Continuous Advances in QCD 2002/Arkadyfest

Dear Arkady!

Happy 60th Birthday!

Theoretical Physics Institute

University of Minnesota

designed by Lada Kirich

Arkady Vainshtein:
40 Year Journey in Theoretical Physics

February 23 февраля
2002

Аркадий Вайнштейн:
40-летнее путешествие в теоретическую физику

Fun Reading for the Participants of CAQCD2002/Arkadyfest

Contents

23 February 2002
Minneapolis

Perturbation theory is the most common tool applied for calculations in quantum mechanics and, especially, field theory. In weakly coupled theories, such as quantum electrodynamics or electroweak model, calculations based on the Feynman graphs (which represent a particular order in the perturbative series) are innumerable. This approach has a solid theoretical foundation, and its remarkable success is no surprise.

There is a deep general question as to the nature of the coupling constant expansion. Half a century ago Dyson argued [1] the the series in α are asymptotic in quantum electrodynamics. The essence of his argument is as follows. Consider N charged moving particles, of one and the same charge e, assuming that $N \gg 1$. The energy E of this system can be represented as

$$E = NT + \frac{N^2}{2} e^2 V \,, \tag{1}$$

where T is the average kinetic energy per particle. The second term represents the Coulomb energy: V stands for the average inverse distance between the particles, $V = \langle r^{-1} \rangle > 0$. The factor $N^2/2$ represents the number of the interacting pairs (in fact, it should be $N(N-1)/2$, but this distinction is negligible at large N). For positive $\alpha \equiv e^2$ the system is stable. However, if α becomes negative, then the potential part of the energy E becomes attractive, and at sufficiently large N it will always take over the kinetic part. Thus, at $N \geq N_* = -T/(V\alpha)$ the energy E of the conglomerate becomes negative and an instability develops. This instability is due to the fact that a spontaneous pair creation becomes energetically expedient. The particles of charge e are attracted to the conglomerate; those of charge $-e$ run away to infinity. The more pairs are produced, the more negative E becomes. This phenomenon — instability — occurs irrespective of the value of α. Of course, the critical value N_* becomes exceedingly larger as $\alpha \to 0$.

Dyson concludes that physical quantities in quantum electrodynamics cannot be analytic in α, and the point $\alpha = 0$ is singular. If so, the expansion in the powers of α cannot be convergent.

Being brilliant, Dyson's argument is qualitatitve. Many years had elapsed before quantitative methods were developed allowing one to calculate the divergence of the perturbative series in high orders. A breakthrough, which paved the way to quantitative analysis, became possible when it was found that : (i) the divergence of the perturbative series at high orders, at physical values of the coupling constant, is related (via the dispersion relation in the coupling constant) to the imaginary part which develops at unphysical values of the coupling constant, when the system under consideration becomes unstable (ii) this imaginary part, in turn, is related to the barrier-penetration phenomenon and can be calculated quasiclassically at small unphysical values of the coupling constant; (iii) the rate of divergence at high orders is fully determined by the tunneling amplitude at weak coupling.

This result was first obtained in quantum mechanics and is usually credited to Bender and Wu [2] (see e.g. such authoritative source as Le Guillou and Zinn-Justin's compilation [3]). Bender and Wu's paper, a benchmark in this area of research, was written in 1972. Very few theorists know that the very same construction was worked out in 1964 in Soviet Union. In fact, this was one of the first research projects of Arkady Vainshtein, who at that time was a student at the Novosibirsk University and Novosibirsk Institute of Nuclear Physics (currently, the Budker Institute of Nuclear Physics). His paper was published in 1964 in Russian, as a Novosibirsk Institute of Nuclear Physics Report [4], which obviously hindered its recognition in the western high-energy physics community. Only experts in the Soviet community were aware of Vainshtein's construction, in particular, Lev Lipatov and Eugene Bogomolny, whose works on the divergences of the perturbative series are well-known.

Now, almost 40 years later, original Vainshtein's report became a rarity, it can hardly be found even in large libraries. I decided to correct the situation, and make it available to the high-energy physics community. On occasion of Arkady's 60^{th} birthday I translated the paper in English. Below you will find both, the English translation and the Russian original.

M. Shifman

1. F.J. Dyson, *Phys. Rev.* **85**, 631 (1952).

2. C.M. Bender and T.T. Wu, *Phys. Rev.* **D7**, 1620 (1973).

3 J.C. Le Guillou and J. Zinn-Justin (Eds), *Large-Order Behaviour of Perturbation Theory* (North-Holland, Amsterdam, 1990).

4. A.I. Vainshtein, *Decaying Systems and Divergence of the Series of Perturbation Theory*, Novosibirsk Institute of Nuclear Physics Report, Decmber 1964.

INSTITUTE OF NUCLEAR PHYSICS OF THE SIBERIAN BRANCH OF THE USSR ACADEMY OF SCIENCES

Preprint

A.I. Vainshtein

DECAYING SYSTEMS AND DIVERGENCE OF THE SERIES OF PERTURBATION THEORY

Novosibirsk — 1964

Abstract

One-dimensional field models are considered. If, for a certain sign of the coupling constant λ, the spectrum is continuous, the perturbative series for the propagator diverges. At large n the n-th term of the perturbative series has the form $n!\,(\alpha\lambda)^n$.

1. In Ref. 1 Dyson argued that the perturbation theory series are divergent in quantum electrodynamics. Dyson's argument was based on the observation that the world in which the square of the electric charge e^2 is negative, has no ground state and decays. Therefore, it is hard to imagine that such a situation can be described by functions analytic in e^2 at $e^2 = 0$.

Thirring investigated [2] the theory with the interaction $L_{\rm int} = \lambda\varphi^3$ and showed that the perturbative series for the polarization operator diverges in the domain of momenta $p^2 < m^2$. At large n the terms of the perturbative series are shown to have the form

$$C(\alpha\lambda)^n\,\frac{(n-4)!}{n^2}\,,$$

where C and α are functions of p^2. The model considered by Thirring is an example of an unstable theory. One can readily show, by virtue of a direct variational method, that there is no ground state in the model of Ref. 3.

We will show that instability of the system implies a divergence of the perturbation theory series in a one-dimensional model.

2. Consider a model in which field operators φ depend only on time, the spatial coordinates are absent. The Hamiltonian and equal-time commutation relations have the form

$$H = \frac{1}{2}\,(\dot\varphi)^2 + \frac{m^2}{2}\varphi^2 + V(\varphi)\,, \qquad [\varphi(t)\,,\,\dot\varphi(t)] = i\,. \tag{1}$$

This is the Hamiltonian and commutation relations of the conventional quantum-mechanical anharmonic oscillator with the frequency $\omega = m$ and mass $\mu = 1$.

For definiteness let us choose the interaction in the form

$$V(\varphi) = -\lambda\varphi^3\,. \tag{2}$$

From what follows it will be clear that in fact our consideration is applicable to all decay-permitting interactions.

Repeating the proof due to Thirring [2] in the one-dimensional case, for the interaction $\lambda\varphi^3$, we will arrive at a result which is identical to that of the four-dimensional problem, namely that the series for the polarization operator diverges, the divergence being the same as in four dimensions. We will connect this divergence with the fact that the system at hand can decay.

Let us consider the causal Green function for the field φ. In the interaction representation it is defined as

$$iG(\tau) = \frac{(0|T\,\varphi(\tau)\,\varphi(0)|0)}{S_{00}} \tag{3}$$

where $\varphi(\tau)$ is the field operator in the interaction representation. It is assumed that the interaction switches on adiabatically.

If we now pass to the Heisenberg operators $\underline{\phi}(\tau)$, we will get

$$\begin{aligned} iG(\tau) &= \frac{(0|S(\infty,0)[T\,\underline{\phi}(\tau)\,\underline{\phi}(0)]S(0,-\infty)|0)}{(0|S(\infty,0)\,S(0,-\infty)|0)}\,, \\ \underline{\phi}(\tau) &= S^{+}(\tau,0)\varphi(\tau)S(\tau,0)\,. \end{aligned} \tag{4}$$

3. Usually the state $|\psi\rangle = S(0,-\infty)|0)$ is considered to be the physical vacuum. If the physical vacuum does exist, this is ensured by adiabatic switching on — the interaction turns on adiabatically. In the model under consideration there is no physical vacuum, the system is unstable. In such cases the mathematical vacuum passes into a corresponding quasi-level after the interaction is turned on adiabatically. The quasi-level is a state with a complex energy describing a decay.

To show this we will consider the problem of an oscillator with the frequency changing with time as

$$\omega^2\left(1-\gamma e^{-\alpha|t|}\right)\,.$$

If $\gamma > 1$ then at $t = 0$ the oscillator turns upside down, and the physical vacuum is absent. It turns out, that if at $t \to -\infty$ we start from the ground state of the oscillator, at $t = 0$ we arrive at a state which, in the limit $\alpha \to 0$ has the energy

$$E = -\frac{i\omega}{2}\sqrt{\gamma-1}\,,$$

and describes the decay. A detailed solution is given in Appendix A.

It is interesting to note that the state $(0|S(\infty,0) = \langle\psi|$ is not obtained from $S(0,\infty)|0)$ by Hermitean conjugation; this is due to the fact that the stability condition $S(\infty,-\infty)|0) = |0)$ is not satisfied. The state $\langle\psi| = (0|S(\infty,0)$ is Hermitean conjugate to the state describing the process reverse to decay. The energy of such state is complex conjugated to that of the quasilevel. In what follows, we will call such state anti-quasilevel.

4. In Appendix B a relation between the energy of the state $|\psi\rangle$ and $G(\tau)|_{\tau=0}$ and $G(p)|_{p=0}$ is derived. Here $G(p)$ is the Fourier-transform of $G(\tau)$. Therefore, for studying the analytical properties of $G(\tau)|_{\tau=0}$ and $G(p)|_{p=0}$, as functions of the coupling constant, it is sufficient to study the analytic behavior of $E(\lambda^2)$ where

$E(\lambda^2)$ is the energy of the state $|\psi\rangle = S(0, -\infty)|0)$. The equation for $|\psi\rangle$ is

$$H\,|\psi\rangle = E\,|\psi\rangle\,, \qquad H = \frac{\dot{\varphi}^2}{2} + \frac{m^2\varphi^2}{2} - \lambda\varphi^3\,. \tag{5}$$

This is a conventional differential equation for anharmonic oscillator. At $\varphi \to -\infty$ the wave function $\psi(\varphi)$ falls off exponentially, while at $\varphi \to \infty$ there is only an outcoming wave. (The constant λ is assumed to be positive.)

Let us continue $\psi(\varphi)$, defined for positive λ, to complex values of λ. Then λ is complex in Eq. (5). Let us now examine the boundary conditions.

At positive λ

$$\begin{aligned} \psi(\varphi) &\to \frac{C}{\sqrt{p}} \exp\left[i\int^{\varphi} p\,d\varphi\right]\,, \text{ at } \varphi \to +\infty\,, \\ \psi(\varphi) &\to \frac{C'}{\sqrt{p}} \exp\left[-i\int^{\varphi} p\,d\varphi\right]\,, \text{ at } \varphi \to -\infty\,, \\ p &= \sqrt{2E - m^2\varphi^2 + 2\lambda\varphi^3}\,. \end{aligned} \tag{6}$$

These are the well-known quasiclassical asymptotics. One can assert that $\psi(\varphi)$ has the same asymptotics for all complex λ in the upper half-plane of the parameter λ. Indeed, as long as λ is in the upper half-plane, $\psi(\varphi)$ falls off exponentially at $\varphi \to \pm\infty$, and the growing exponent cannot appear.

Let us pass in the λ plane from the positive semi-axis to negative, via the upper half-plane. Then Eq. (6) implies that after the rotation $\psi(\varphi)$ falls off exponentially at $\varphi \to +\infty$, while at $\varphi \to -\infty$ the wave function $\psi(\varphi)$ represents a wave running into the well. That is to say, starting from the problem of a quasilevel, we arrived at the problem of anti-quasilevel. This means that the function $E(\lambda^2)$ has a cut along the positive semi-axis in the λ^2 plane. The imaginary part $\mathrm{Im}E\,(\lambda^2)$ experiences a jump on this cut.

Consider the integral

$$\int_C dz\,\frac{E(z)}{z - z_0} = 2\pi i\,E(z_0)\,, \qquad z = \lambda^2\,, \tag{7}$$

where the contour C is indicated in Fig. 1. The radius of the circle in Fig. 1 is Δ, while $|z_0| < \Delta$. The integral over the circle is an analytic function for all z_0 inside the circle; therefore, we will not consider it since we are interested in the part of $E(z)$ nonanalytic at the origin,

$$E(z_0) = \frac{1}{\pi}\int_0^{\Delta} dz\,\frac{\mathrm{Im}\,E(z)}{z - z_0}\,. \tag{8}$$

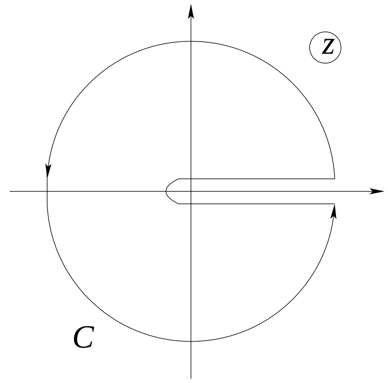


FIGURE 1. Integration contour in the integral (7).

The expansion of $E(z_0)$ in z_0 (at $z_0 \to 0$) immediately follows from Eq. (8),

$$E(z_0) = \sum_{n=0}^{\infty} z_0^n \left(\frac{1}{\pi} \int_0^{\Delta} dz \, \frac{\operatorname{Im} E(z)}{z^{n+1}} \right) . \tag{9}$$

The integrals on the right-hand side converge since $\operatorname{Im} E(z)$ falls off exponentially at $z \to 0$.

Indeed, $\operatorname{Im} E(\lambda^2)$ is proportional (at $\lambda \to 0$) to the barrier transmission coefficient

$$D = \exp \left[-2 \int_{\varphi_1}^{\varphi_2} d\varphi \, \sqrt{m^2\varphi^2 - 2\lambda\varphi^3 - 2E} \right] .$$

where the integral is to be taken between two turning points. At $\lambda \to 0$

$$D = \frac{\alpha'}{\sqrt{\lambda^2}} \exp \left[-\frac{\beta' m^5}{\lambda^2} \right] , \tag{10}$$

where α' and β' are constants.

Since the radius Δ can be chosen to be sufficiently small, substituting

$$\operatorname{Im} E(z) = \frac{\alpha}{\sqrt{z}} \exp \left[-\frac{\beta}{z} \right]$$

in Eq. (9) one gets the expansion coefficients that coincide with the exact ones at $n \to \infty$.

Thus, the function

$$\overline{E}(z_0) = \frac{\alpha}{\pi} \int_0^{\infty} \frac{1}{\sqrt{z}} \frac{e^{-\beta/z}}{z - z_0} dz = C \left(-\frac{\beta}{z_0} \right)^{1/2} \Psi \left(\frac{1}{2}, \frac{1}{2}, -\frac{\beta}{z_0} \right) \tag{11}$$

has the same expansion coefficients, in the limit $n \to \infty$, as the exact $E(z)$. (The fact that we added the integral from Δ to ∞ is of no importance, since this added integral gives a function analytic at the point $z_0 = 0$. Moreover, $\Psi\left(\frac{1}{2}, \frac{1}{2}, x\right)$ is the degenerate hypergeometric function.)

The expansion of $\overline{E}$ has the form

$$\overline{E}(z) = C \sum_{n=0}^{\infty} \left(\frac{z}{\beta}\right)^n \Gamma\left(n + \frac{1}{2}\right) . \tag{12}$$

Since $E(\lambda^2)$ is related to the Green function as follows (see Appendix B)

$$\begin{aligned} iG(\tau)|_{\tau=0} &= \frac{1}{m^2}\left[E - 5\lambda^2 \frac{\partial E}{\partial \lambda^2}\right], \\ \tilde{G}(p)\Big|_{p=0} &= -\frac{1}{m^2} + \frac{9\lambda^2}{m^8}\left[25\,(\lambda^2)^2 \frac{\partial^2 E}{\partial(\lambda^2)^2} + 35\lambda^2 \frac{\partial E}{\partial \lambda^2} - 3E\right], \end{aligned} \tag{13}$$

we arrive at the conclusion that the perturbation theory series diverges: the expansion coefficients grow factorially at large n. Nevertheless, the series is asymptotic.

5. One can consider interactions of other types in perfectly the same way. It is clear that if a given system decays after the interaction switches on, then the imaginary part of the quasilevel energy is a quantity which is exponentially small in the limit of the vanishing coupling constant. This implies the factorial growth of the expansion coefficients in the coupling constant series. There will be no potential barrier if $m = 0$. But in this case the perturbation theory integrals diverge at the lower limit of integration.

Of particular interest is the interaction $V = -\lambda\varphi^4$. At $\lambda > 0$ this interaction corresponds to a decaying system. Performing the same consideration as for $\lambda\varphi^3$ we will obtain that at large n the terms of the perturbative series for $E(\lambda)$ grow as

$$C\left(\frac{\lambda}{\gamma}\right)^n \Gamma\left(n + \frac{1}{2}\right) .$$

At $\lambda < 0$ the system is stable. However, the perturbative series is the same both for positive and negative λ. Thus, there emerges a situation of the type suggested by Dyson in quantum electrodynamics. It is interesting that all terms of the series are of the same sign in the instability domain of negative λ.

The majority of nontrivial theories are seemingly unstable at some phase of the coupling constant, which leads to asymptotic nature of the perturbative series. Equations in such theories have solutions nonanalytic in the coupling constant at the origin. It is unclear, though, to which extent these solutions are physical in the instability domain. In such theories the point $\lambda = 0$ is a branching point. Moreover, if $m \neq 0$, it presents an essential singularity.

What remains unclear is the relation between the decaying nature of the system and the perturbative series divergence in four-dimensional theories. One should note that if small spatial momenta are of importance, the theory becomes one-dimensional; however, the impact of renormalizations calls for a study. It is interesting that if an arbitrary graph with the vanishing external momenta is considered in four dimensions, one can readily get the following inequality:

$$\int \frac{1}{m^2 - p_1^2} \cdots \frac{1}{m^2 - p_i^2} \prod d^4 q \geq \frac{1}{m^{6i}} \left[\int \frac{1}{m^2 - (p_1^0)^2} \cdots \frac{1}{m^2 - (p_i^0)^2} \prod dq^0 \right]^4 \quad (14)$$

where p_k are the internal line momenta, q are the integration momenta, while p_k^0 stand for the time-like components of p_k. Then what appears on the right-hand side of Eq. (14) is the corresponding one-dimensional diagram, and we could built a minorant for the four-dimensional theory, if it were not for the necessity of renormalizations.

I am deeply grateful to V.M. Galitsky for suggesting me this topic for research and for guidance. I would like to thank I.B. Khriplovich for valuable discussions.

Appendix A

Let us consider an oscillator with the time-dependent frequency changing as

$$\omega^2 \left(1 - \gamma\, e^{-\alpha|t|}\right) .$$

We are interested in the time development of the state which tends to the ground state of the frequency ω oscillator at $t \to -\infty$. We demote it $\Psi_\alpha(t)$. In the interaction representation $\Psi_\alpha(t)$ satisfies the following equation:

$$i\frac{\partial \Psi_\alpha}{\partial t} = -\frac{\gamma\omega^2}{4}\, e^{-\alpha|t|}\, x^2(t)\Psi_\alpha\,, \tag{A.1}$$

$$x(t) = \frac{1}{\sqrt{2}}\left[a^+(t) + a^-(t)\right] = \frac{a^+ e^{i\omega t} + a^- e^{-i\omega t}}{\sqrt{2}}\,, \tag{A.2}$$

where

$$[a^+, a^-] = -1\,.$$

We look for $\Psi_\alpha(t)$ in the form

$$\Psi_\alpha(t) = K_\alpha(t) \exp\left[(a^+)^2 f_\alpha(t)\right] |0) \tag{A.3}$$

where $K_\alpha(t)$ and $f_\alpha(t)$ are functions of time, while $|0)$ is the ground state of the oscillator with the frequency ω, so that $a|0) = 0$. Substituting Eq. (A.3) in (A.1) and performing the commutation we obtain terms with $\exp((a^+)^2 f_\alpha)|0)$ and $(a^+)^2 \exp((a^+)^2 f_\alpha)|0)$. Requiring the coefficients in front of these terms to vanish, we arrive at the following equations:

$$i\frac{K'_\alpha}{K_\alpha} = -\frac{\gamma\omega}{4}\, e^{-\alpha|t|}\,(1 + 2f_\alpha)\,, \tag{A.4}$$

$$if'_\alpha = -\frac{\gamma\omega}{4}\, e^{-\alpha|t|}\,\left(e^{2i\omega t} + 4f_\alpha + 4f_\alpha^2 e^{-2i\omega t}\right)\,, \tag{A.5}$$

with the boundary condition

$$f_\alpha(t) \to 0 \quad \text{at} \quad t \to -\infty\,.$$

Consider $t < 0$ and introduce a new function $y(t)$

$$f_\alpha(t) = -\frac{1}{i\gamma\omega}\, e^{(2i\omega-\alpha)t}\, \frac{y'(t)}{y(t)} - \frac{1}{i\gamma\omega}\,\left(-i\omega + \frac{\alpha}{2}\right)\, e^{(2i\omega-\alpha)t} - \frac{1}{2}\, e^{2i\omega t}\,. \tag{A.6}$$

Then we get the following equation for $y(t)$:

$$y'' + \left[\left(\omega + \frac{i\alpha}{2}\right)^2 - \gamma\omega^2\, e^{\alpha t}\right]\, y = 0\,. \tag{A.7}$$

The solution of this equation is

$$y(t) = C_1 J_\nu(z) + C_2 J_{-\nu}(z)\,, \tag{A.8}$$

where

$$\nu = \frac{2i\omega}{\alpha} - 1\,, \qquad z = \frac{2i\omega\sqrt{\gamma}}{\alpha}\, e^{\alpha t/2}\,,$$

and $J_\nu(z)$ is the Bessel function. Using the fact that $f_\alpha(t)$ vanishes at $t \to -\infty$ we find

$$f_\alpha(t) = -\frac{1}{i\gamma\omega}\, e^{(2i\omega-\alpha)t} \left[-i\omega + \frac{\alpha}{2} + \frac{\lambda\omega}{2}\, e^{\alpha t} + \frac{d(J_\nu(z))/dt}{J_\nu(z)}\right]. \tag{A.9}$$

We are interested in the limit

$$\lim_{\alpha\to 0} \Psi_\alpha(0) = \Psi(0)\,.$$

Using the quasiclassical asymptotics of the Bessel functions [4] we find

$$\begin{aligned} f(0) &= \frac{1}{\gamma}\left[1 - \frac{\gamma}{2} + i\sqrt{\gamma - 1}\right], \quad \gamma > 1\,, \\ f(0) &= \frac{1}{\gamma}\left[1 - \frac{\gamma}{2} - \sqrt{1 - \gamma}\right], \quad \gamma < 1\,. \end{aligned} \tag{A.10}$$

At $\gamma < 1$ we arrive at the ground state of the oscillator with the frequency $\omega\sqrt{1-\gamma}$, a “physical vacuum”. If $\gamma > 1$ then

$$\Psi(0) = \exp\left((a^+)^2 f(0)\right)|0)$$

has the following form in the x representation:

$$\Psi(0) = \exp\left(i\omega\sqrt{\gamma - 1}\,\frac{x^2}{2}\right). \tag{A.11}$$

This state describes an outflux of particles from the origin to $\pm\infty$. The energy of this state is

$$E = -\frac{i\omega}{2}\sqrt{\gamma - 1}\,.$$

We see that $n = E/\omega$ is an adiabatic invariant for complex ω too.

If one considers the state which at $t \to \infty$ goes to the vacuum of the frequency ω oscillator, one obtains that at $t = 0$ and $\alpha \to 0$ one deals with the state of an anti-quasilevel with

$$E = \frac{i\omega}{2}\sqrt{\gamma - 1}\,.$$

Appendix B

The Green function in the Heisenberg representation has the form

$$iG(\tau) = \frac{\langle\psi|\underline{\phi}(\tau)\underline{\phi}(0)|\psi\rangle}{\langle\psi|\psi\rangle}\,. \tag{B.1}$$

The connection between $G(\tau)|_{\tau=0}$ and the energy of the state $|\psi\rangle$ is known [5]. We will derive this relation for completeness, however. The equation for $|\psi\rangle$ is

$$(H-E)\,|\psi\rangle = 0\,, \qquad H = \frac{1}{2}\,\dot{\varphi}^2 + \frac{m^2}{2}\,\varphi^2 - \lambda\varphi^3\,. \tag{B.2}$$

Differentiating Eq. (B.2) with respect to m^2 and multiplying by $\langle\psi|$ from the left we get

$$iG(\tau)|_{\tau=0} = \frac{\langle\psi|\underline{\phi}^2(0)|\psi\rangle}{\langle\psi|\psi\rangle} = 2\,\frac{\partial E}{\partial m^2}\,. \tag{B.3}$$

From dimensional arguments

$$E = m\,\Phi\left(\frac{\lambda^2}{m^5}\right)\,.$$

Therefore,

$$iG(\tau)|_{\tau=0} = \frac{1}{m^2}\left(E - 5\lambda^2\frac{\partial E}{\partial\lambda^2}\right)\,. \tag{B.4}$$

Let us derive now a relation between E and $G(p)|_{p=0}$ where

$$G(\tau) = \int_{-\infty}^{\infty}\frac{dp}{2\pi}\,G(p)\,e^{-ip\tau}\,.$$

First of all let us note that given the interaction $\lambda\varphi^3$

$$\overline{\varphi} = \frac{\langle\psi|\underline{\phi}(0)|\psi\rangle}{\langle\psi|\psi\rangle} \neq 0\,.$$

Therefore, there is a constant in τ part in $G(\tau)$ having no physical meaning. In the p representation it yields $\delta(p)$. It is more correct to consider

$$i\tilde{G}(\tau) = \frac{T\,\langle\psi|(\underline{\phi}(\tau)-\overline{\varphi})\,(\underline{\phi}(0)-\overline{\varphi})|\psi\rangle}{\langle\psi|\psi\rangle} = iG(\tau) - \overline{\varphi}^2\,. \tag{B.5}$$

Using the definition of $\underline{\phi}(\tau)$ in terms of the Schrödinger φ,

$$\underline{\phi}(\tau) = e^{iH\tau}\,\varphi\,e^{-iH\tau}$$

we have

$$\tilde{G}(p) = \frac{1}{\langle\psi|\psi\rangle} \left\langle \psi \middle| (\varphi - \overline{\varphi}) \left[\frac{1}{p - (H - E - i\epsilon)} - \frac{1}{p + (H - E - i\epsilon)} \right] (\varphi - \overline{\varphi}) \middle| \psi \right\rangle , \tag{B.6}$$

$$\tilde{G}(p)\Big|_{p=0} = -\frac{2}{\langle\psi|\psi\rangle} \left\langle \psi \middle| (\varphi - \overline{\varphi}) \frac{1}{H - E} (\varphi - \overline{\varphi}) \middle| \psi \right\rangle . \tag{B.7}$$

Moreover, $i\epsilon$ can be omitted since

$$\langle \psi \,|\varphi - \overline{\varphi}|\, \psi \rangle = 0 \,. \tag{B.8}$$

Let us introduce a term $f\varphi$ in the Hamiltonian, where f is a parameter. Then we differentiate Eq. (B.2) twice with respect to f,

$$(H - E) \frac{\partial |\psi\rangle}{\partial f} + \left(\frac{\partial H}{\partial f} - \frac{\partial E}{\partial f} \right) |\psi\rangle \,, \tag{B.9}$$

$$(H - E) \frac{\partial^2 |\psi\rangle}{\partial f^2} + 2 \left(\frac{\partial H}{\partial f} - \frac{\partial E}{\partial f} \right) \frac{\partial |\psi\rangle}{\partial f} - \frac{\partial^2 E}{\partial f^2} |\psi\rangle \,. \tag{B.10}$$

Now multiplying by $\langle\psi|$ from the left we get

$$\frac{\partial E}{\partial f} = \frac{1}{\langle\psi|\psi\rangle} \left\langle \psi \middle| \frac{\partial H}{\partial f} \middle| \psi \right\rangle = \overline{\varphi} \,, \tag{B.11}$$

$$\frac{\partial^2 E}{\partial f^2} = \frac{2}{\langle\psi|\psi\rangle} \left\langle \psi \middle| \frac{\partial H}{\partial f} - \frac{\partial E}{\partial f} \middle| \frac{\partial \psi}{\partial f} \right\rangle = \overline{\varphi} \,. \tag{B.12}$$

Furthermore, Eq. (B.9) implies

$$\frac{\partial |\psi\rangle}{\partial f} = - \frac{1}{H - E} \left(\frac{\partial H}{\partial f} - \frac{\partial E}{\partial f} \right) |\psi\rangle \,. \tag{B.13}$$

In Eq. (B.13) one can add $|\psi\rangle$ with an arbitrary coefficient. This additional term will vanish, however, upon substitution in Eq. (B.12). Thus,

$$\frac{\partial^2 E}{\partial f^2} = - \frac{2}{\langle\psi|\psi\rangle} \left\langle \psi \middle| (\varphi - \overline{\varphi}) \frac{1}{H - E} (\varphi - \overline{\varphi}) \middle| \psi \right\rangle . \tag{B.14}$$

Now one can set $f = 0$, arriving at

$$\frac{\partial^2 E}{\partial f^2} = \tilde{G}\,(p)|_{p=0} \,. \tag{B.15}$$

The relation (B.15) can be rewritten in terms of derivatives over λ^2. To this end we introduce a new operator η instead of φ,

$$\varphi = \eta + \varphi_0 \,, \qquad \varphi_0 = \frac{m^2 - \sqrt{m^4 + 12\lambda f}}{6\lambda} \,. \tag{B.16}$$

Then the Hamiltonian does not contain terms linear in η, and one can write

$$E = E^0 + M\Phi\left(\frac{\lambda^2}{M^5}\right) \,, \tag{B.17}$$

$$E^0 = \frac{m^2\varphi_0^2}{2} + f\varphi_0 - \lambda\varphi_0^3 \,, \qquad M^2 = m^2 - 6\lambda\varphi_0 \,. \tag{B.18}$$

Then Eq. (B.15) goes into

$$\tilde{G}(p)\Big|_{p=0} = -\frac{1}{m^2} + \frac{9\lambda^2}{m^8}\left[25\,(\lambda^2)^2\,\frac{\partial^2 E}{\partial(\lambda^2)^2} + 35\lambda^2\frac{\partial E}{\partial\lambda^2} - 3E\right] \,. \tag{B.19}$$

References

1. F.J. Dyson, *Phys. Rev.* **85**, 631 (1952).
2. W. Thirring, *Helv. Phys. Acta* **26**, 33 (1953).
3. G. Baym, *Phys. Rev.* **117**, 886 (1960).
4. A.Z. Patashinsky, V.L. Pokrovsky, and I.M. Khalatnikov, *ZhETF* **44**, 2062 (1961).
5. V.M. Galitsky and A.B. Migdal, *ZhETF* **34**, 139 (1958).

Responsible for the release — I.B. Khriplovich
Signed into print on December 2, 1964 — Glavlit MH00663
Number of copies printed — 150
Order number 052, Free of Charge

Printed in the Institute of Nuclear Physics of the Siberian Branch of the USSR Academy of Sciences

ИНСТИТУТ ЯДЕРНОЙ ФИЗИКИ СИБИРСКОГО ОТДЕЛЕНИЯ
АН СССР

Препринт

А.И. Вайнштейн

РАСПАДАЮЩИЕСЯ СИСТЕМЫ И РАСХОДИМОСТЬ РЯДА ТЕОРИИ ВОЗМУЩЕНИЙ

Новосибирск — 1964 год

Аннотация

Рассматриваются одномерные полевые модели. Если при каком-либо знаке константы связи λ спектр является непрерывным, то ряд теории возмущений для пропагатора расходится, причем общий член ряда имеет вид $n!\,(\alpha\lambda)^n$ для больших n.

1. Дайсон в работе [1] привел аргументы в пользу того, что ряды теории возмущений в квантовой электродинамике являются расходящимися. Он основывался на том, что мир, в котором квадрат заряда e^2 отрицателен, не имеет основного состояния и распадается. Поэтому трудно себе представить, что такая ситуация может описываться функциями аналитичными по e^2 в точке $e^2 = 0$.

Тирринг [2] исследовал теорию с взаимодействием $L_{\text{int}} = \lambda\varphi^3$ и показал, что ряд теории возмущений для поляризационного оператора расходится в области импульсов $p^2 < m^2$. При больших n члены ряда имеют вид

$$C(\alpha\lambda)^n \, \frac{(n-4)!}{n^2}\,,$$

где C и α — функции p^2. Рассмотренная Тиррингом модель является примером неустойчивой теории. С помощью прямого вариационного метода легко показать, что в модели нет нижнего состояния [3].

Мы покажем, что распадность системы приводит к расходимости ряда теории возмущений в одномерной модели.

2. Рассмотрим модель, в которой полевые операторы φ зависят только от времени, то есть нет пространственных координат. Гамильтониан и одновременные перестановочные соотношения имеют вид

$$H = \frac{1}{2}\,(\dot\varphi)^2 + \frac{m^2}{2}\varphi^2 + V(\varphi)\,, \qquad [\varphi(t)\,,\,\dot\varphi(t)] = i\,. \tag{1}$$

Это — гамильтониан и перестановочные соотношения обычного квантово-механического нелинейного осциллятора с частотой $\omega = m$ массой $\mu = 1$.

Взаимодействие $V(\varphi)$ возьмём для определенности в виде

$$V(\varphi) = -\lambda\varphi^3\,. \tag{2}$$

Из дальнейшего будет видно, что рассмотрение пригодно для всех распадных взаимодействий.

Повторяя доказательство Тирринга [2] в одномерном случае для взаимодействия $\lambda\varphi^3$, мы придём к такому же, как и в четырехмерном варианте, результату, то-есть, что ряд для поляризационного оператора расходится, причем таким же образом. Мы свяжем это с распадностью системы.

Будем рассматривать причинную функцию Грина поля φ. В представлении взаимодействия она определяется как

$$iG(\tau) = \frac{(0|T\,\varphi(\tau)\,\varphi(0)|0)}{S_{00}} \tag{3}$$

где $\varphi(\tau)$ — полевой оператор в представлении взаимодействия. Усреднение идет по математическому вакууму. Предполагается адиабатическое включение.

Если мы перейдём к гейзенберговским операторам $\underline{\phi}(\tau)$, то получим

$$\begin{aligned} iG(\tau) &= \frac{(0|S(\infty,0)[T\,\underline{\phi}(\tau)\,\underline{\phi}(0)]S(0,-\infty)|0)}{(0|S(\infty,0)\,S(0,-\infty)|0)}\,, \\ \underline{\phi}(\tau) &= S^{+}(\tau,0)\varphi(\tau)S(\tau,0)\,. \end{aligned} \tag{4}$$

3. Обычно состояние $|\psi\rangle = S(0,-\infty)|0)$ считают равным физическому вакууму. Если физический вакуум существует, то это обеспечивается адиабатическим включением взаимодействия. В рассматриваемой модели физического вакуума нет, система неустойчива. В таких случаях математический вакуум при адиабатическом включении взаимодействия переходит в соответствующий квазиуровень — состояние с комплексной энергией, описывающее распад. Чтобы показать это мы рассмотрели задачу об осцилляторе, у которого частота менялась со временем как

$$\omega^2\left(1-\gamma e^{-\alpha|t|}\right)\,.$$

Если $\gamma > 1$, то при $t = 0$ осциллятор был перевернут, и физический вакуум отсутствовал. Действительно, оказалось, что если при $t \to -\infty$ мы имели основное состояние, то при $t = 0$ мы приходим к состоянию, котороые в пределе $\alpha \to 0$ имеет энергию

$$E = -\frac{i\omega}{2}\sqrt{\gamma-1}\,,$$

и описывает распад. Подробное решение дано в приложении A.

Интересно отметить, что состояние $(0|S(\infty,0) = \langle\psi|$ не получается эрмитовым сопряжением из $S(0,\infty)|0)$, что связано с невыполнением условия устойчивости $S(\infty,-\infty)|0) = |0)$. Состояние $\langle\psi| = (0|S(\infty,0)$ является эрмитово сопряженным к состоянию, описывающему процесс, обратный к распаду. Энергия такого состояния комплексна сопряжена к энергии квазиуровня. Такое состояние мы в дальнейшем будем называть антиквазиуровнем.

4. В приложении B выведена связь между энергией состояния $|\psi\rangle$ и $G(\tau)|_{\tau=0}$ и $G(p)|_{p=0}$. Здесь $G(p)$ — Фурье-образ $G(\tau)$. Поэтому для изучения аналитических свойств $G(\tau)|_{\tau=0}$ и $G(p)|_{p=0}$, как функции константы связи, достаточно это сделать для $E(\lambda^2)$, где $E(\lambda^2)$ — энергия состояния $|\psi\rangle = S(0,-\infty)|0)$. Уравнение для $|\psi\rangle$ таково

$$H\,|\psi\rangle = E\,|\psi\rangle\,, \qquad H = \frac{\dot{\varphi}^2}{2} + \frac{m^2\varphi^2}{2} - \lambda\varphi^3\,. \tag{5}$$

Это — обычное дифференциальное уравнение нелинейного осциллятора. При $\varphi \to -\infty$ волновая функция $\psi(\varphi)$ экспоненциально падает, а при $\varphi \to \infty$ имеется только выходящая волна. (Мы считаем $\lambda > 0$).

Продолжим $\psi(\varphi)$, определённую для положительных λ, на комплексные λ. Тогда в (5) λ комплексно. Разберёмся, что будет с граничными условиями.

При положительных λ

$$\begin{aligned}
\psi(\varphi) &\;\to\; \frac{C}{\sqrt{p}}\exp\left[i\int^{\varphi} p\,d\varphi\right], \quad \varphi \to +\infty\,,\\
\psi(\varphi) &\;\to\; \frac{C'}{\sqrt{p}}\exp\left[-i\int^{\varphi} p\,d\varphi\right], \quad \varphi \to -\infty\,,\\
p &\;=\; \sqrt{2E - m^2\varphi^2 + 2\lambda\varphi^3}\,.
\end{aligned} \tag{6}$$

Это — известные квазиклассические асимптотики. Можно утверждать, что $\psi(\varphi)$ имеет эти же асимптотики и для всех комплексных λ в верхней полуплоскости параметра λ. Действительно, пока λ находится в верхней полуплоскости, $\psi(\varphi)$ экспоненциально падает при $\varphi \to \pm\infty$, и растущая экспонента не может появиться.

Перейдем в плоскости λ с положительной полуоси на отрицательную через верхнюю полуплоскость. Тогда из (6) видно, что после поворота $\psi(\varphi)$ экспоненциально падает при $\varphi \to +\infty$, а при $\varphi \to -\infty$ представляет собой волну, бегущую в яму. То-есть, начав с задачи о квазиуровне, мы пришли к задаче об антиквазиуровне. Это означает, что функция $E(\lambda^2)$ имеет в плоскости λ^2 разрез по положительной полуоси. На этом разрезе терпит скачок $\mathrm{Im}E\,(\lambda^2)$.

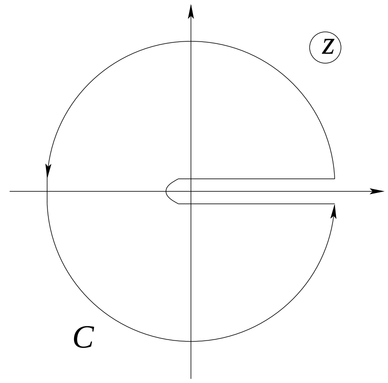


Рис. 1.

Рассмотрим интеграл

$$\int_C dz\,\frac{E(z)}{z-z_0} = 2\pi i\,E(z_0)\,, \qquad z=\lambda^2\,, \tag{7}$$

где контур C показан на рис. 1. Радиус окружности на рис. 1 равен $\Delta\,,\quad |z_0|<\Delta$. Интеграл по окружности является аналитической функцией для всех z_0 внутри окружности, поэтому мы не будем его рассматривать, так как нас интересует неаналитическая в нуле часть $E(z)$,

$$E(z_0) = \frac{1}{\pi}\int_0^\Delta dz\;\frac{\mathrm{Im}\,E(z)}{z-z_0}\,. \tag{8}$$

Из (8) сразу следует разложение $E(z_0)$ в ряд при $z_0\to 0$,

$$E(z_0) = \sum_{n=0}^{\infty} z_0^n\;\left(\frac{1}{\pi}\int_0^\Delta dz\;\frac{\mathrm{Im}\,E(z)}{z^{n+1}}\right)\,. \tag{9}$$

Интегралы сходятся, так как $\mathrm{Im}\,E(z)$ экспоненциально убывает при $z\to 0$. Действительно, $\mathrm{Im}\,E(\lambda^2)$ при $\lambda\to 0$ пропорциональна коэффициенту прохождения через барьер

$$D = \exp\left[-2\int_{\varphi_1}^{\varphi_2} d\varphi\;\sqrt{m^2\varphi^2-2\lambda\varphi^3-2E}\right]\,.$$

Интеграл берется между двумя точками поворота. При $\lambda\to 0$

$$D = \frac{\alpha'}{\sqrt{\lambda^2}}\,\exp\left[-\frac{\beta' m^5}{\lambda^2}\,,\right]\,, \tag{10}$$

где α' и β' — константы.

Так как Δ можно выбрать достаточно малым, то подстановка в (9)

$$\mathrm{Im}E(z) = \frac{\alpha}{\sqrt{z}}\exp\left[-\frac{\beta}{z}\right]$$

приведёт к коэффициентам разложения совпадающим с точными при $n \to \infty$.

Таким образом, функция

$$\overline{E}(z_0) = \frac{\alpha}{\pi} \int_0^\infty \frac{1}{\sqrt{z}} \frac{e^{-\beta/z}}{z - z_0} dz = C \left(-\frac{\beta}{z_0}\right)^{1/2} \Psi\left(\frac{1}{2}, \frac{1}{2}, -\frac{\beta}{z_0}\right) \tag{11}$$

имеет такие же коэффициенты разложения в пределе $n \to \infty$, как и точная $E(z)$. (Добавление интеграла от Δ до ∞ не имеет значения, так как этот интеграл даёт функцию аналитическую в точке $z_0 = 0$. Напомним, что $\Psi\left(\frac{1}{2}, \frac{1}{2}, x\right)$ — вырожденная гипергеометрическая функция).

Разложение $\overline{E}$ имеет вид

$$\overline{E}(z) = C \sum_{n=0}^{\infty} \left(\frac{z}{\beta}\right)^n \Gamma\left(n + \frac{1}{2}\right) . \tag{12}$$

Так как $E(\lambda^2)$ связана с функцией Грина соотношениями (см. приложение B)

$$\begin{aligned} iG(\tau)\big|_{\tau=0} &= \frac{1}{m^2}\left[E - 5\lambda^2 \frac{\partial E}{\partial \lambda^2}\right], \\ \tilde{G}(p)\Big|_{p=0} &= -\frac{1}{m^2} + \frac{9\lambda^2}{m^8}\left[25\,(\lambda^2)^2 \frac{\partial^2 E}{\partial(\lambda^2)^2} + 35\lambda^2 \frac{\partial E}{\partial \lambda^2} - 3E\right], \end{aligned} \tag{13}$$

то мы приходим к выводу, что ряд теории возмущений расходится, причем коэффициенты разложения факториально растут при больших n. Тем не менее, ряд является асимптотическим.

5. Совершенно аналогичным способом можно рассмотреть другиые типы взаимодействий. Понятно, что если при включении взаимодействия система распадается, то мнимая часть энергии квазиуровня есть величина экспоненциально малая при константе связи стремящейся к нулю, что приводит к факториальному росту коэффициентов ряда по степеням константы связи. Потенциального барьера не будет, если $m = 0$. Но в этом случае интегралы теории возмущений расходятся на нижнем пределе.

Представляет интерес взаимодействие $V = -\lambda\varphi^4$. При $\lambda > 0$ оно соответствует распадающейся системе. Проделав такое же как и для $\lambda\varphi^3$ рассмотрение, мы получим что при больших n члены ряда для $E(\lambda)$ ведут себя как

$$C \left(\frac{\lambda}{\gamma}\right)^n \Gamma\left(n + \frac{1}{2}\right) .$$

При $\lambda < 0$ система устойчива. Но ряд будет общим и для положительных λ и для отрицательных. Ситуация возникает такого типа, которую предполагает Дайсон для квантовой электродинамики. Интересно, что все члены ряда имеют один знак в области неустойчивости.

Повидимому, большинство нетривиальных теорий являются неустойчивыми при какой-либо фазе константы связи, что приводит к асимптотичности рядов. Уравнения теорий имеют решения неаналитичные по константе связи в нуле, правда, неясно, насколько эти решения физичны в области неустойчивости. Точка $\lambda = 0$ является в таких теориях точкой ветвления и, если $m \neq 0$, существенно особой точкой.

Остаётся неясным вопрос о связи распадности с расходимостью ряда в четырехмерных теориях, хотя надо отметить, что, если играют роль малые пространственные импульсы, то теория становися одномерной, однако требует выяснения влияние перенормировок. Интересно, что если рассмотреть произвольную диаграмму четырехмерной теории с внешними импульсами равными нулю, то легко получить неравенство

$$\int \frac{1}{m^2 - p_1^2} \cdots \frac{1}{m^2 - p_i^2} \prod d^4 q \geq \frac{1}{m^{6i}} \left[\int \frac{1}{m^2 - (p_1^0)^2} \cdots \frac{1}{m^2 - (p_i^0)^2} \prod dq^0 \right]^4 , \quad (14)$$

где p_k — импульсы внутренних линий, q — импульсы интегрирования, p_k^0 — временные компоненты. Тогда в правой части (14) стоит соответствующая одномерная диаграмма, и мы могли бы поставить миноранту для четырехмерной теории, если бы не было необходимости перенормировок.

Приношу глубокую благодарность В.М. Галицкому за предложение темы и руководство работой. Автор благодарен И.Б. Хрипловичу за ценные дискуссии.

Приложение A

Рассмотрим осциллятор у которого частота меняется со временем по закону

$$\omega^2\left(1-\gamma\, e^{-\alpha|t|}\right)\,.$$

Нас интересует развитие во времени состояния, которое при $t\to-\infty$ стремится к вакууму осциллятора с частотой ω. Обозначим его через $\Psi_\alpha(t)$. В представлении взаимодействия $\Psi_\alpha(t)$ удовлетвотяет уравнению

$$i\frac{\partial\Psi_\alpha}{\partial t} = -\frac{\gamma\omega^2}{4}\, e^{-\alpha|t|}\, x^2(t)\Psi_\alpha\,, \tag{A.1}$$

$$x(t) = \frac{1}{\sqrt{2}}\left[a^+(t)+a^-(t)\right] = \frac{a^+e^{i\omega t}+a^-e^{-i\omega t}}{\sqrt{2}}\,, \tag{A.2}$$

где

$$[a^+,a^-]=-1\,.$$

Ищем $\Psi_\alpha(t)$ в виде

$$\Psi_\alpha(t) = K_\alpha(t)\exp\left[(a^+)^2 f_\alpha(t)\right]|0) \tag{A.3}$$

где $K_\alpha(t)$ и $f_\alpha(t)$ — функции времени, $|0)$ — вакуум осциллятора с частотой ω, так что $a|0)=0$. Подставляя (A.3) в (A.1) и производя коммутации, мы получим члены с $\exp((a^+)^2 f_\alpha)|0)$ и с $(a^+)^2\exp((a^+)^2 f_\alpha)|0)$. Приравняв коэффициенты при них нулю, мы придём к уравнениям

$$i\frac{K'_\alpha}{K_\alpha} = -\frac{\gamma\omega}{4}\, e^{-\alpha|t|}\,(1+2f_\alpha)\,, \tag{A.4}$$

$$if'_\alpha = -\frac{\gamma\omega}{4}\, e^{-\alpha|t|}\,\left(e^{2i\omega t}+4f_\alpha+4f_\alpha^2 e^{-2i\omega t}\right)\,, \tag{A.5}$$

с граничным условием

$$f_\alpha(t)\to 0 \quad \text{at} \quad t\to-\infty\,.$$

Будем рассматривать $t<0$ и введем новую функцию $y(t)$,

$$f_\alpha(t) = -\frac{1}{i\gamma\omega}\, e^{(2i\omega-\alpha)t}\,\frac{y'(t)}{y(t)} - \frac{1}{i\gamma\omega}\left(-i\omega+\frac{\alpha}{2}\right)\, e^{(2i\omega-\alpha)t} - \frac{1}{2}\, e^{2i\omega t}\,. \tag{A.6}$$

Для $y(t)$ получим уравнение

$$y'' + \left[\left(\omega+\frac{i\alpha}{2}\right)^2 - \gamma\omega^2\, e^{\alpha t}\right] y = 0\,. \tag{A.7}$$

Его решение таково

$$y(t) = C_1 J_\nu(z) + C_2 J_{-\nu}(z)\,, \tag{A.8}$$

где

$$\nu = \frac{2i\omega}{\alpha} - 1\,, \qquad z = \frac{2i\omega\sqrt{\gamma}}{\alpha}\, e^{\alpha t/2}\,,$$

и $J_\nu(z)$ — функция Бесселя.

Используя обращение $f_\alpha(t)$ в нуль при $t \to -\infty$, найдем

$$f_\alpha(t) = -\frac{1}{i\gamma\omega}\, e^{(2i\omega-\alpha)t} \left[-i\omega + \frac{\alpha}{2} + \frac{\lambda\omega}{2}\, e^{\alpha t} + \frac{d(J_\nu(z))/dt}{J_\nu(z)}\right]. \tag{A.9}$$

Нас интересует

$$\lim_{\alpha\to 0} \Psi_\alpha(0) = \Psi(0)\,.$$

Воспользовавшись квазиклассическими асимптотиками функции Бесселя [4], найдём

$$\begin{aligned} f(0) &= \frac{1}{\gamma}\left[1 - \frac{\gamma}{2} + i\sqrt{\gamma - 1}\right], \quad \gamma > 1\,, \\ f(0) &= \frac{1}{\gamma}\left[1 - \frac{\gamma}{2} - \sqrt{1 - \gamma}\right], \quad \gamma < 1\,. \end{aligned} \tag{A.10}$$

При $\gamma < 1$ мы приходим к основному состоянию осциллятора с частотой $\omega\sqrt{1-\gamma}$ —“физическому вакууму”. При $\gamma > 1$

$$\Psi(0) = \exp\left((a^+)^2 f(0)\right)|0)$$

в x-представлении имеет вид

$$\Psi(0) = \exp\left(i\omega\sqrt{\gamma - 1}\,\frac{x^2}{2}\right). \tag{A.11}$$

Это состояние описывает разлетание частиц из области начала координат на $\pm\infty$. Его энергия равна

$$E = -\frac{i\omega}{2}\sqrt{\gamma - 1}\,.$$

Мы видим, что $n = E/\omega$ является адиабатическим инвариантом и для комплексных ω.

Если рассмотреть состояние, которое при $t \to \infty$ переходит в вакуум осциллятора с частотой ω, то получим, что при $t = 0$ и $\alpha \to 0$ мы имеем состояние антиквазиуровня с

$$E = \frac{i\omega}{2}\sqrt{\gamma - 1}\,.$$

Приложение B

Функция Грина в гейзенберговском представлении определяется как

$$iG(\tau) = \frac{\langle\psi|\underline{\phi}(\tau)\underline{\phi}(0)|\psi\rangle}{\langle\psi|\psi\rangle}\,. \tag{B.1}$$

Связь между $G(\tau)|_{\tau=0}$ и энергией состояния $|\psi\rangle$ известна [5]. Но для полноты изложения мы её выведем. Уравнение для $|\psi\rangle$ таково

$$(H-E)\,|\psi\rangle = 0\,, \qquad H = \frac{1}{2}\,\dot{\varphi}^2 + \frac{m^2}{2}\,\varphi^2 - \lambda\varphi^3\,. \tag{B.2}$$

Дифференцируя (B.2) по m^2 и умножая на $\langle\psi|$ слева, получим

$$iG(\tau)|_{\tau=0} = \frac{\langle\psi|\underline{\phi}^2(0)|\psi\rangle}{\langle\psi|\psi\rangle} = 2\,\frac{\partial E}{\partial m^2}\,. \tag{B.3}$$

Из размерных соображений

$$E = m\,\Phi\left(\frac{\lambda^2}{m^5}\right)\,.$$

Поэтому

$$iG(\tau)|_{\tau=0} = \frac{1}{m^2}\left(E - 5\lambda^2\frac{\partial E}{\partial\lambda^2}\right)\,. \tag{B.4}$$

Выведем теперь связь E и $G(p)|_{p=0}$, где

$$G(\tau) = \int_{-\infty}^{\infty}\frac{dp}{2\pi}\,G(p)\,e^{-ip\tau}\,.$$

Прежде всего отметим, что при взаимодействии $\lambda\varphi^3$

$$\overline{\varphi} = \frac{\langle\psi|\underline{\phi}(0)|\psi\rangle}{\langle\psi|\psi\rangle} \neq 0\,.$$

Поэтому в $G(\tau)$ есть постоянная по τ часть, не имеющая физического смысла, которая в p-представлении даёт $\delta(p)$. Правильнее рассматривать

$$i\tilde{G}(\tau) = \frac{T\,\langle\psi|(\underline{\phi}(\tau)-\overline{\varphi})\,(\underline{\phi}(0)-\overline{\varphi})|\psi\rangle}{\langle\psi|\psi\rangle} = iG(\tau) - \overline{\varphi}^2\,. \tag{B.5}$$

Используя определение $\underline{\phi}(\tau)$ через шредингеровское φ,

$$\underline{\phi}(\tau) = e^{iH\tau}\,\varphi\,e^{-iH\tau}$$

имеем

$$\tilde{G}(p) = \frac{1}{\langle\psi|\psi\rangle}\left\langle\psi\left|(\varphi-\overline{\varphi})\left[\frac{1}{p-(H-E-i\epsilon)}\right.\right.\right. \tag{B.6}$$

$$\left.\left.\left. - \frac{1}{p+(H-E-i\epsilon)}\right](\varphi-\overline{\varphi})\right|\psi\right\rangle ,$$

$$\tilde{G}(p)\Big|_{p=0} = -\frac{2}{\langle\psi|\psi\rangle}\left\langle\psi\left|(\varphi-\overline{\varphi})\frac{1}{H-E}(\varphi-\overline{\varphi})\right|\psi\right\rangle . \tag{B.7}$$

заметим, что $i\epsilon$ можно опустить, так как

$$\langle\psi\,|\varphi-\overline{\varphi}|\,\psi\rangle = 0\,. \tag{B.8}$$

Введем в гамильтониан член $f\varphi$, где f — параметр. Продиффенцируем уравнение (B.2) дважды по параметру f,

$$(H-E)\frac{\partial|\psi\rangle}{\partial f} + \left(\frac{\partial H}{\partial f} - \frac{\partial E}{\partial f}\right)|\psi\rangle\,, \tag{B.9}$$

$$(H-E)\frac{\partial^2|\psi\rangle}{\partial f^2} + 2\left(\frac{\partial H}{\partial f} - \frac{\partial E}{\partial f}\right)\frac{\partial|\psi\rangle}{\partial f} - \frac{\partial^2 E}{\partial f^2}|\psi\rangle\,. \tag{B.10}$$

Умножая на $\langle\psi|$ слева, получим

$$\frac{\partial E}{\partial f} = \frac{1}{\langle\psi|\psi\rangle}\left\langle\psi\left|\frac{\partial H}{\partial f}\right|\psi\right\rangle = \overline{\varphi}\,, \tag{B.11}$$

$$\frac{\partial^2 E}{\partial f^2} = \frac{2}{\langle\psi|\psi\rangle}\left\langle\psi\left|\frac{\partial H}{\partial f} - \frac{\partial E}{\partial f}\right|\frac{\partial\psi}{\partial f}\right\rangle = \overline{\varphi}\,. \tag{B.12}$$

Из (B.9) находим $\partial|\psi\rangle/\partial f$,

$$\frac{\partial|\psi\rangle}{\partial f} = -\frac{1}{H-E}\left(\frac{\partial H}{\partial f} - \frac{\partial E}{\partial f}\right)|\psi\rangle\,. \tag{B.13}$$

К (B.13) можно прибавить с произвольным коэффициентом $|\psi\rangle$, но при подстановке в (B.12) эта добавка даст нуль,

$$\frac{\partial^2 E}{\partial f^2} = -\frac{2}{\langle\psi|\psi\rangle}\left\langle\psi\left|(\varphi-\overline{\varphi})\frac{1}{H-E}(\varphi-\overline{\varphi})\right|\psi\right\rangle . \tag{B.14}$$

Теперь f можно положить равным нулю,

$$\frac{\partial^2 E}{\partial f^2} = \tilde{G}\,(p)|_{p=0}\ . \tag{B.15}$$

Связь (B.15) можно записать через производные по λ^2. Для этого вводим вместо φ новый оператор η,

$$\varphi = \eta + \varphi_0\,, \qquad \varphi_0 = \frac{m^2 - \sqrt{m^4 + 12\lambda f}}{6\lambda}\,. \tag{B.16}$$

Тогда гамильтониан не содержит линейного по η члена, и можно записать

$$E \;=\; E^0 + M\Phi\left(\frac{\lambda^2}{M^5}\right)\,, \tag{B.17}$$

$$E^0 \;=\; \frac{m^2\varphi_0^2}{2} + f\varphi_0 - \lambda\varphi_0^3\,, \qquad M^2 = m^2 - 6\lambda\varphi_0\,. \tag{B.18}$$

Тогда (B.15) перейдёт в

$$\tilde{G}(p)\Big|_{p=0} = -\frac{1}{m^2} + \frac{9\lambda^2}{m^8}\left[25\,(\lambda^2)^2\,\frac{\partial^2 E}{\partial(\lambda^2)^2} + 35\lambda^2\frac{\partial E}{\partial\lambda^2} - 3E\right]. \tag{B.19}$$

Литература

1. F.J. Dyson, *Phys. Rev.* **85**, 631 (1952).

2. W. Thirring, *Helv. Phys. Acta* **26**, 33 (1953).

3. G. Baym, *Phys. Rev.* **117**, 886 (1960).

4. А.З. Паташинский, В.Л. Покровский, И.М. Халатников, ЖЭТФ, **4**, 2062 (1961).

5. В.М. Галицкий, А.Б. Мигдал, ЖЭТФ, **34** , 139 (1958).

Ответственный за выпуск — И.Б. Хриплович
Подписано к печати МН00663 2.12.1964
Формат бумаги 270 × 290, тираж 150
Заказ № 052. Бесплатно

Отпечатано на ротапринте в Институте ядерной физике СО АН СССР.

Physics in a Cold Climate

Fun Reading for the Arkadyfest Participants

E. Shuryak
V. Zelevinsky
V. Sokolov
M. Shifman
S. Gasiorowicz

ARKADY IN SIBERIA

EDWARD SHURYAK
Department of Physics and Astronomy, State University of New York,
Stony Brook, NY 11794, USA

These are random recollections on the "middle years" of Arkady's life in science, from the late 1960's to late 1980's. One cannot write about Arkady in Siberia without first describing a general atmosphere in the Budker Institute of Nuclear Physics and Akademgorodok, Novosibirsk, in the 1960's and 1970's. I guess it may be interesting for our international friends and colleagues to learn about it, and to those who were there at the time, to recall Akademgorodok once again.

First, about the place. Siberia, with its area of the size of the whole US, is still poorly populated, and for a reason. Arkady's parents moved there during the World War II, fleeing from advancing German troops from their native Donetsk in Ukraine.

Although there are several large industrial cities in Siberia (e.g. Novosibirsk's population is about 1.5 million) there were no strong universities[a] or technical schools there until the end of the 1950's, when Khrushchev, with his characteristic decisiveness, endorsed construction of one of the world largest scientific centers. A large variety of research institutes covering all hard sciences are situated there, and a brand new Novosibirsk State University. In the 1960's, Akademgorodok had a population of about 30 thousand, (eventually it grew to over 100 thousand) with, perhaps, half of them involved in scientific research, in one way or another.

Arkady (and his wife Nelly, and many friends) happened to be in the first graduating class of the newly-born University. I am sure their student years were very colorful, but I cannot say anything about this because I moved to Akademgorodok later, in 1964 at age 16, spent my last high-school year in a FMS (a specialized physics and mathematics school the NSU had established to attract the brightest), entered the university next year, and met Arkady for the first time in his capacity of an instructor of the Quantum Mechanics course (with Prof. S.T. Belyaev as the lecturer) in 1966.

One good thing about this University was that there were practically no funds for professors' salaries, and nearly all of them were from research In-

[a] Well, there was Tomsk University, since the mid-nineteen century, but I met no physicists from this university so far.

stitutes. Teaching there simply fell on people who had enough energy to do it, practically for the fun of it, with salaries being rather symbolic, even by Russian standards.

Another good thing — following from the first — was that policies toward student curriculum were rather liberal. In order to demonstrate a good deal of enthusiasm aimed at jump-starting immediate work at the front-line of science, let me give my own example. In my *freshman* year I took a course by Yu.B. Rumer and A.I. Fet "Unitary Symmetries," on SU(3) and quarks.[b] Taking it *before* quantum mechanics had little sense, but *after* it, quantum mechanics looked like an enlightenment sent by God.

I attended many Arkady's talks and started communicating with him since about 1967, when I was allowed to attend seminars at the Institute of Nuclear Physics. It is now called the Budker Institute, and very rightly so: Gersh Budker indeed managed to build a world-class laboratory in this remote place, and he did so against quite visible and ever growing hostility towards him on the part of the Akademgorodok and Novosibirsk local authorities. A pioneer of electron-electron, electron-positron and proton-antiproton colliders in 1960, he pointed out already in the mid-1970's that the future of high energy physics lay in linear electron colliders.[c] Perhaps, a less known talent of Budker (which would be so cherished in this country) was his ability to invent applications of accelerator technology, produce hardware and make good deals with industry. Due to this, his institute was, to a large extent, a self-sustaining enterprise.[d]

Gersh Budker was not only *the* Director but a true intellectual center of this Institute. I am sure all of us, who were lucky to communicate with him, or just hear his talks or lectures. will never forget him. Arkady and myself, as members of various "round tables" (something like a standing committee meeting each week at 12, for an hour or more), were seeing him for his last years, dealing with science, strategic and day-by-day issues as they were coming along. This is where we learned what physics is all about and how one should deal with it (yes, of course, with a good joke).

One of the most memorable moments of a strong interaction between Budker and Arkady happened sometime in the early 1970's. Budker got fascinated

[b] Note that the timing of this course was quite remarkable since the year was 1965, just the next year after seminal Gell-Mann and Ne'eman's papers.

[c] This fact got recognition only this year in the US Long Range Plan.

[d] I recall that in one of his speeches Panofsky addressed Budker as "a director of a capitalistic Institution in a socialistic country", while he (Panofsky) referred to himself as a director in the inverse situation— he had to beg for money from the funding agencies all the time. This feature which was always handy but became crucial for the survival of the Institute in the early 1990's when the infrastructure of what remained of the Soviet Union nearly collapsed.

then by prospects of studying CP violation in kaon-antikaon system originating from the ϕ-meson decays[e] and started asking theorists a series of pointed questions, trying to work out an experimental program. Questions were copious and appeared in rapid sequences: basically only Arkady was able to provide answers, usually right away at the blackboard. It went on for several months at these weekly meetings, in small installments but with an increasing sophistication. The audience watched them both in amazement. It was a good lesson: neither of these two could possibly proceed by himself, and yet doing it together they worked out a beautiful program of experiments, with fine interplay of Bose statistics, interfering amplitudes and CP violation. Another lesson: as far as I know, neither Budker nor Arkady cared to write down and publish what they had done: for them, understanding was enough a reward by itself.

Let me now come to an important problem which Budker Institute had in the 1960's: its theory group lacked its own intellectual center.[f] However, as we all know, theoretical physics is transferred mostly as a kind of Olympic flame, from one leader to the next. Budker knew it, tried to seduce one or another senior theorist (such as Yakov Zeldovich) but it did not work. Professor V.M. Galitsky played this role for a while, but was gone well before my time. Galitsky was Arkady's physics adviser. He realized that Arkady was interested not in many-body theory he could teach him, but, rather, in high-energy physics. Departing from Novosibirsk, Galitsky managed to "sell" Arkady to Boris Ioffe.[g] It was a tremendous piece of luck: it gave Arkady not only Boris Ioffe as an excellent adviser, but the ability to come regularly to ITEP, sometimes for an extended time. ITEP had one of the most established theory groups in Russia, hand-picked by Landau and Pomeranchuk, with a large number of young and active people. They became Arkady's life-long collaborators and friends.

Some ITEP theorists were allowed to go to international conferences. Upon return, they would bring news which were then reported at ITEP seminars and discussed at length. Thus, on a large number of occasions, it was Arkady (a frequent visitor to ITEP) who told us what was happening in the world. And there were plenty of things to discuss: the emergence of the Weinberg-Salam

[e] Again, this was way before anybody else thought of this possibility; even now, thirty years later, this is not yet done but is supposed to be done at Frascati. Similar physics could be studied at b factories, another project developed early in Budker's Institute.

[f] Eventually S. Belyaev, V. Baier, I. Khriplovich, B. Chirikov and others created schools of their own, but that took time.

[g] Ioffe recalled that it was a not-so-well-heard phone conversation he received in a noisy corridor of his then-"communal" apartment; Ioffe just did not managed to say "no". He did not regret this later, as far as I could tell.

model, then QCD, then the "November Revolution" of 1974 when J/ψ was discovered. Yulik Khriplovich and Arkady Vainshtein's review in Uspekhi,[h] on gauge theories of weak interactions, was an example of how close they were to the front-line of research, and how well prepared they were for applications of all these new theories. Celebrated "penguin diagrams" by Arkady and collaborators were a prime example of this era.

Now I should describe my interactions with Arkady in the late 1970's, when the celebrated QCD sum rules appeared, focusing the thoughts of many on the mysteries of nonperturbative QCD. In 1976-1978 I completed my first set of finite-temperature QCD papers, and thought I was ready to jump into the game. However, running after the Vainshtein-Zakharov-Shifman trio was not an easy thing, even with generous explanations which I could always get from Arkady. Only one of my QCD-sum-rule-related papers got any notice, the 1981 one,[i] which was the first occurrence of the"heavy quark symmetry".

As a part of my efforts to catch up with these guys, I convinced Arkady to work with me on a project close to QCD sum rules, the so called higher-twist effects in deep inelastic scattering. We wrote two papers,[j] both quite reasonably cited in the literature now, but both having a completely negligible effect then. These papers had interesting physics points, but mostly were about derivation of some lengthy general formulae for these effects. Obviously, I was not very useful in that, frankly just a drag to Arkady, who knew how to deal with technical problems *en route*. His view however was that if there were two authors, both should independently derive *all* formulae, from the beginning to the very end, and only then compare the whole thing. After I weeded out all my mistakes in derivation of the operator expansion expressions and thought it was finally over, Arkady announced that without radiative corrections responsible for the mixing of the operators under consideration, the paper was incomplete and could not be published. It was the first time in my life I had to deal with a "perfectionist"-type theorist. It was not an easy experience. What added to frustration is that after a very influential (at least for me) paper[k] of the same trio plus Novikov entitled "Are all hadrons alike?" which appeared at the same

[h] A.I. Vainshtein and I.B. Khriplovich, *Renormalizable Models of the Electromagnetic and Weak Interactions*, Uspekhi Fiz. Nauk, **112**, 685 (1974) [Soviet Physics - Uspekhi, **17**, 263 (1974)].

[i] E. V. Shuryak, *Hadrons Containing a Heavy Quark and QCD Sum Rules* Nucl. Phys. B **198**, 83 (1982).

[j] E. V. Shuryak and A. I. Vainshtein, *Theory Of Power Corrections To Deep Inelastic Scattering In Quantum Chromodynamics. Parts 1 and 2*, Nucl. Phys. B **199**, 451 (1982), and Nucl. Phys. B **201**, 141 (1982).

[k] V.A. Novikov, M.A. Shifman, A.I. Vainshtein, and V.I. Zakharov, Nucl. Phys. **B191**, 301 (1981).

time, we both knew that there was much more in the QCD vacuum than any operator product expansion could explain. And we both realized that, doing the same expansion but inside the nucleon, one could not possibly come to a different conclusion. The lesson I would like to deduce from this part of the story is that it almost never pays to join already existing development and simply widen its applications. It is much more instructive to think about its limitations and deep origins of these limitations.

To go back to a lighter part, Arkady was also my first teacher in downhill skiing. (In this case, as in science, he is not responsible for my bad style.) Unlike in physics, in this case he only considered it important to get a newcomer on the lifts and get him/her as high as he/she may be fooled to go. Then he would give primary instructions and, convinced that the person would know by himself/herself how to fall in a proper time and has enough common sense not to get killed, would happily disappear.

Of course, the Siberian flats around Novosibirsk were not suited for downhill skiing, so Arkady's instruction took place at Bakuriani Winter School in Georgia.[l] The same is true for many people in the room: let as recall and thank the Bakuriani School organizers once again. I recall, once we came to the slope, on top of a large truck as usual, but that day there was a problem with the lift. All except Arkady (and Pontecorvo Jr.) disappointedly went back: these two were not intimidated at all, they climbed the mountain Kokhta (not a small one) *twice* this day, with skis and boots and other heavy stuff in their hands, and happily glided down. I mention this episode because, obviously, Arkady's attitude toward scientific problems is exactly the same.

Many good features of Arkady has been discussed: now let me come to "problems". Arkady had no students, at least during the Novosibirsk years (and perhaps, beyond). A simplistic theory of this phenomenon goes as follows: Arkady is not patient enough, he solves any problem he can think of too quickly, he does not need a student to slow him down. I think the true explanation is the opposite: my observation was he has infinite time and infinite patience. Explaining something, Arkady simply cannot stop until he is convinced the other person got it, to the tiniest detail. It may go on for hours or days, and Arkady will put away any part of his own work to do so. But as one very seasoned person (in a good sportish shape then) told me, after physics conversations with Arkady he used to have strong headaches. Another one went as far as to suggest that after such conversations one always has a feeling of being hit by a passing truck.

This leads me to a final proposition. Arkady: your noble age notwithstand-

[l] I mean here Georgia in the former Soviet Union. How can we forget the famous statement from a local Georgian lift operator: "Physicist? Then pay."

ing, please proceed with the intensity you like. Still, please, take it somewhat easier on others...

OF A SUPERIOR BREED

VLADIMIR ZELEVINSKY
Department of Physics and Astronomy, Michigan State University,
East Lancing, MI 48824, USA

To me Arkady always seemed to be a striking and extremely impressive sample of a human breed, an evidence for the existence of a person who very naturally reached a summit of human abilities.

I got acquainted with him (and Nelly) almost 40 years ago, in the fall of 1962. I was not particularly close to him at that time. But I remember very well that Professor Viktor M. Galitsky, a wise man and excellent physicist himself, was of an extremely high opinion of Arkady, his new Siberian student. Various conversations inevitably used to end in a comparison of Arkady with several Moscow graduates who came to Siberia with Galitsky. Sure enough, this comparison was not in favor of the Muscovites, although some of them later made quite successful careers in theoretical physics.

I can honestly say (and I am sure that this is not only my opinion) that very soon we accepted and got used to the fact that Arkady was stronger, deeper, smarter, and so on, than anybody else in our circle. This was merely a fact of life. Later Arkady became really a legendary figure, omnipotent and omni-knowledgeable, capable of helping in any problem related to physics, science at large, and everyday life ...

I have never worked with Arkady directly, as a co-author. My memory keeps, however, a few interesting "snapshots." They reflect two types of Arkady's behavior in response to my rather frequent attempts to seek Arkady's advice regarding particular scientific problems (I know that other people had quite similar experiences too). I do not remember anymore which questions were raised. This is not so important, after all. What is important is that Arkady's response was always either of one type or another. Either he would immediately know the correct answer (or the problem was so stupid that the answer was trivial right from the start, from his standpoint, of course). In this case he would start his reply with something like that:

— "Of course, you very well understand yourself that... "

And in a few minutes the author of the question would be forced to confess that, certainly, the answer was absolutely clear, and that this transparency was obvious even before the question was asked ...

A little bit different (and more rare) version of the situation was that

Arkady would not know the answer immediately. This could happen if the question was related to a scientific area remote from Arkady's current interests. Then one could have enjoyed the most remarkable performance: Arkady would switch on his phenomenal thinking machine , starting from scratch, frequently on blackboard. Usually the desired answer would be found very quickly. It would happen so naturally that the inquirer would usually get puzzled: why the hell he was unable to arrive at the same result by himself. The immediate punishment for weaker intellectual abilities was unavoidable: Arkady would go into all details and consequences, often far away from the original question, and continue his explanations to the point when the inquirer would become fully exhausted and unable to grasp anything ...

My memoir would not be complete without at least a few words on Arkady in everyday life. I remember, for instance, that one nice morning we woke up in an apartment of Victor Chernyak in the East-Siberian city of Irkutsk, on the shore of the famous Lake Baikal, where there was a conference. We stayed there overnight — Arkady, myself and my young sister-in-law who traveled with me to tour Lake Baikal. And, gosh, this morning was special — I am sorry to say, something happened to the sewer system in Chernyak's apartment building, and a part of sewage water gushed out to the floor from nowhere. We discovered this disaster after waking up, when the disaster had already happened. Arkady was *the only* person who did not lose his spirit in this tragicomic situation, and organized, in a business-like manner, our damage control operation in the most efficient way, using all available improvised means.

Women see and evaluate things differently, they have another kind of vision. That's why I want to conclude my mini-essay by a passage written by my wife Vera:

"Arkady is a truly outstanding person, outstanding in all meanings of this word, including his appearance. He is immediately singled out in the crowd, everybody says that.

What makes Arkady so remarkable? First and foremost, his outstanding intelligence. This is obvious. There is something else, however. Each facet of his personality is bright: absolute selflessness, optimism without limits, almost childish ... No matter what he does — physics research, hiking, wrestling with computers — he does it with full concentration, leaving everything else aside, forgetting about the outside world, his family including. Everyone who had the pleasure of hiking, skiing or dancing with Arkady at least once will confirm this. I cannot forget a sauna festival Arkady and Nelly once arranged at their *dacha* near Novosibirsk. Lots of people came, they were so different and so sincere, as probably never before. I think, that was due to an atmosphere of a "festival of life" ... Arkady made it happen. I asked Nelly how she could cope with such pace of life.

— Sometimes I get tired, terribly tired, she answered. My housewife's side has to be sacrificed. So what? We are always surrounded by great people. We will never be alone.

By the way, the very same fall Arkady was repairing something on the roof of their *dacha* cottage, broke it and fell through. Luckily, there were no dire consequences.

Sincerity — that's Arkady's precious gift attracting to him all of us. We all remember how hard it was to survive back there. One could not survive without support of one's friends. And Arkady was very generous with his support. A long time ago we were moving from one apartment to another. Arkady immediately volunteered to be a mover. I remember him grabbing a refrigerator, putting it on his back and crawling with it to the second floor of our new apartment building. He did it alone. Then he found out that our kids had already gone to bed by the time he was done with the refrigerator. He just dropped by their bedroom, and in a second it exploded, a joyful chorus of of three happy "piglets." My "piglets" were happy. Absolute sincerity is the advantage of children. There are not so many adults who have it to that extent. This is God's gift to Arkady, perhaps even more precious than his intellect."

DEFYING ZENO'S PROCEDURE

VALENTIN SOKOLOV
Budker Institute of Nuclear Physics, University,
East Lancing, MI 48824, USA

It is somewhat strange but, in spite of my quite vivid memory of Arkady's excellent personality and many conversations and discussions I had with him, I cannot recall anything reasonably coherent. There were very few amusing or funny incidents since he was always wise and did everything so well. Still it is my feeling that, being very certain and resolute in his scientific judgments, he may look rather indecisive in everyday life and sometimes just sinks in all those "from the one hand..., but from the other...".

I remember how I heard of Arkady for the first time. Roald Sagdeev was one of the examiners at Novosibirsk University (most probably, this was an examination in classical electrodynamics). After the examination Sagdeev shared with us his impressions. He repeatedly suggested the same problem to many students and nobody was able to solve it. The problem contained a sequence of events, and the question was what will be the result after a great many steps. Roald knew a trick which allowed one to obtain the result in a rather economic way. There was only one student in class who solved the problem correctly though by a lengthy direct summation. Of course, this was Arkady. However, the most memorable was Roald's sad tone when he pensively said:

—" Well, hmm, this student solves any problem he is asked to."

Alas, I cannot recall now the problem itself...

Another episode, I am afraid, can be interesting only to a narrow circle of people. After one of our traditional tea-and-cake gatherings on the "theoretical floor" at the Budker Institute, (that's where all theorists had their offices) a good piece of cake was left over and brought to Pavel Isaev's office. I happened to be in this office at that time, and watched people entering from time to time. Everybody would bashfully cut off a half of the remaining piece, leaving another half to the next newcomer —- exactly Zeno's procedure! I made a comment, something about how considerate people in our small theoretical community were. Almost immediately after my comment, Arkady entered the office and made the entire procedure convergent in one step — just by swallowing the whole remaining piece! And he could not understand why everybody bursted into laughter so loudly....

With Arkady everything always was quite normal. He is excellent and that is it. Isn't this strange? He is really an absolutely remarkable person. And everybody remembers his brilliance rather than some particular amusing events.

REMINISCENCES IN PASTELS[m]

M. SHIFMAN
Theoretical Physics Institute, University of Minnesota
Minneapolis MN 55455, USA

Glimpses of ITEP

For about twenty years, I was a member of the ITEP theory group. ITEP was more than an institute. It was our refuge where the insanity of the surrounding reality was, if not eliminated, was reduced to a bearable level. Doing physics there was something which gave a meaning to our lives, making it interesting and even happy. Our theory group was like a large family. As in any family, of course, this did not mean that everybody loved everybody else, but we knew that we had to stay together and to rely on each other, no matter what, in order to survive and to be able to continue doing physics. This was considered by our teachers to be the most important thing, and this message was always being conveyed, in more than one way, to young people joining the group. We had a wonderful feeling of stability in our small brotherhood. A feeling so rare in the western laboratories where a whirlpool of postdocs, visitors, sabbatical years come and go, there are a lot of new faces, and a lot of people whom you do not care so much about.

The rules of survival were quite strict. First, seminars – what is now known worldwide as the famous Russian-style seminars. The primary goal of the speaker was to *explain* to the audience his or her results, not merely to advertise them. And if the results were nontrivial, or questionable or just unclear points would surface in the course of the seminar, the standard two hours were not enough to wind up. Then the seminar could last for three or even four hours, until either everything was clear or complete exhaustion, whichever came first. I remember one seminar in Leningrad in 1979, when Gribov was still there, which started at eleven in the morning. A lunch break was announced from two to three, and then it continued from three till seven in the evening.

In ITEP we had three, sometimes more, theoretical seminars a week. The most important were a formal seminar on Mondays, and an informal coffee

[m]The first part of this article is an abbreviated version of the Foreword to M. Shifman, *ITEP Lectures on Particle Physics and Field Theory*, (World Scientific, 1999).

seminar which at first took place every Friday at 5 o'clock, when the official work day was over, but later was shifted to Thursdays,at the same time. Usually, these were by far the most exciting events of the week. The leaders and the secretaries of the seminars were supposed to find exciting topics, either by recruiting ITEP or other "domestic" authors, or, quite often, by picking up a paper or a preprint from the outside world and asking somebody to learn and report the work to the general audience. This duty was considered to be a moral obligation. The tradition dated back to the time when Pomeranchuk was the head of the theory group, and its isolation had been even more severe than during my times. As a matter of fact, in those days there were no preprints, and getting fresh issues of *Physical Review* or *Nuclear Physics* was not taken for granted at all. When I, as a student, joined the group – this was a few years after Pomeranchuk's death – I was taken, with pride, to the Pomeranchuk memorial library, his former office where a collection of his books and journals was kept. Every paper, in every issue, was marked by Chuk's hand (that's how his students and colleagues would refer to him), either with a minus or a plus sign. If there was plus, there would also be the name of one of his students who had been asked to "dig into" the paper and give a talk for everyone's benefit. This was not the end of the story, however. Before the scheduled day of the seminar, Pomeranchuk would summon the speaker-to-be to his office to give a pre-talk to him alone, so that he could judge whether the subject had been worked out with sufficient depth and that the speaker was "ripe enough" to face the general audience and their blood-thirsty questions. In my time, the secretaries of the seminars were less inclined to sacrifice themselves to that extent, but, still, it was not uncommon that pre-talks were arranged for unknown, young or inexperienced speakers.

Scientific reports of the few chosen to travel abroad for a conference or just to collaborate for a while with western physicists, were an unquestionable element of the seminar routine. The attendance of an international conference by A or B by no means was considered as a personal matter of A and B alone. Rather, these rare lucky guys were believed to be our ambassadors, and were supposed to represent the whole group. In practical terms, this meant that once you had made your way to a conference, you could be asked to present important results of other members of the group. Moreover, you were supposed to attend as many talks as physically possible, including those which did not exactly belong to your field, make extensive notes and then, after returning home, deliver an exhaustive report of all new developments discussed, all interesting questions raised, rumors, etc.

The scientific rumors, as well as nonscientific impressions, were like an exotic dessert, usually served after nine. I remember that, after his first visit to the Netherlands, Simonov mentioned that he was very surprised to see a lot of people on the streets just smiling. He said he could not understand why they looked so relaxed. Then he added that he finally figured out why: "... because they were not concerned with building communism..." This remark almost immediately became known to "Big Brother" who was obviously watching us this evening, as usual, and it cost Simonov a few years of sudden "unexplainable allergy" to any western exposure. His "health condition", of course, would not allow him to accept any invitation to travel there. I cannot help mentioning another curious episode with Big Brother. Coffee, which we used to have during the coffee seminars, was prepared in turn, by all members of the group. Once, when it was Ioffe's turn, he brought a small bottle of cognac and added a droplet or two in every cup. I do not remember why, perhaps, it was his birthday or something like that. That was Friday evening. Very early on the next Monday morning, he was summoned to the corresponding ITEP branch office to give explanations concerning his "obviously subversive activities"!

The coffee seminars typically lasted till nine, but sometimes much later, for instance, in the stormy days of the November revolution in 1974. The few months following the discovery of J/ψ were the star days of QCD and, probably, the highest emotional peak of the ITEP theory group. Never were the mysteries of physics taken so close to our hearts as then. There was a spontaneously arranged team of enthusiasts working practically nonstop. A limit to our discussions was set only by the schedule of the Moscow metro – those who needed to catch the last train had to be leaving before 1 a.m.

The ITEP seminars were certainly one of the key elements in shaping the principles and ideals of our small community, but not the only one. The process of selecting students who could eventually grow up into particle theorists played a crucial role and was, probably, as elaborate as the process of becoming a knight of the British crown. Every year we had about 20 new students, at the level roughly corresponding to that of graduate students in American universities. They came mostly from the Moscow Institute for Physics and Technology, a small elite institution near the city, a counterpart of MIT in the States. Some students were from the Moscow Engineering and Physics Institute, and a few from the Moscow State University. They were offered (actually, obliged to take) such a spectrum of courses in special disciplines which I have never heard of anywhere else in the world: everything from radiophysics and accelerator physics; several levels of topics in quantum mechanics, including intricacies of theory of scattering; radiation theory and nuclear physics; mathematical physics (consisting of several separate parts); not less than three courses in particle phenomenology (weak, electromagnetic and strong interactions); quantum electrodynamics, numerous problem-solving sessions, etc.

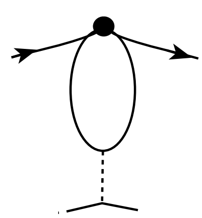
And yet, only those who successfully passed additional examinations, covering the famous course of theoretical physics by Landau and Lifshitz, were allowed, after showing broad erudition and ingenuity in solving all sorts of tricky problems, to join the theory group. Others were supposed to end up as experimentalists or engineers. Needless to say, the process of passing these examinations could take months, even years, and was notoriously exhausting, but there was never a lack of volunteers trying their luck. They were always seen around Ter-Martirosian and Okun who were sort of responsible for the program. It should be added that the set of values to be passed from the elders to the young generations included the idea that high energy physics is an experimental science that *must* be very closely related to phenomena taking place in nature. Only those theoretical ideas which, at the end of the day, could produce a number which could be confronted with phenomenology were cherished. Too abstract and speculative constructions, and theoretical phantoms, were not encouraged, to put it mildly. The atmosphere was strongly polarized against what is now sometimes called "theoretical theory". Even extremely bright students, who were too mathematically oriented, like, say, Vadim Knizhnik, were having problems in passing these examinations. Vadim, by the way, never made it to the end, got upset and left ITEP. Well, nothing is perfect in this world, and I do not want to make an impression that the examination routine in the ITEP theory group was without flaws.

The ITEP theory group was large – about 50 theorists – and diverse. Moreover, it was a natural center of attraction for the whole Moscow particle physics community. Living in the capital of the last world empire had its advantages. There is no question, it was the evil empire, but what was good, as it usually happens with any empire, all intellectual forces tended to cluster in the capital. So, we had a very dynamic group where virtually every direction was represented by at least several theorists, experts in the given field. If you needed to learn something new, there was an easy way to do it, much faster and more efficient than through reading journals or textbooks. You just needed to talk to the right person. Educating others, sharing your knowledge and expertise with everybody who might be interested, was another rule of survival in our isolated community. In such an environment, different discussion groups and large collaborations were naturally emerging all the time, creating a strong and positive coherent effect. The brain-storming sessions used to produce, among other results, a lot of noise, so once you were inside the old mansion occupied by the theorists, it was very easy to figure out which task force was where – just step out in the corridor and listen. And, certainly, all these sessions were open to everybody.

The isolation of the ITEP theory group had a positive side effect. Everybody, including the youngest members, could afford to work on problems not belonging to the fashion of the day, without publishing a single line for a year or two. Who cared about what we were doing there anyway? This was okay. On the other hand, it was considered indecent to publish results of dubious novelty, incomplete results (of the status report type) or just papers with too many words per given number of formulae. Producing dense papers was a norm. This style, which was probably perceived by the outside readers as a chain of riddles, is partly explained by tradition, presumably dating back to the Landau times. It was also due to specific Soviet conditions, where everything was regulated, including the maximal number of pages any given paper could have. Compressing derivations and arguments to the level considered acceptable, was an art which had its grandmasters.

It is high time for Arkady to appear on these pages. Arkady Vainshtein was especially good at inventing all sorts of tricks which allowed him to squeeze in extra formulae with very few explanatory remarks. I remember that in 1976, when we were working on the large JETP paper on penguins in weak decays,[n] we had to make 30 pages out of the original 60-page preprint version, and he managed to do that without losing any equations and even inserting a few extra ones! This left a strong impression on me.

By the way, about penguins. From time to time students ask how this word could possibly penetrate high energy physics. This is a funny story indeed. The first paper where the graphs that are now called penguins were considered in the weak decays appeared[o] in JETP Letters in 1975, and there they did not look like penguins at all. Later on they were made to look like penguins:



and called penguins by John Ellis. Here is his story as he recollects it himself.

[n]By "we" I mean Zakharov, Vainshtein and myself. Arkady Vainshtein had a permanent position at the Budker Institute of Nuclear Physics in Novosibirsk. He commuted between Moscow and Novosibirsk for many years, and was considered, essentially, as a member of the ITEP theory group. The large penguin paper was published in Zh. Eksp. Teor. Fiz. **72** (1977) 1275 [Sov. Phys. JETP **45** (1977) 670].

[o]A. Vainshtein, V. Zakharov and M. Shifman, *Pis'ma ZhETF* **22** (1975) 123 [*JETP Lett.* **22** (1975) 55].

"Mary K. [Gaillard], Dimitri [Nanopoulos] and I first got interested in what are now called penguin diagrams while we were studying CP violation in the Standard Model in 1976... The penguin name came in 1977, as follows.

In the spring of 1977, Mike Chanowitz, Mary K and I wrote a paper on GUTs predicting the *b* quark mass before it was found. When it was found a few weeks later, Mary K, Dimitri, Serge Rudaz and I immediately started working on its phenomenology. That summer, there was a student at CERN, Melissa Franklin who is now an experimentalist at Harvard. One evening, she, I and Serge went to a pub, and she and I started a game of darts. We made a bet that if I lost I had to put the word penguin into my next paper. She actually left the darts game before the end, and was replaced by Serge, who beat me. Nevertheless, I felt obligated to carry out the conditions of the bet.

For some time, it was not clear to me how to get the word into this *b* quark paper that we were writing at the time. Then, one evening, after working at CERN, I stopped on my way back to my apartment to visit some friends living in Meyrin where I smoked some illegal substance. Later, when I got back to my apartment and continued working on our paper, I had a sudden flash that the famous diagrams look like penguins. So we put the name into our paper, and the rest, as they say, is history."

A few touches on Arkady's portrait

You can view the previous part as an extended introduction intended to convey a flavor of the epoch. Of course, it would be better if I could write about the Institute of Nuclear Physics in Novosibirsk, of which Arkady was a permanent member. This institution was a remarkable phenomenon in the USSR. I do not think it had parallels. Budker was running it on a unique fuel, a mixture of east and west, capitalist entrepreneurship and communist reality, the usual Russian sloppiness and equally usual creativity. I heard many incredible legends about it from Khriplovich, Eidelman, Zolotorev and others. It is a pity that neither of them volunteered to put these stories in writing. I was in this Institute perhaps a dozen of times. Each time it was a short visit, however — from a few days to a couple of weeks — too short a time to become an insider. Writing a glorious chronicle of the Budker Institute of Nuclear Physics,[p] with all anecdotal evidence (which does deserve to be preserved for the future generations) included, is a task for other people.

As I have already mentioned, Arkady Vainshtein was considered, essentially, as a member of the ITEP theory group. He would visit two or three

[p] In the 1970's Budker was still alive, and one could hardly even dream that a time would come when the Institute, his child, would bear his name.

times a year, each time staying for a a month or more. The 1974/75 academic year was special. Arkady's daughter Tanya got sick: an awkward move during a physical exercise led to a spine injury. Out of all clinics in the USSR only one could provide necessary medical treatment. Sure enough, this was a Moscow clinic. It was very hard to get her admitted to this clinic for treatment, but Budker made it happen. He gave a one-year paid leave of absence to Arkady, and sent him to Moscow. For me it was a blessing in disguise.

It was Arkady and Valya Zakharov who got me involved, in earnest, in quantum chromodynamics. This happened in the late fall or winter of 1973, in the very beginning of my PhD work. This involvement shaped my entire career.

Arkady is a deep thinker. He is the deepest thinker of all people I am closely acquainted with. When he gets seriously interested in a certain physics problem — let us call it "problem A" — his mind sends a powerful urge to start digging. The outside world ceases to exist, the work continues almost on the 24/7 basis. A sophisticated fantasmagoric construction gradually emerges in Arkady's mind. Being left to himself, he would never return back. The problem A would lead to a set of subproblems a_1, a_2, and so on, which, in turn, would continuously evolve into a set of sub-subproblems $\alpha_{1\ell}$, $\alpha_{2\ell}$, etc. Let alone related problems B, C, D, ... The fractal nature of such an approach requires from Arkady a noncommensurate amount of time and effort. A little baroque exercise at level α whose impact on the general picture is minute, is as important to him as everything else. It may take weeks or months. Nevermind. Being left to himself, Arkady would never say: "this is *the* answer, I pause here to let other people know of what I have achieved." For him, the pleasure of finding out how things work is sufficient by itself. You may call him superperfectionist. Yes, that's the right word, extreme perfectionist.

Only strong external impulses can extract him from the deepening fractal structure of his making. The onset of the vacation season may serve as such an impulse. Another option is to distract him by suggesting a new and more challenging problem. In this latter case the attraction of the new problem must be overwhelming, to overcome the inertia of the original motion.

Upon forced return from the n-th intellectual journey, nothing can be taken for granted with Arkady. Even a solid baggage of results and insights acquired *en route* is no guarantee that the corresponding paper will ever see the light of the day. To make a decision to start writing a paper is a torture for Arkady. Even more so the process of writing. Every research project, its merits notwithstanding, has loose ends and dark corners. At the discussion stage everything is volatile, up in the air. What was a loose end today might find a perfect match tomorrow. But when you put this on paper, this is it. Every string of Arkady's superperfectionist *ego* protests. The necessity to document things before they are fully complete (and they never are) burns Arkady out. Literally.

I remember a funny story that happened in 1982. We were working on a large project entitled *Two-Dimensional Sigma Models: Modeling Nonperturbative Effects of Quantum Chromodynamics.*[q] A motivation for this project was "donated" to us by Sasha Polyakov. As usual, Sasha had a wealth of interesting calculations in his treasure trove which he did not consider to be important enough to warrant publication. In a private discussion he made a remark which turned Arkady on. At that time we were excited about the gluon condensate which we had introduced just a few years earlier.[r] Polyakov said:

"Look, guys, both $G^2_{\mu\nu}$ in Yang-Mills and $(\partial_\mu \vec{n})^2$ in the $O(3)$ sigma model are negatively defined in the Euclidean. And in general, these theories are very similar. You claim that the gluon condensate is positive. I found $\langle(\partial_\mu \vec{n})^2\rangle$ in the sigma model, and I am certain that this condensate is negative. How come?"

The work on this project lasted for over a year; by 1983 the material accumulated became so vast it was hard to manage. A paper was drafted in Moscow and was sent to Arkady, who at that time was in Novosibirsk. He was supposed to read the draft, make any corrections/alterations he wanted, and then return it back.

When I say the paper was drafted I mean it. It was a hand-written manuscript. We had no access to photocopying machines. The copy sent to Novosibirsk (through a reliable person, certainly not by mail) was the only one.

In the subsequent telephone conversations Arkady seemed to deliberately avoid this topic. This went on and on. In half a year I came to Novosibirsk, and discovered the truth.

Arkady would carry the draft in his briefcase — in the morning from his home to office, where he would put it on his desk, open and look in desperation at all those disgusting logical leaps, omissions and other shortcomings which are unavoidable in the first draft, being unable to delve there, postponing the beginning of the work till the evening, when he would carry the draft in the opposite direction. Next day — the same story ... One night something happened in his garage, which required an immediate intervention. There was no electricity there and Arkady had to make an improvised torch. He fished out a few sheets of paper from his briefcase to lighten the place. In haste he did not notice that this was a good portion of the unlucky draft. When it was

[q] V. Novikov, M. Shifman, A. Vainshtein, and V. Zakharov, Phys. Rept. **116** (1984) 103.
[r] M. Shifman, A. Vainshtein, and V. Zakharov, Nucl. Phys. **B 147** (1979) 385.

all over, he was just afraid to tell us of what had happened. It was Nelly who told me about the burnt manuscript when I came to Novosibirsk.

Well, they say manuscripts do not burn. It took us about a year to produce a new one. I hasten to add that a new version was much better than previous. Arkady's misadventure turned out to be a blessing in disguise.

By the way, I have just mentioned the telephone conversations. Physics issues were discussed in the telephone conversations with Arkady on a regular basis. That's how we worked together. It was not allowed to call long distance from ITEP (at least, it was not allowed to me). So, I had to call from my home phone. As a result, my phone bills exceeded any reasonable number I could afford. (What I could afford was close to zero, if not negative, anyway). The large JETP paper on penguins was done essentially in the telephone mode. After that my wife revolted. I had to limit phone physics from my home phone to one hour a week at most. Fortunately, by that time Arkady discovered that Budker's policy on long-distance calls was much more liberal than that of ITEP — Arkady could call us from his office with very mild limitations.

In retrospect, trying to summarize what was typical for our scientific and nonscientific interactions over the years, I see, first of all, endless and *very exhausting* (but very fulfilling, too) discussions of various physics issues. My collaboration with Arkady lasts for almost 30 years. He was and still is one of my teachers. I am happy that I had the opportunity to discuss with him all aspects of high energy physics an almost infinite number of times.

I see, very clearly in my memory, other episodes too. For instance, guess what was the major concern of esteemed Professor Arkady Vainshtein each time he would come to Moscow, towards the end of his visit? He always had a huge backpack with him. Real huge. And each time before returning home to Novosibirsk he used to spend two or three days hunting for food and other basic necessities (such as toothpaste, razor blades and the like), which in the 1980's could still be found, from time to time, in Moscow but were obliterated in Novosibirsk stores. I close my eyes and see him leaving, with his backpack (weighing, perhaps, 30 kilos) full of oranges, cheese, shoes for his lovely daughters and other similar exotic stuff which was not considered by communists to be vitally important for the survival of the country.

The shortage (or, better to say, almost complete absence) of everything in Novosibirsk had a positive side effect on scientific aspirations and careers of the Siberian physicists. First of all, nothing distracted young people from work. More importantly, there was a primitive but very powerful direct relation between one's promotion and one's nutrition. Basic goods were rationed and delivered to the Novosibirsk scientific community through a system of the so-called distribution centers closed to general public. One's scientific standing was in one-to-one correspondence with the access to higher-level centers. Young researchers at the pre-PhD stage were entitled to next-to-nothing. Getting PhD was a step forward. PhD holders (in Russian they are called "Candidates of Science") could get meat and other protein-rich products. Of course, the amount was very limited, which kept them aggressive in their research work. (And young people should do research aggressively, I think everybody will agree.) Here it should be explained that the academic hierarchy in Russia follows the German rather than the Anglo-American pattern. An approximate equivalent of PhD in the US is the *Candidate of Science* degree. The highest academic degree, doctoral, is analogous to the German *Habilitation*. The doctoral dissertation is usually prepared at a mature stage of the academic career; only a fraction of the *Candidate* degree holders make it to the doctoral level. Well, defending the doctoral dissertation was a major leap, opening access to a distribution center almost as good as the one for Academicians. Doctors of Science were supposed to have meat in their diet on a regular basis.

I do not really know whether this long digression belongs here. Upon reflection, I decided to keep it because it gives an idea of the environment in which Arkady lived and worked for many years.

In spite of our 30 friendly years, surprisingly, I cannot say that I know Arkady well, beyond physics. Complicated processes take place deep inside him, and one can only guess of what is going on from rare outbursts. Perhaps, I have a general idea, but details and nuances are blurred ... The only thing of which I am certain, is that Arkady is the most selfless person of all people I am closely acquainted with. (Remember, I started this section on the same note). If he sees that someone needs his help, he is always ready to help. There is no limit to his patience. If there is something he can share — be it his computer or skiing skills, or just his strong shoulders — he will always offer his assistance, generously investing his time, with no back thoughts.

BILL FINE, TPI AND ARKADY

STEVE GASIOROWICZ
Theoretical Physics Institute, University of Minnesota
Minneapolis MN 55455, USA

The Theoretical Physics Institute at the University of Minnesota is a direct result of the interest and generosity of Bill Fine. It was roughly 20 years ago that he and I became acquainted, and I discovered that Bill had a deep interest in physics, specifically High Energy physics. It was through conversations about this subject that we came to a point at which Bill indicated that he wanted to do something for the field: the idea of a theoretical physics institute was born! Bill and I tried to do some fund-raising, but the general public, or at least the part that we could approach seemed less than enthusiastic about giving money. Furthermore, the college administration at the time was also less than interested (Bill and I talked about "the instinct for the capillary"). In 1985 Minnesota hosted the 6th Workshop on Grand Unification, and on this occasion that Gloria Lubkin entered the picture. It was she who pointed out that the proposal was on too small a scale and that it was necessary to bring the top levels of the University administration into the planning. She suggested bringing in Leo Kadanoff as spokesman and potential director to give reality to the proposal. In the summer of 1986, during a festive and intensive get together in Minneapolis, Bill and Leo, with strong support by Chuck Campbell, outgoing head of the School of Physics and Astronomy, and Marvin Marshak, his successor, persuaded then-President Ken Keller of the merits of building a Theoretical Physics Institute at the University. Building on a very generous pledge by Bill Fine, the University committed itself to matching Bills gift to create two chairs (subsequently split into three) and to provide permanent funding of a magnitude to support an active, vibrant institute. The Theoretical Physics Institute (renamed the William I Fine Theoretical Physics Institute on the occasion of the 15-th anniversary of its creation) became a reality. I was appointed acting director and during 1987-89 conducted a vigorous search for director. In 1989 in a fortunate alignment of stars, several things happened: (1) *perestroika*, (2) Larry McLerran became the first director and (3) Larry with the strong support of Gloria Lubkin— an active member of the oversight committee —decided to take advantage of the unique opportunities provided by (1). Larry had been to Russia many times, and knew at any given time where to find people. The people we recruited were known to us, at least by name, although I had met Misha Voloshin in Aspen and at DESY earlier. In any case, the first recruits were Boris Shklovskii in condensed matter physics, Misha Voloshin and Arkady. Misha Shifman came a year later, as did Leonid Glazman, and and a few years later, Anatoly Larkin. The first year was quite miraculous. In addition to these people, a large number of visitors came. Since we could not pay them a regular salary —-this was still the time when the Soviet government wanted a cut of the pay — the whole group lived on per diems and were housed together at 110 Grant, a comfortable highrise in the center of town. I can only describe it as a year-long summer camp. The tradition, born in periods of deprivation, that if you could get hold of some good food you had a party, carried over, and there were *always* parties. Arkady and Nelly were among the main organizers of social activities and took it as their duty to look after the guests. Arkady may have been the only person who was an experienced driver, and our aged Subaru became the vehicle that brought people to and from the airport, to and from 110 Grant. It was a time when we learned about Russian-style seminars—you bring sandwiches, a thermos and sometimes a sleeping bag. I discovered that if you asked Arkady a question, he could not only answer it, but had probably written a paper about it. Ten or so years later, everything settled into something of a routine. Most of the families settled in, their children moved to successful careers, but there is still something magical about being on the 4-th floor of the physics building. When the door is open, its like being at an opera (Mussorgsky?): you dont understand a word, but t he music is powerful and enchanting (and loud!). The creation of what some people have called Moscow (and Novosibirsk) on the Mississippi has been a wonderful adventure, and the new friendships we have made with Arkady and Nelly, and with all the other newcomers, have enriched us enormously. So thank you Bill, thank you Mr. Gorbachev and thank you Arkady!