to Bethe's cut-off. The unfortunate delay in publication meant that others published ahead of French and Weisskopf (1949). In his autobiography, Viki expresses unhappiness because he had not had the insight to pursue more diligently his 1936 work in which he realized that just the charge and mass of the electron were affected by short-distance (high frequency) divergences; he and French did not work hard or fast enough to have made a prediction of the "Lamb shift" before its experimental observation (rather unlikely, given the chronology) (Weisskopf, 1991 p169); and his fear of publishing a wrong result caused them to miss being the first to publish the correct result (Weisskopf, 1991 p170).

Nuclear physics

At the same time he embarked on the book Theoretical Nuclear Physics with John Blatt. The book (Blatt and Weisskopf, 1952) became the bible of nuclear theory for many years. In nuclear physics research, Viki found a perfect collaborator in Herman Feshbach. Together with students and postdocs they published a series of papers on nuclear reactions. These papers are noteworthy for the clarity, plausibility and simplicity of their assumptions. A paper with Feshbach and David Peaslee (Feshbach, Peaslee and Weisskopf, 1947) gave a simple description of nuclear resonances in terms of the logarithmic derivative of the incident particle's radial wave function at the nuclear surface, in contrast to the more formal treatment of Wigner and collaborators. Another paper (Feshbach and Weisskopf, 1949) gave a schematic description of fast neutron reactions using an incoming wave exp(-iKr) just inside the nuclear surface.

Cloudy crystal-ball model

The most influential paper of this period was one with Feshbach and Charles Porter (Feshbach, Porter and Weisskopf, 1954). Called the cloudy crystal-ball model or just "Feshbach, Porter, Weisskopf," it is a description of the total and elastic scattering cross sections of fast neutrons through a blend of the single-particle shell model and Bohr's compound nucleus. The idea is that for a time the incident neutron retains its identify and seeks out the single-particle shell model states that are appropriate for its excitation and the size of the combined nucleus before sharing its energy and losing its identity, as in Bohr's picture. A vast amount of experimental data is described remarkably well with their approach (see figure 5).

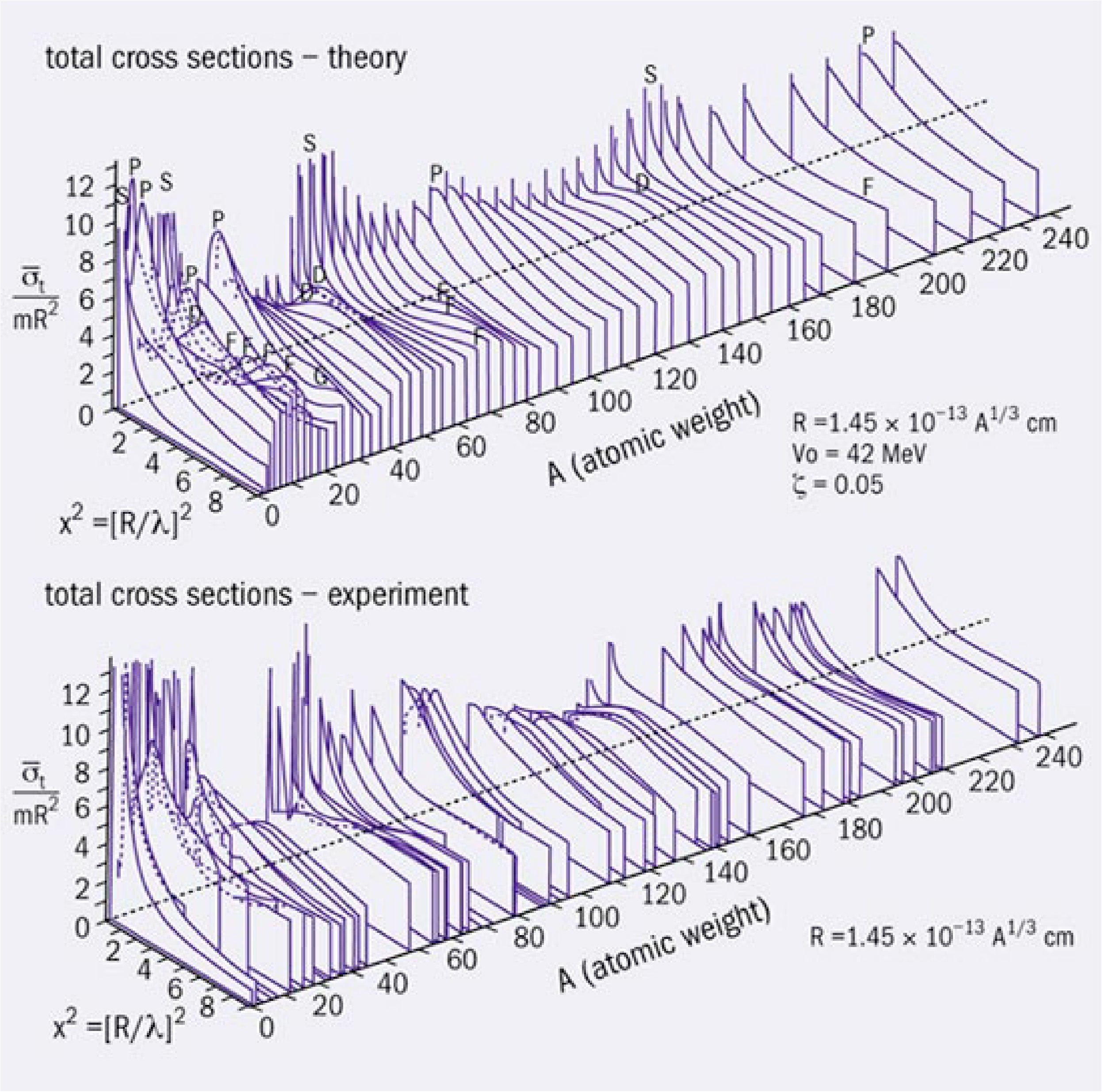


Figure 5
Experimental and theoretical cloudy crystal-ball total cross sections of neutrons on nuclei as a function of mass number A and energy. Figures 2(b) and 3 from H Feshbach, C E Porter and V F Weisskopf 1954 Physical Review 96 448-464. (Copyright 1954, American Physical Society.)

By 1959-1960 Viki had begun to move into what he called the third stage of a physicist's career, that of elder statesman. He is shown in 1959 at age 51 in figure 6, with Heinz Barschall - responsible for much of the fast-neutron data interpreted successfully by Feshbach, Porter and Weisskopf (1954) - and Feshbach at a conference in Florida.

Figure 6
Left to right: Victor Weisskopf, Heinz Barschall and Herman Feshbach at the 1959 conference on the nuclear optical model, Tallahassee, Florida. (AIP Emilio Segrè Visual Archives, Bromley and Physics Today collections.)

Summary to 1960

Viki published many important papers in theoretical physics. As Hans Bethe has said in another context, at least three of his contributions changed the course of physics: Weisskopf-Wigner theory of line breadth and the lifetimes of excited states; self-energy of the electron (only a logarithmic divergence with inverse size); and the cloudy crystal-ball model of neutron scattering (features of individual particle motion shine through the chaos of the compound nucleus model of Bohr). I can add a fourth: the vacuum polarization paper, with its idea of charge and wave-function renormalization. And a fifth: Pauli-Weisskopf.

PHASE 4: BEYOND PERSONAL RESEARCH

Viki had nearly 42 more years of his life, a life full of further accomplishments including the leadership of CERN. Those years are described by others and by Viki in his autobiography. I present only a brief and partial list to indicate the richness of his later career.

Research

Papers with Roger Van Royen (1967), Arnon Dar (1968-1969), Julius Kuti (1971) and collaborators on the "MIT Bag" model (1974).

Honours

Institute Professor, MIT (1966), Pontifical Academy of Sciences (1975), Wolf Prize (1982), Public Welfare medal of the US National Academy of Sciences (1991), governmental honours from the US, France, Germany and other nations and numerous honorary degrees and memberships of academies and societies.

Professional and public service

Co-founder of the Federation of Atomic Scientists (1946); president, American Physical Society (1960); director-general, CERN (1961-1965); chair, Physics Department, MIT (1967-1973); first chair, High-Energy PhysicsAdvisory Panel (1967-1972); president, American Academy of Arts and Sciences (1976-1979).

Other publications

Knowledge and Wonder (1963),
Physics in the Twentieth Century, essays (1972),
Concepts of Particle Physics (with Kurt Gottfried), 2 vols (1984, 1989),
The Privilege of Being a Physicist, more essays (1989),
The Joy of Insight, autobiography (1991),
plus numerous articles in CERN Courier, Physics Today, Bulletin of Atomic Scientists, etc.

Speeches

Viki gave innumerable talks and speeches.
A final personal note as one of Viki's physics children. It was an honour and a privilege to be invited to speak about Viki's career and research at the CERN symposium on 17 September 2002. In 1946, starting out as a graduate student, classically trained in the Canadian "backwoods", I had my eyes opened to the wonderful world of quantum physics in the first course that Viki taught at MIT. Yes, the lectures were full of algebraic mistakes, but the physics was clear and beautiful. Viki is rightly renowned as one of the giants of the golden age of quantum physics. He was also an inspirational teacher and mentor.

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Author:
J D Jackson, Lawrence Berkeley National Laboratory.