CERN LIBRARIES, GENEVA

CM-P00042123

TPI-MINN-01/57
UMN-TH-2038/01

From Heisenberg to Supersymmetry

Talk at the Symposium "100 Years Werner Heisenberg — Works and Impact,"

26-30 September, 2001, Bamberg, Germany

M. Shifman

Theoretical Physics Institute, University of Minnesota
116 Church Str. S.E. Minneapolis, MN 55455, USA

Abstract

There is a little-known connection between Heisenberg's research in the 1960's and supersymmetry. First, I try to explain, in laymen terms, what supersymmetry is and why it gives rise to such high expectations in high-energy physics. After a brief excursion into origins of supersymmetry I present evidence that a section in an essentially forgotten Heisenberg's book, which contained unorthodox ideas, was inspirational for Dmitry Volkov, one of the co-discoverers of supersymmetry.

1 Introduction

I am honored to give this talk at the Heisenberg Centennial Symposium. The theme of this Symposium is the impact of Heisenberg's work on modern theoretical physics. In the previous talks we have heard how deeply various Heisenberg's ideas are intertwined in the fabric of today's theory. I will focus on supersymmetry. This might seem surprising. You might say that supersymmetry has nothing to do with Heisenberg's work, it does not belong here.

In fact, there is a little-known connection between one of Heisenberg's late physics projects and supersymmetry, a direction of research which gained dominant positions in theoretical high-energy physics in the 1990's, twenty years after Heisenberg's death. I will try to tell you this curious story.

The outline of my talk is as follows. First, I will try to explain, in laymen terms, what supersymmetry is. My explanations will be deliberately brief, primitive and,

Figure 1: A mechanical analogy for the scalar field theory.

hopefully, graphic. I will keep in mind that non-experts comprise a significant part of this audience. Second, I will outline why supersymmetry is so cherished and why it gives rise to such high expectations in the community. Third, I will have to say a few words about the triple discovery of supersymmetry. This will bring me to my main story. In 1966 Heisenberg published a book “Introduction to the Unified Field Theory of Elementary Particles.” A section in this book gave inspiration to Dmitry Volkov, one of the co-discoverers of supersymmetry. Heisenberg’s remark served as an initial impetus for Volkov’s work which eventually led to a breakthrough discovery. Thus, this remark turned out to be visionary.

I will conclude my talk by recommending a few publications which might be useful to those who are interested in the issue, both physicists and historians of science.

2 Supersymmetry in Field Theory

To visualize conventional (non-supersymmetric) field theory one usually thinks of a space filled with a large number of coupled anharmonic oscillators. For instance, in the case of 1+1 dimensional field theory, with a single spatial dimension, one can imagine an infinite chain of penduli connected by springs (Fig. 1). Each pendulum represents an anharmonic oscillator. One can think of it as of a massive ball in a gravitational field. Each spring works in the harmonic regime, i.e. the corresponding force grows linearly with the displacement between the penduli. Letting the density of penduli per unit length tend to infinity, we return to field theory.

If a pendulum is pushed aside, it starts oscillating and initiates a wave which propagates along the chain. After quantization one interprets this wave as a scalar particle.

Can one present a fermion in this picture? The answer is yes. Imagine that each pendulum acquires a spin degree of freedom (i.e. each ball can rotate, see Fig. 2). Spins are coupled to their neighbors. Now, in addition to the wave that propagates in Fig. 2, one can imagine a spin wave propagating in Fig. 3. If one perturbs a single spin, this perturbation will propagate along the chain.

Our world is 1+3 dimensional, one time and three space coordinates. In this

Figure 2: A mechanical analogy for the spinor field theory.

world bosons manifest themselves as particles with integer spins. For instance, scalar (spin-0) particle from which we started is a boson. Photon (spin-1 particle) is a boson too. At the same time particles with semi-integer spins — electrons, protons, etc. — are fermions.

Conventional symmetries, such as, say, isotopic invariance, do not mix bosons with fermions. Isosymmetry tells us that the proton and neutron masses are the same. It also tells us that the masses of π^0 and π^+ are the same. However, no prediction for the ratio of the pion to proton masses emerges.

Supersymmetry is a very unusual symmetry. It connects masses and other properties of bosons, on the one hand, and fermions on the other. Thus, each known particle acquires a superpartner: photon's superpartner is *photino* (spin 1/2), electron's superpartner is *selectron* (spin 0). Since spin is involved, and spin is related to geometry of space-time, it is clear that supersymmetry has a deep geometric nature. Unfortunately, I have no time to dwell on further explanations. Instead, I'd like to present here a quotation from Witten which nicely summarizes the importance of this concept for modern physics. Witten writes [1]:

“... One of the biggest adventures of all is the search for supersymmetry. Supersymmetry is the framework in which theoretical physicists have sought to answer some of the questions left open by the Standard Model of particle physics.

Supersymmetry, if it holds in nature, is part of the quantum structure of space and time. In everyday life, we measure space and time by numbers, “It is now three o'clock, the elevation is two hundred meters above sea level,” and so on. Numbers are classical concepts, known to humans since long before Quantum Mechanics was developed in the early twentieth century. The discovery of Quantum Mechanics changed our understanding of almost everything in physics, but our basic way of thinking about space and time has not yet been affected.

Showing that nature is supersymmetric would change that, by revealing a quantum dimension of space and time, not measurable by ordinary numbers. Discovery of supersymmetry would be one of the real milestones in physics.”

Figure 3: Superspace

I have tried to depict “a quantum dimension of space and time” in Fig. 3. Two coordinates, x and y represent the conventional space-time. I should have drawn four coordinates, x , y , z and t , but this is impossible — we should try to imagine them.

The axis depicted by a dashed line (going in the perpendicular direction) is labeled by θ (again, one should try to imagine four distinct θ 's rather than one). The dimensions along these directions cannot be measured in meters, the coordinates along these directions are very unusual, they anticommute,

$$\theta_1\theta_2 = -\theta_2\theta_1, \quad (1)$$

and, as a result, $\theta^2 = 0$. This is in sharp contrast with ordinary coordinates for which 5 meters $\times$ 3 meters is, certainly, the same as 3 meters $\times$ 5 meters. In mathematics θ 's are known as Grassmann numbers, the square of every given Grassmann number vanishes. These extra θ directions are purely quantum structures. In our world they manifest themselves through the fact that every integer spin particle has a half-integer spin superpartner.

A necessary condition for any theory to be supersymmetric is the balance between the number of the bosonic and fermionic degrees of freedom, having the same mass and the same “external” quantum numbers, e.g. electric charge. To give you an idea of supersymmetric field theories let us turn to the most familiar and simplest gauge theory, quantum electrodynamics (QED). This theory describes electrons and positrons (one Dirac spinor, four degrees of freedom) interacting with photons (an Abelian gauge field, with two physical degrees of freedom). Correspondingly, in its supersymmetric version, SQED, one has to add one massless Majorana spinor, photino (two degrees of freedom), and two complex scalar fields, selectrons (four degrees of freedom).

Balancing the number of degrees of freedom is the necessary but not sufficient condition for supersymmetry in dynamically nontrivial theories, of course. All interaction vertices must be supersymmetric too. This means that each line in every vertex can be replaced by that of a superpartner. Say, we start from the electron-electron-photon coupling (Fig. 4a). Now, as we already know, in SQED the elec-

Figure 4: Interaction vertices in QED and its supergeneralization, SQED. (a) $\bar{e}e\gamma$ vertex; (b) selectron coupling to photon; (c) electron-selectron-photino vertex. All vertices have the same coupling constant. The quartic self-interaction of selectrons is also present, but not shown.

tron is accompanied by two selectrons. Thus, supersymmetry requires the selectron-selectron-photon vertices, (Fig. 4b), with the same coupling constant. Moreover, the photon can be replaced by its superpartner, photino, which generates the electron-selectron-photino vertex (Fig. 4c), with the same coupling.

With the above set of vertices one can show that the theory is supersymmetric at the level of trilinear interactions, provided that the electrons and selectrons are degenerate in mass, while the photon and photino fields are both massless. To make it fully supersymmetric one should also add some quartic terms, describing self-interactions of the selectron fields. Historically, SQED was the first supersymmetric theory in four dimensions to be discovered [2].

3 Promises of supersymmetry

Supersymmetry has yet to be discovered experimentally. In spite of the absence of the direct experimental evidence, immense theoretical effort was invested in this subject in the last thirty years, over 30,000 papers published. The so-called Minimal Supersymmetric Standard Model became a generally accepted paradigm in high-energy physics. In this respect the phenomenon is rather unprecedented in the history of physics. Einstein's general relativity, the closest possible analogy one can give, was experimentally confirmed within several years after its creation. Only in one or two occasions, have theoretical predictions of a comparable magnitude had to wait for experimental confirmation that long. For example, the neutrino had a time lag of 27 years. A natural question arises: why we believe this concept to be so fundamental?

Supersymmetry may help us solve the deepest mysteries of nature — the cosmological term problem and the hierarchy problem.

3.1 Cosmological term

An additional term in the Einstein action of the form

$$\Delta S = \int d^4x \sqrt{g} \Lambda \quad (2)$$

goes under the name of the cosmological term. It is compatible with the general covariance and, therefore, can be added freely; this fact was known to Einstein. Empirically Λ is very small, see below. In classical theory there is no problem with fine-tuning Λ to any value.

The problem arises at the quantum level. In conventional quantum field theory it is practically inevitable that

$$\Lambda \sim M_{\text{Pl}}^4 \quad (3)$$

where M_{Pl} is the Planck scale, $M_{\text{Pl}} \sim 10^{19}$ GeV. This is to be confronted with the experimental value of the cosmological term,

$$\Lambda_{\text{exp}} \sim (10^{-12} \text{ GeV})^4. \quad (4)$$

The divergence between theoretical expectations and experiment is 124 orders of magnitude! This is probably the largest discrepancy in the history of physics.

Why supersymmetry may help? In supersymmetric theories Λ is strictly forbidden by supersymmetry, $\Lambda \equiv 0$. Of course, supersymmetry, even if it is there, must be broken in nature. People hope that the breaking might occur in a way ensuring splittings between the superpartners' masses in the ball-park of 100 GeV, with the cosmological term in the ball-park (4).

3.2 Hierarchy problem

Masses of spinor particles (electrons, quarks) are protected against large quantum corrections by chirality (“handedness”). For scalar particles the only natural mass scale is M_{Pl} . Even if originally you choose this mass in the “human” range of, say, 100 GeV, quantum loops will inevitably drag it to M_{Pl} . A crucial element of the Standard Model of electroweak interactions is the Higgs boson (it has not been yet discovered). Its mass has to be in the ball-park of 100 GeV. If you let its mass to be $\sim M_{\text{Pl}}$, this will drag, in turn, the masses of the W bosons. Thus, you would expect $(M_W)_{\text{theor}} \sim 10^{19}$ GeV while $(M_W)_{\text{exp}} \sim 10^2$ GeV. The discrepancy is 17 orders of magnitude.

Again, supersymmetry comes to the rescue. In supersymmetry the notion of chirality extends to bosons, through their fermion superpartners. There are no quadratic divergences in the boson masses, at most they are logarithmic, just like in the fermion case. Thus, the Higgs boson mass gets protected against large quantum corrections.

Having explained that supersymmetry may help solve two most challenging problems in high-energy physics, I hasten to add that it does a lot of other good things, right now. It proved to be a remarkable tool in dealing with previously “uncrackable” issues in gauge theories at strong coupling. Let me give a brief list of achievements: (i) first finite four-dimensional field theories; (ii) first exact results in four-dimensional gauge theories [3]; (iii) first fully dynamical (toy) theory of confinement [4]; (iv) dualities in gauge theories [5]. The latter finding was almost immediately

generalized to strings which gave rise to a breakthrough discovery of *string dualities*. This topic is beyond the scope of my talk, however.

To conclude this section, I present an *arrow of time in supersymmetry* (Fig. 5). It will also serve as a natural bridge to the main point of my today's talk — and may, I please, remind you that this main point is the impact of a virtually forgotten Heisenberg's book on the birth of supersymmetry.

4 Heisenberg and supersymmetry

In the late 1950's Heisenberg found himself in an almost complete scientific isolation. Initially it was probably caused by alienation due to Heisenberg's role in the German atomic project during WWII. I think that later it was Heisenberg's deliberate choice to distance himself from “popular” topics on which the major efforts of the theoretical community were focussed. Naturally, such topics were also points of attraction for young and ambitious researches.

Instead, Heisenberg embarked on the investigation of a “unified field theory of elementary particles.” In 1966 he published a book [6] where he summarized his work on this subject. I do not think that many people in the world studied this book carefully. In fact, it was to a large extent obsolete by the time of its publication.

Heisenberg's idea was to use a fundamental Dirac field, endowed with a four-fermion interaction of a special type, to write and nonperturbatively solve the emerging nonlinear field equations. He hoped to get in this way a complete set of “elementary” particles known at that time (both, hadrons and leptons) and dynamically describe their properties in terms of one or two input constants. From today's perspective it is absolutely obvious that this direction was a dead end. Not only it could not be made viable theoretically, it contradicted experimental data which started appearing in the 1960's. (For instance, Heisenberg did not believe that Gell-Mann's $SU(3)$ could be a fundamental symmetry and insisted that $SU(3)$ -based relations were a numerical coincidence.) Moreover, if you open the book, you will see that even in the framework of the postulates accepted by Heisenberg, his derivations were sometimes inconsistent, sometimes not compelling, with wide gaps and lots of handwaving. The man who wrote this book does not seem to be the Heisenberg of the pre-WWII time.

One might say that the whole program was a wasted effort. Let us not make hasty conclusions, however. As it happens with great minds, Heisenberg's intuition (or a direct line to God, if you wish) worked by itself, with no factual basis in the construction he was trying to develop. In this book, Heisenberg put forward a deep idea that got a life of its own, in spite of the fact that it was absolutely unsubstantiated in the framework of Heisenberg's own postulates. The idea was that massless particles must emerge from nonlinear field equations as a result of a spontaneous breaking of a continuous global symmetry. He conjectured, in particular, that *neutrinos* could be Goldstone particles. The continuous symmetry considered

Figure 5: SUSY time arrow.

by Heisenberg was isosymmetry which he himself had introduced in the early 1930's. Although Heisenberg certainly knew the Goldstone theorem and discussed it more than once in his book, he somehow got himself confused as to the quantum numbers of the corresponding Goldstone bosons. Sometimes he speaks of pions in this context, and in Chapter 8 he suggests that photons might be Goldstones emerging from the spontaneous breaking of isosymmetry. Of course, we now know that the isotopic invariance is a vectorial symmetry which cannot be spontaneously broken, and even if it were, this breaking could produce only a scalar Goldstone, definitely not pseudoscalar and not vector.

Heisenberg's approach was wrong — this is beyond any doubt. What is important for us now, is that on the other side of the Iron Curtain it ignited the imagination of Dmitry Volkov, a theoretical physicist from Kharkov (Ukraine) who was also very isolated, but for totally different reasons.

The Kharkov theoretical physics community was small. It was far from the main scientific centers, which automatically meant, under perverted Soviet conditions, that outside scientific contacts were cut to a minimum. Not only travel abroad was virtually beyond reach, even participation in conferences and seminars in Moscow was quite a rare occasion. Journals and preprints from the West arrived sporadically, from time to time, and the collection was far from being complete. Under these circumstances, physics books published in Russian became one of the most important sources of information.

Heisenberg's book [6] was translated in Russian and published by *Mir Publishers* in 1968. It was widely available. Its price was only 1 ruble and 1 kopek. I do not know the origin of this weird number, but I well remember that I bought this book at the time of publication in a kiosk (I was the third year student at that time), and then made several attempts to go through it with a pencil in my hand. After a few weeks I gave up, having decided that it was of no concern to me — it gave no appropriate food for my imagination. Apparently, this was a wrong conclusion (which is certainly explained by the lack of experience on my side).

Dmitry Volkov, who read this book carefully at the very same time, came to a different understanding. He posed himself a question: "OK, Heisenberg's idea of neutrino as a Goldstone particle does not follow from his construction. Is there a way to make it right?" In search of the answer, Volkov, together with his student Vladimir Akulov, invented a non-linear realization of supersymmetry.

A few comments on the birth of supersymmetry are in order here, but before making them, I think it is time to listen to Volkov himself. This will give us a much better idea of his thinking process. In his last interview Prof. Volkov said [7]:

"... a couple of words about how I came to the discovery of supersymmetry and supergravity. The starting point was the idea of W. Heisenberg. Let me tell you what this idea was. At the end of the 1960's, Heisenberg proposed the idea that all elementary particles can be described by a uniform theory on the basis of the nonlinear equation formulated

by him [6]. He started this work together with W. Pauli, but sometime later Pauli dissociated himself from this theory and even sharply criticized Heisenberg for his assumptions. But, nevertheless what did Heisenberg contribute to the discovery of supersymmetry?

Heisenberg tried to explain the spectrum of all elementary particles on the basis of his theory. And thanks to his great intuition, he guessed the places of the particles and predicted how the photon should appear in this theory. Moreover, he found a place for the neutrino within his theory and assumed that the neutrino emerges as a result of spontaneous symmetry breaking. This was a very unusual assumption, because all known Goldstone particles emerging as a result of spontaneous symmetry breaking had spin zero in all theories known at that time. This idea of Heisenberg was revolutionary, because he was the first to formulate the thought that there might exist Goldstone particles in nature with spin one-half. To tell the truth, he found this particle by an incorrect method, but nonetheless it was an idea that had a strong impact on me and from that time I often, although not constantly, would think about whether this idea could be realized.

And when I started to consider how such particle might appear in the theory, I understood that this requires an extension of the usual physical groups, which is the basis for all relativistic processes. That means an extension of the Lorenz group and an extension of the Poincaré group so that new operators would be present, which would correspond to a quantum number of the neutrino. Thus, the main result that we obtained was that we managed to create such an extension of the Poincaré group, which is now called the Poincaré supergroup.

Later on, we encountered certain difficulties and, if one speaks about the direct application to the neutrino, this idea nonetheless did not work. Why? Because the group that we were considering contained the Poincaré group and it is known that the Poincaré group leads eventually to the general theory of relativity, if one considers the local transformations of the group. That means that the same local transformations of the supergroup would lead to the emergence of certain superpartners of the ordinary gravity field, and these superpartners would totally absorb the Goldstone particles.

And thus, when I understood such ideas, I, together with my collaborators, proposed an extension even of Einstein's general theory of relativity, which would include just what we call supersymmetry. So, in fact, certain superpartners would emerge. Moreover, in the extension of this theory arose not only superpartners – particles with spin $3/2$ – but also particles with spin 1, with spin $1/2$ and with spin zero. That is, there arose the idea that all elementary particles might be included into the

system of supergravity. [...]

Heisenberg's idea was, if one can say so, a physical idea, but in order to give this idea shape in a new precise mathematical theory, a certain mathematical formalism was required. And here I am very thankful to J. Schwinger, whom I personally knew, and who in a number of cases could have discovered supersymmetry. ..."

This is a very instructive testimony which teaches us a few things: that the development of thought is very nonlinear; that conjectures of deep minds may have more truth in them than it might seem at first sight, that it is of paramount importance to maintain a versatile scientific community working on a variety of topics, not necessarily those constituting the fashion of the day; that personal and other scientific contacts are indispensable, and so on.

To put Volkov's work in a proper perspective, I have to say a few words about the earliest stages of supersymmetry. I will not dwell on details of this complex issue — when, where, how and why supersymmetry was discovered. An extensive account of this story can be found in the book [8] which has just been published. There you will find both, testimonies of the discoverers and pioneers, and historical essays.

The history of supersymmetry is unique because it was discovered practically *simultaneously and independently* on the both sides of the Iron Curtain *three times* in the early 1970's (see Fig. 5). As so often when exploring new ground, much of the early work on supersymmetry was hit and miss. Golfand and Likhtman of the Lebedev Institute in Moscow were the first — they reported a construction of the super-Poincaré algebra and a version of massive super-QED in 1971. The formalism contained a massive photon and photino, a charged Dirac spinor and two charged scalars (spin-0 particles). Likhtman found algebraic representations that could be viewed as chiral and vector supermultiplets, and he observed the vanishing of the vacuum energy in supersymmetric theories.

Subsequent to the work of Golfand and Likhtman, contributions from the East were made by Volkov and Akulov (Kharkov Institute for Physics and Technology) who in 1972 found a massless fermion, appearing due to the spontaneous supersymmetry breaking, and tried to associate it with the neutrino [9]. Within a year, Volkov and Soroka gauged the super-Poincaré group which led to elements of supergravity [10]. They suggested that a spin 3/2 graviton's superpartner becomes massive upon "eating up" the Goldstino that Akulov and Volkov had discussed earlier: the existence of this "super-Higgs mechanism" in full-blown supergravity was later established in the West.

In the West, a completely different approach was taken. As is well-known, a breakthrough into the superworld was made by Wess and Zumino in 1973. This work was done independently because western researchers knew little if anything about the work done in the Soviet Union. The pre-history on which Wess and

Zumino based their inspiration, has common roots with string theory — another pillar of modern theory — which in those days was referred to as the “dual model.”

Subsequent progress followed rapidly. In a series of papers, Wess and Zumino, Iliopoulos and Zumino, and Ferrara, Iliopoulos, and Zumino described miraculous cancelations concerning the renormalizability of supersymmetric theories. The superspace/superfield formalism was worked out by Salam and Strathdee. Key non-renormalization theorems were proven by West and others. Non-Abelian gauge theories were supersymmetrized, simultaneously, by Ferrara and Zumino, and Salam and Strathdee in 1974. Mechanisms for the spontaneous breaking of supersymmetry through F- and D-terms were found by O’Raifeartaigh, and Fayet and Iliopoulos. Foundations of what is now known as the minimal supersymmetric standard model were laid by Fayet. In parallel, local supersymmetry was being developed too. This process culminated in 1976 with the publication of two papers (Ferrara, Freedman, and van Nieuwenhuizen, and Deser and Zumino). These authors assembled together various “super-elements” which were in circulation at that time, completing the elegant construction of modern supergravity.

5 What to read?

I conclude my talk with a few recommendations on the literature. People often ask: is there anything to read about supersymmetry for the general audience? I should say that this theoretical development is rather fresh and the literature for non-experts is not abundant. I may refer you to Gordy Kane’s book quoted in Ref. [1]. As for history of supersymmetry, several relevant publications appeared recently [11, 8, 12]. They present an extensive and, to my mind, very instructive source of information for curious physicists and historians of science. The articles collected there contain exhaustive references covering all stages of the development of supersymmetry.

Acknowledgments

I am deeply grateful to Alexander von Humboldt-Stiftung for organizing this marvelous and stimulating meeting and for inviting me to give this talk. Financial support from Alexander von Humboldt-Stiftung is gratefully acknowledged. This work was also supported in part by DOE grant DE-FG02-94ER408.

References

- [1] E. Witten, in G. Kane, *Supersymmetry: Unveiling the Ultimate Laws of Nature* (Perseus Books, 2000).
- [2] Yu.A. Golfand and E.P. Likhtman, *JETP Lett.* **13**, 323 (1971) [Reprinted in *Supersymmetry*, Ed. S. Ferrara, (North-Holland/World Scientific, Amsterdam – Singapore, 1987), Vol. 1, page 7].
- [3] V. A. Novikov, M. A. Shifman, A. I. Vainshtein and V. I. Zakharov, *Nucl. Phys. B* **229**, 381 (1983); *Phys. Lett. B* **166**, 329 (1986).
- [4] N. Seiberg and E. Witten, *Nucl. Phys. B* **426**, 19 (1994), (E) **B 430**, 485 (1994); [hep-th/9407087]. *Nucl. Phys. B* **431**, 484 (1994) [hep-th/9408099].
- [5] N. Seiberg, Proceedings 4th Int. Symposium on Particles, Strings, and Cosmology (PASCOS 94), Syracuse, New York, May 1994, Ed. K. C. Wali (World Scientific, Singapore, 1995), p. 183 [hep-th/9408013]; *Int. J. Mod. Phys. A* **12** (1997) 5171 [hep-th/9506077].
- [6] W. Heisenberg, *Introduction to the Unified Field Theory of Elementary Particles*, (Interscience Publishes, London, 1966).
- [7] D. Volkov, in *Supersymmetry and Quantum Field Theory*, Eds. J. Wess and V. Akulov (Springer, Berlin, 1998), p. 1, see also Ref. [8].
- [8] G. Kane and M. Shifman (Eds.), *The Supersymmetric World: The Beginnings of the Theory* (World Scientific, Singapore, 2000).
- [9] D.V. Volkov and V.P. Akulov, *Phys. Lett. B* **46**, 109 (1973).
- [10] D.V. Volkov and V. Soroka, *JETP Lett.* **18**, 312 (1973); *Theor. Math. Phys.* **20**, 829, (1974).
- [11] *The Many Faces of the Superworld*, Yuri Golfand Memorial Volume, Ed. M. Shifman (World Scientific, Singapore, 2000).
- [12] *SUSY 30*, Proc. Int. Symp. Celebrating 30 years of Supersymmetry, Minneapolis, MN, USA, 13–17 October 2000, Eds. K. Olive, S. Rudaz and M. Shifman (North-Holland, Amsterdam, 2001).