consequences for both microscopic physics and cosmology. On the microscopic physics side, this would allow studying quantum gravity and its high-energy extension (possibly string theory) at colliders, while on the cosmological side, the entire picture of the early Universe would have to be revised. Inflation, if any, would have to occur either at low energy density or in the state of strong quantum gravity effects. The highest temperatures in the usual expansion history would be at most in the TeV range, such that dark matter and baryon asymmetry would have to be generated either below TeV temperatures or in the quantum gravity mode. Even more intriguing would be the study of the quantum gravity cosmological epoch, with hints from colliders gradually coming in. This, probably, is too optimistic an outlook to be realistic.

It is more likely that the LHC will find something entirely new, something theorists have not thought about, or, conversely, find so little that we will have to get serious about the anthropic principle. In any case, the LHC results will definitely change the landscape of fundamental physics, cosmology included.

References

1. Gorbunov D S, Rubakov V A *Vvedenie v Teoriyu Rannei Vselennoi. Teoriya Goryachego Bol'shogo Vzryva* (Introduction to the Theory of the Early Universe. Hot Big Bang Theory) (Moscow: URSS, 2008) [Translated into English (Singapore: World Scientific, 2011)]
2. Brandenberger R H, hep-ph/9701276
3. Freedman W L, Turner M S *Rev. Mod. Phys.* **75** 1433 (2003); astro-ph/0308418
4. Rubakov V *PoS* (RTN2005) 003 (2005); http://pos.sissa.it/archive/conferences/019/003/RTN2005_003.pdf
5. Peacock J A, in *Proc. 1998 European School of High-Energy Physics, St. Andrews, Scotland, 23 Aug. – 5 Sep. 1998*
6. Shaposhnikov M, in *Proc. 2000 European School of High-Energy Physics, Caramulo, Portugal, 20 Aug. – 2 Sep. 2000*
7. Tkachev I I, in *Proc. 2003 European School on High-Energy Physics, Tsakhkadzor, Armenia, 24 Aug. – 6 Sep. 2003*; hep-ph/0405168
8. Jungman G, Kamionkowski M, Griest K *Phys. Rep.* **267** 195 (1996); hep-ph/9506380
9. Bottino A, Fornengo N, hep-ph/9904469
10. Olive K A, astro-ph/0301505
11. Bertone G, Hooper D, Silk J *Phys. Rep.* **405** 279 (2005); hep-ph/0404175
12. Dolgov A D, hep-ph/9707419
13. Rubakov V A, Shaposhnikov M E *Usp. Fiz. Nauk* **166** 493 (1996) [*Phys. Usp.* **39** 461 (1996)]; hep-ph/9603208
14. Riotto A, Trodden M *Annu. Rev. Nucl. Part. Sci.* **49** 35 (1999); hep-ph/9901362
15. Trodden M *Rev. Mod. Phys.* **71** 1463 (1999); hep-ph/9803479
16. Komatsu E et al. *Astrophys. J. Suppl.* **192** 18 (2011); arXiv:1001.4538
17. Seljak U et al. *Phys. Rev. D* **71** 103515 (2005); astro-ph/0407372
18. Komatsu E et al. *Astrophys. J. Suppl.* **180** 330 (2009); arXiv:0803.0547
19. Malinovsky A M et al. *Pis'ma Astron. Zh.* **34** 490 (2008) [*Astron. Lett.* **34** 445 (2008)]
20. Sahni V, Starobinsky A *Int. J. Mod. Phys. D* **9** 373 (2000); astro-ph/9904398
21. Weinberg S, astro-ph/0005265
22. Chernin A D *Usp. Fiz. Nauk* **171** 1153 (2001) [*Phys. Usp.* **44** 1099 (2001)]
23. Padmanabhan T *Phys. Rep.* **380** 235 (2003); hep-th/0212290
24. Peebles P J E, Ratra B *Rev. Mod. Phys.* **75** 559 (2003); astro-ph/0207347
25. Sahni V *Lect. Notes Phys.* **653** 141 (2004); astro-ph/0403324
26. Copeland E J, Sami M, Tsujikawa S *Int. J. Mod. Phys. D* **15** 1753 (2006); hep-th/0603057
27. Vysotskii M I, Nevzorov R B *Usp. Fiz. Nauk* **171** 939 (2001) [*Phys. Usp.* **44** 919 (2001)]
28. Krasnikov N V, Matveev V A *Usp. Fiz. Nauk* **174** 697 (2004) [*Phys. Usp.* **47** 643 (2004)]; hep-ph/0309200
29. Tikhonov A V, Klypin A *Mon. Not. R. Astron. Soc.* **395** 1915 (2009); arXiv:0807.0924
30. Salucci P, arXiv:1008.4344
31. Gorbunov D S, Dubovskii S L, Troitskii S V *Usp. Fiz. Nauk* **169** 705 (1999) [*Phys. Usp.* **42** 623 (1999)]; Dubovskii S L, Gorbunov D S, Troitskii S V, hep-ph/9905466
32. Gorbunov D, Khmelnitsky A, Rubakov V *JHEP* (12) 055 (2008); arXiv:0805.2836
33. 't Hooft G *Phys. Rev. Lett.* **37** 8 (1976)
34. Kuzmin V A, Rubakov V A, Shaposhnikov M E *Phys. Lett. B* **155** 36 (1985)
35. Belavin A A et al. *Phys. Lett. B* **59** 85 (1975)
36. Klinkhamer F R, Manton N S *Phys. Rev. D* **30** 2212 (1984)
37. Rubakov V *Klassicheskie Kalibrovochnye Polya* (Classical Theory of Gauge Fields) (Moscow: URSS, 1999) [Translated into English (Princeton, NJ: Princeton Univ. Press, 2002)]
38. Kajantie K et al. *Phys. Rev. Lett.* **77** 2887 (1996); hep-ph/9605288
39. Karsch F et al. *Nucl. Phys. B* **474** 217 (1996); hep-lat/9603004
40. Karsch F et al. *Nucl. Phys. B Proc. Suppl.* **53** 623 (1997); hep-lat/9608087
41. Carena M, Quirós M, Wagner C E M *Phys. Lett. B* **380** 81 (1996); hep-ph/9603420
42. Carena M et al. *Nucl. Phys. B* **503** 387 (1997); hep-ph/9702409
43. Carena M et al. *Nucl. Phys. B* **650** 24 (2003); hep-ph/0208043
44. Rubakov V A *Usp. Fiz. Nauk* **171** 913 (2001) [*Phys. Usp.* **44** 871 (2001)]; hep-ph/0104152

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V L Ginzburg and higher-spin fields

M A Vasiliev

1. Higher-spin fields yesterday and today

Relativistic fields are characterized by two types of quantum numbers: mass $m \geqslant 0$, and spin $s = 0, 1/2, 1, 3/2, \ldots, \infty$. To date, only two types of particles have been observed experimentally: particles of spin $s = 1/2$ — that is, $\mathrm{e}, \nu, \mu, \mathrm{u}, \mathrm{d} \ldots$, which describe matter fields, and those of spin $s = 1$, like photons, gluons, and W and Z bosons, which serve as mediators of interactions.

The main goal of the LHC is to find the hypothetical particle of spin 0, the Higgs boson H. Massless particles of spin 2 (graviton) and spin 3/2 (gravitino) remain to be discovered, although gauge theories related to them, namely gravity and supergravity, are well known, at least at the classical level.

The theory of free fields of any spin and mass is perfectly defined at the Lagrangian level. A nontrivial and highly interesting problem arises once the question of the structure of the theory of interacting fields of spins $s > 2$ is raised.

The foundation of the theory of free higher-spin fields was laid in the classical work of Dirac [1] and Fierz and Pauli [2]. The history of the development of higher-spin theory can be roughly split into two stages. Before the creation of supergravity [3], i.e., approximately from 1936 till 1976, the main goal was to describe higher-spin resonances. During this period, the main focus was on the study of massive particles in four dimensional spacetime. After the creation of super-

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gravity, i.e., since 1976 up to now, interest has shifted to the study of fundamental interactions based on the gauge symmetry principle, which requires first of all the study of massless higher-spin fields. In addition, the development of superstring theory and supergravity led to the necessity of studying gauge theories in higher dimensions $d > 4$.

Vitaly Lazarevich Ginzburg actively worked on higher-spin fields at the beginning of the 1940s, i.e., at a quite early stage of the development of the theory. By his own account and published memoirs [4–6], as well as from remarks in his early papers (see, e.g., the paper on the theory of spin 3/2 [7]), we know that many fundamental results of the theory were obtained independently by Tamm and his collaborators at approximately the same time as analogous results by Western authors, although they turned out to be published somewhat later (it should not be forgotten that these were years of war). In particular, this concerns the work of Davydov [8], published only in 1943, where the Lagrangian for spin-3/2 particles was constructed, found independently by Rarita and Schwinger in 1941 [9]. Tamm acquainted Ginzburg with the results of his joint investigations with Davydov, and with the permission of the authors, Ginzburg used them in his paper [7]. Ginzburg's Habilitation thesis, "On the theory of elementary particles" [10], was defended in 1942 and published (with some abridgment) in Refs [11, 12].[1]

The key idea of Ginzburg's studies was that using systems of fields of different spins [10–13] may provide a means for overcoming the difficulties arising in the quantum theory of interacting fields. Interestingly, this idea also remains of key importance at present, with the only distinction that appropriate spectra of fields are dictated by one symmetry principle or another. For instance, the addition of the spin-0 Higgs field makes it possible to construct a consistent quantum theory of a massive spin-1 field. Details of the unification of fields of spins 1 and 0 in the Standard Model are dictated by gauge symmetry.

Ginzburg's favorite system consisted of fields of spins 1/2 and 3/2. As a matter of fact, the theories he considered [10–13] were prototypes of the theory of supergravity with spontaneously broken supersymmetry. The study of the systems of fields of different spins drove Ginzburg to the idea phrased in his habilitation work that most natural relativistic models should probably describe systems of fields of all integer spins $s = 0, 1, 2, \ldots$ and/or half-integer spins $s = 1/2, 3/2, 5/2, \ldots$. Later on, this idea was fully confirmed. Thus, superstring theory, which resolves many of the problems of local field theory, indeed describes infinite systems of fields of all spins with the Regge character of the dependence of mass on spin. Higher-spin gauge theories also necessarily contain infinite systems of fields of unbounded spins whose pattern is dictated by higher-spin symmetries.

Due to Ginzburg's interest in higher-spin theory, Efim Samoilovich Fradkin got a position in the Theory Department of the Lebedev Physical Institute (FIAN in *Russ. abbr.*). Being on the front lines of the army and having no systematic education, Fradkin was able soon after the end of the war to understand Ginzburg's papers on the theory of spin-3/2 fields and generalized them to the case of spin 5/2 [14]. When Fradkin approached Vitaly Lazarevich with his work on the theory of a massive spin-5/2 field, Ginzburg was so impressed that soon after Efim Samoilovich found his place in the Theory Department of FIAN. In this way, the interest in the theory of higher-spin fields propagated from Ginzburg to Fradkin, then to his pupils, and then to their pupils. During this period, priorities in higher-spin theory changed significantly. The main modification in the ideology of the development of the theory occurred in the last quarter of the 20th century, becoming the principle of gauge invariance.

Let us focus in some more detail on the paper by Ginzburg and Tamm, "To the theory of spin" [15], where an attempt was undertaken at a unified description of particles of different spins and masses. The main subject of this work was the field $\Psi(x, u)$, which depends not only on space–time coordinates x^n, $n = 0, 1, 2, 3$, but also on auxiliary variables u_n subjected to the condition $u_n u^n = 1$. The equations for $\Psi(x, u)$ have the form

$$\left(\Box - m^2 + \frac{\beta}{2}\,\alpha M^{mn} M_{mn}\right)\Psi(x, u) = 0\,, \tag{1.1}$$

$$\left(\alpha M^{il} M_l^{\,j}\,\partial_i \partial_j - \Box\right)\Psi(x, u) = 0\,, \tag{1.2}$$

where

$$M_{ij} = u_i \frac{\partial}{\partial u^j} - u_j \frac{\partial}{\partial u^i}\,.$$

An alternative version of the theory is related to the introduction of auxiliary variables, which form an antisymmetric tensor $u_n \to u_{nm} = -u_{mn}$. In both cases, this model faces difficulties. Without additional condition (1.2) it leads to a nonphysical spectrum with experimentally unacceptable points of condensation of states at finite masses.[2] Introduction of the additional condition (1.2) resolves this problem, but obstructs the introduction of interactions.

Although the original Ginzburg–Tamm model itself was not successful, it is quite interesting as possessing many features of modern theories. Indeed, states of string theory are described by a vector in the space of states of string:

$$\left|\Psi(x)\right\rangle = \sum \psi_{m_1 \ldots m_{s_1},\, n_1 \ldots n_{s_2},\, \ldots}(x)\, a_{-1}^{m_1} \ldots a_{-1}^{m_{s_1}} a_{-2}^{n_1} \ldots a_{-2}^{n_{s_2}} \ldots |0\rangle$$

that satisfies the condition

$$Q\left|\Psi(x)\right\rangle = 0\,, \tag{1.3}$$

where Q is the Beckey–Rue–Stora–Tyutin (BRST) string operator satisfying the condition $Q^2 = 0$, which implies invariance of the theory under the gauge transformations $\delta|\psi\rangle = Q|\varepsilon\rangle$. The analogy between the variables u^n and string creation operators a_i^n which, however, form an infinite set in the case of string ($i = 0, 1, 2, \ldots \infty$), is obvious.

The mass scale of string theory is provided by the string tension parameter $m^2 \sim 1/\alpha'$. In the tensionless limit $\alpha' \to \infty$, all string excitations become massless and one can expect the appearance of additional symmetries of string theory in the high-energy limit as was discussed, for instance, in paper [16]. Whatever construction underlies string theory, if in a certain limit it exhibits higher-spin symmetries, it can be interpreted in this limit as a higher-spin gauge theory.

[1] For convenience of readers, the chapter 'Higher spins' from book [5] will be placed on *PU*'s site www.ufn.ru as an Appendix to this paper by M A Vasiliev along with a number of rather inaccessible at present papers by V L Ginzburg covering the subject matter of interest. (*Editor's note.*)

[2] Notice that this property is a consequence of the condition imposed in paper [15] that Ψ has to form a unitary representation of the Lorentz group, the necessity of which raises serious questions today.

The central role in higher-spin gauge theory is played by gauge symmetries. The case of symmetric massless fields of any spin was considered by Fronsdal in 1978 [17]. In the Fronsdal formulation, a symmetric massless field of spin s is described by a rank s symmetric tensor $\varphi_{n_1 \ldots n_s}$ subjected to the double tracelessness condition $\eta^{n_1 n_2}\eta^{n_3 n_4}\varphi_{n_1 \ldots n_s} = 0$. The gauge transformation takes the form

$$\delta\varphi_{k_1 \ldots k_s} = \partial_{(k_1}\varepsilon_{k_2 \ldots k_s)}\,, \qquad \varepsilon^{m}{}_{m k_3 \ldots k_{s-1}} = 0\,.$$

In the spin-1 case, the gauge transformations with the parameter $\varepsilon(x)$ describe inner symmetries, while the corresponding nonlinear gauge theory gives rise to electrodynamics and Yang–Mills theory.

Spin 2 is related to vector gauge parameters $\varepsilon_n(x)$, which correspond to changes in coordinates $x^n \to x^n + \varepsilon^n(x)$ in the nonlinear theory of gravity.

The gauge parameter $\psi_{n\alpha}$ for the fermion field of spin 3/2 considered in Refs [8, 9] turns out to be a spinor $\varepsilon_\alpha(x)$ and corresponds to supersymmetry transformations, while the corresponding nonlinear gauge theory is called supergravity [3].

The key question in the theory of higher-spin fields, to which fields with spins $s > 2$ are attributed after the creation of supergravity, is what the structure of the corresponding nonlinear theories is. The answer to this question is closely related to the fundamental question of the structure of non-Abelian higher-spin symmetries. For instance, a pattern of fields in a consistent model is determined to a large extent by representations of its symmetry group. At least as important is that symmetries of the theory determine the structure of the space where they can be realized. For instance, the symmetries of the Poincaré group, which contain spacetime translations and Lorentz rotations, are realized geometrically in Minkowski spacetime. Supersymmetry is naturally realized in superspace. The 'nongeometricity' of higher-spin symmetries in Minkowski space suggests the necessity of revising conventional conceptions of spacetime.

Up to the end of the 1970s, dominating statements in the literature on the possibility of the existence of interacting higher-spin theories were negative. They were mostly based on two kinds of arguments. The first-kind arguments were in the spirit of the Coleman–Mandula theorem [18], which states that a nontrivial S-matrix in Minkowski space does not admit higher-spin symmetries. Negative arguments of the second kind were based on the direct analysis of the compatibility of higher-spin symmetries with the symmetries of gravity (diffeomorphisms), as in the paper by Aragone and Deser [19].

The proper way started to become clear in the mid-eighties of the last century. By the example of a scalar field, it was found out that there exist conserved higher-spin currents [20–22] that contain higher derivatives:

$$J_s \sim \sum_{n=0}^{s} a_n \partial^n \phi \partial^{s-n} \phi\,.$$

The number of derivatives increases with spin. An important conclusion on the structure of interactions of higher-spin fields that agreed with the results of the earlier analysis in the framework of the light-cone gauge [23] was that gauge invariant interactions of higher spins contain higher derivatives:

$$L^3 = \sum_{p,q,r} (D^p\varphi)(D^q\varphi)(D^r\varphi)\,\rho^{p+q+r+1/2d-3}\,.$$

The appearance of interactions with higher derivatives requires the introduction of a dimensionful constant ρ, which compensates for extra dimensions carried by higher derivatives. In string theory, the parameter ρ is expressed via string tension: $\rho^2 \sim \alpha'$. In the theory of higher-spin gauge fields, which describes massless fields, an independent mass scale is absent. An unexpected way out of this situation is to consider the theory in the space with nonzero curvature $M \sim \lambda = \rho^{-1}$, which sets a nontrivial scale unrelated to the mass scale of the theory.

As a result, choosing de Sitter (dS) or anti-de Sitter (AdS) space as the most symmetric one with a nonzero curvature tensor (for definiteness we will talk about anti-de Sitter space), it can be shown that, while not admitting a consistent formulation in Minkowski space, higher-spin gauge theory admits a formulation in AdS space [24]. This generalization not only allowed avoiding the no-go statements valid in flat space, but also turned out to be preparation for what was at that time an unknown conjecture on the correspondence between conformal theories in d dimensions and a theory in the $(d+1)$ dimensional space of nonzero curvature (AdS/CFT) [25–27].

2. Frame-like formulation as the key to symmetry

Symmetries can be conveniently studied by describing gauge fields as differential forms valued in one symmetry algebra or another. For instance, a spin-1 field is described by a 1-form $A_\nu{}^i{}_j\,(\mu, \nu = 0, 1, 2, 3)$ valued in a Yang–Mills algebra g. Spin 2 in the Cartan–Weyl formulation is described by the vierbein $e_\nu{}^a$ and Lorentz connection $\omega_\nu{}^{ab}$. It is useful to identify the $e_\nu{}^a$ and $\omega_\nu{}^{ab}$ fields with the gauge fields of the Lie algebras of the groups of Poincaré iso(1,3), de Sitter SO$(d,1)$, or anti-de Sitter SO$(d-1,2)$. A spin-3/2 field $\psi_\nu{}^\alpha$ admits natural interpretation as a gauge field associated with the generators Q_α of supersymmetry in the supersymmetric extension of the Poincaré or AdS symmetry algebras. (Notice that the dS algebra SO$(d,1)$ allows no consistent supersymmetric extension.)

The frame-like formulation for free fields of an arbitrary spin [28–30] requires the introduction of the following set of fields:

$$e_\nu^{a_1 \ldots a_{s-1}}\,, \; \omega_\nu^{a_1 \ldots a_{s-1}, b}\,, \; \ldots, \; \omega_\nu^{a_1 \ldots a_{s-1}, b_1 \ldots b_t}\,, \; 0 \leqslant t \leqslant s-1\,,$$

which, in turn, dictates the pattern of symmetry parameters associated with the field of a fixed spin s:

$$\varepsilon^{a_1 \ldots a_{s-1}}\,, \; \varepsilon^{a_1 \ldots a_{s-1}, b}\,, \; \ldots, \; \varepsilon^{a_1 \ldots a_{s-1}, b_1 \ldots b_t}\,, \; 0 \leqslant t \leqslant s-1\,.$$

(Both the fields and the symmetry parameters are symmetric traceless tensors with respect to the Lorentz indices a and b, subject to the condition that the symmetrization of any of the indices b with all indices a gives zero.)

The simplest higher-spin algebra with such a set of parameters was originally found for the case of a four-dimensional theory [31]. The spectrum of spins in the higher-spin gauge theory, which possesses such a symmetry, contains fields of all integer spins $s = 0, 1, 2, 3, \ldots, \infty$, precisely corresponding to the spin spectrum conceived as most natural to Ginzburg.

One of the important properties of higher-spin symmetries is that fields of lower-spins $s = 0, 1, 2$ do transform under the higher-spin symmetry transformations. In particular, the metric tensor loses covariant meaning in the framework of higher-spin gauge theory. Implying that the notion of a distance between infinitesimally closed points of spacetime has no invariant sense in the higher-spin gauge theory, this property itself indicates the nonlocality of the latter. Finite-dimensional subalgebras of higher-spin algebras correspond to the sets of fields of lower-spins $s \leqslant 2$ associated with supergravity. One can expect that these fields can remain massless (light) after the spontaneous breaking of higher-spin symmetries to their finite-dimensional subgroups, precisely corresponding to the class of field-theoretical models considered in the modern theories of fundamental interactions. This scenario precisely corresponds to a picture where present-day field-theoretical models should correspond to a low-energy approximation of some complete nonlocal theory.

The fact that higher-spin symmetries mix fields of all spins means that the spin-2 field should not play a preferred role in phase with unbroken higher-spin symmetries. Nevertheless, we assume that, as any other theory in the framework of gravity, higher-spin gauge theory should be formulated in a coordinate-independent form in agreement with the Einstein equivalence principle. To preserve the independence from the coordinate choice without the explicit use of a metric, it is very useful to apply the Cartan formalism of exterior forms. The key property of this formalism is that antisymmetrized derivatives of antisymmetric tensors

$$\partial_{[\nu_1} A_{\nu_2 \ldots \nu_{p+1}]} \qquad (2.1)$$

turn out to be automatically covariant without introducing Christoffel symbols, because the latters can always be chosen symmetric with respect to lower indices, hence dropping out of the expressions fully antisymmetrized with respect to the world indices ν_i. The compact form of formula (2.1), viz.

$$dA\,, \qquad d = \mathrm{d}x^\nu \frac{\partial}{\partial x^\nu}\,, \qquad A = \mathrm{d}x^{\nu_1} \wedge \ldots \wedge \mathrm{d}x^{\nu_p} A_{\nu_1 \ldots \nu_p}\,,$$

is achieved by virtue of introducing anticommutative symbols

$$\mathrm{d}x^\mu \wedge \mathrm{d}x^\nu = -\,\mathrm{d}x^\nu \wedge \mathrm{d}x^\mu\,.$$

The central fact expressing the symmetry of second derivatives consists in the following:

$$d^2 = 0\,. \qquad (2.2)$$

As a consequence of formula (2.2), the Abelian field strength $F = dA$ turns out to be gauge invariant:

$$\delta A(x) = d\varepsilon(x)\,, \qquad \delta F = 0\,.$$

The non-Abelian generalization is achieved via covariant derivative extension

$$d \to D = d + \omega\,, \qquad \omega(x) = \mathrm{d}x^\nu \omega_\nu(x)\,,$$

where the 1-form[3] ω is valued in some matrix or operator algebra (higher-spin algebra in the case under consideration).

Higher-spin gauge fields in four dimensions take values in the algebra of functions of oscillators:

$$\omega(\hat{Y}|x)\,, \quad [\hat{Y}_A\,, \hat{Y}_B] = 2\mathrm{i}C_{AB}\,, \quad C_{AB} = -C_{BA}\,,$$

[3] A polynomial of degree p of $\mathrm{d}x^\nu$ or, equivalently, an antisymmetric tensor of rank p is called p-form.

where $\hat{Y}_A$ is a noncommutative spinor, and C_{AB} is the charge conjugation matrix. $A, B = 1, \ldots 4$ are Majorana indices in four dimensions.

Spin-s fields are described by homogeneous polynomials of $\hat{Y}$:

$$\omega(\mu\hat{Y}|x) = \mu^{2(s-1)}\omega(\hat{Y}|x)\,.$$

This construction is analogous in many respects to the Ginzburg–Tamm construction. The difference is that $\omega(\hat{Y}|x) = \mathrm{d}x^\nu\omega_\nu(\hat{Y}|x)$ depends on the auxiliary spinor $\hat{Y}_A$, rather than on the vector, and carries the differential form index ν. The latter circumstance is, however, quite significant, providing natural realization of higher-spin symmetries with 0-forms $\epsilon(\hat{Y}|x)$ as gauge parameters.

3. Unfolded dynamics

The formulation in terms of differential forms has a number of advantages, allowing, in particular, a representation of equations in partial derivatives in the so-called unfolded form. This formulation is based on the direct generalization of the well-known trick allowing one to represent ordinary differential equations in the form of first-order equations:

$$\dot{q}^i(t) = \varphi^i\big(q(t)\big)\,,$$

by virtue of introducing new variables for all those derivatives of the dynamical variables that are not determined by the original equations. Such a formulation has a number of advantages, allowing, in particular, the control of a number of degrees of freedom, which coincides with the number of dynamical variables.

The field theory studies systems with an infinite number of degrees of freedom, described by functional spaces. In the Hamiltonian formulation of the Maxwell theory, for example, generalized coordinates are identified with the space components of the vector potential $\mathbf{A}(x)$, while generalized momenta are identified with components of the electric field $\mathbf{E}(x)$. Given all merits of the Hamiltonian approach to the field theory, its substantial disadvantage is the loss of covariance with respect to both Lorentz symmetry and the ambiguity in the coordinate choice.

Unfolded dynamics represents a multidimensional covariant generalization of the first-order formulation of ordinary differential equations, achieved by virtue of the replacement of the time derivative by the exterior differentiation, and a set of variables $q^i(t)$ by a set of differential forms $W^\Omega(x)$ which play the role of dynamical variables:

$$\frac{\partial}{\partial t} \to d\,, \quad q^i(t) \to W^\Omega(x) = \mathrm{d}x^{\nu_1} \wedge \ldots \wedge \mathrm{d}x^{\nu_p} W^\Omega_{\nu_1 \ldots \nu_p}(x)\,.$$

Unfolded equations have the form [32]

$$dW^\Omega(x) = G^\Omega\big(W(x)\big)\,, \quad d = \mathrm{d}x^\nu \partial_\nu\,, \qquad (3.1)$$

where $G^\Omega(W)$ is some function of dynamical differential forms $W^\Omega(x)$:

$$G^\Omega(W) = \sum_{n=1}^{\infty} f^\Omega{}_{A_1 \ldots A_n} W^{A_1} \wedge \ldots \wedge W^{A_n}\,.$$

Due to the use of the language of differential forms, equations (3.1) turn out to be coordinate-independent, i.e., are insensitive to the coordinate choice.

For $d > 1$, compatibility conditions with the property (2.2) impose nontrivial restrictions on the form of functions

$G^{\Omega}(W)$:

$$G^{A}(W)\wedge\frac{\partial G^{\Omega}(W)}{\partial W^{A}}\equiv 0\,, \tag{3.2}$$

equivalent to generalized Jacobi identities

$$\sum_{n=0}^{m}(n+1)f^{\Gamma}{}_{[A_1\ldots A_{m-n}}f^{\Omega}{}_{\Gamma A_{m-n+1}\ldots A_m]}=0\,.$$

The problem is to find such functions $G^{A}(W)$ that satisfy (3.2) for any W^{Ω}.

The unfolded form of equations possesses a number of remarkable properties.

First of all, being coordinate independent, unfolded equations are ideally adjusted for the description of gravity. The use of the formalism of differential forms also guarantees gauge invariance of equations (3.1) under the gauge transformations

$$\delta W^{\Omega}=d\varepsilon^{\Omega}+\varepsilon^{A}\,\frac{\partial G^{\Omega}(W)}{\partial W^{A}}\,,$$

where the gauge parameter $\varepsilon^{\Omega}(x)$ is a $(p_{\Omega}-1)$-form if the corresponding gauge field W^{Ω} is a p_{Ω}-form (0-forms W^{Ω} have no gauge parameters).

An important property of the unfolded formulation is its general applicability. Any system of partial differential equations can be represented in the unfolded form by virtue of introducing an appropriate set of auxiliary variables. Interactions are described as nonlinear deformations of the function $G^{\Omega}(W)$ in Eqn (3.1).

Unfolded equations allow a fruitful interpretation in terms of Lie algebras and their cohomology that, in particular, provide the possibility of systematical classification of g-invariant equations in terms of g-modules (see, e.g., Refs [33, 34]).

The degrees of freedom of a dynamical system formulated in the unfolded form are described by a subset of 0-forms $C^{i}(x)$ of the full set of forms $W^{\Omega}(x)$. p-forms W^{Ω} of nonzero degrees $p^{\Omega}>0$ are determined by 0-forms up to the gauge transformations. Values of $C^{i}(x_0)$ at any $x=x_0$ determine the local evolution of the system, similarly to how $q(t_0)$ determines the local evolution for ordinary differential equations rewritten in the first-order form. The space of fields C^{i} is analogous (dual) to the space of single-particle states of the corresponding field theory.

A surprising property of the unfolded formulation is that space–time coordinates x play a secondary role. In this language, spacetime geometry turns out to be encoded by the function $G^{\Omega}(W)$.

If the set of functions $W^{\Omega}(x)$ can be described by a finite set of functions $W(Y|x)$ of auxiliary variables Y_A, unfolding acquires the meaning of the covariant Penrose transform (i.e., the twistor transform).

4. Nonlinear higher-spin equations

The nonlinear higher-spin dynamics is formulated in terms of star-product

$$(f\star g)(Z,Y)=\int \mathrm{d}S\,\mathrm{d}T f(Z+S,Y+S)\times g(Z-T,Y+T)\exp\left(-\mathrm{i}S_A T^{A}\right), \tag{4.1}$$

which describes the associative algebra of oscillators that satisfy the relations

$$[Y_A,Y_B]_\star=-[Z_A,Z_B]_\star=2\mathrm{i}C_{AB}\,,\quad Y^{A}=C^{AB}Y_B\,,$$
$$Z_A=(z_\alpha,\bar z_{\dot\alpha})\,,\quad Y_A=(y_\alpha,\bar y_{\dot\alpha})\,,\quad \alpha,\ \dot\alpha=1,2\,.$$

More precisely, product (4.1) describes the normal ordering of the oscillators $Z-Y$ and $Z+Y$. The star-product (4.1) admits the introduction of inner Klein operators

$$\kappa=\exp\left(\mathrm{i}z_\alpha y^{\alpha}\right),\quad \bar\kappa=\exp\left(\mathrm{i}z_{\dot\alpha}\,y^{\dot\alpha}\right)$$

possessing the following properties

$$\kappa\star f(Z,Y)=f(\widetilde Z,\widetilde Y)\star\kappa\,,\qquad \kappa\star\kappa=1\,,$$

where $(\tilde a_\alpha,\tilde{\bar a}_{\dot\alpha})=(-a_\alpha,\bar a_{\dot\alpha})$.

The full system of higher-spin equations can be written out in the form [35, 36]

$$dW+W\star W=0\,, \tag{4.2}$$

$$dB+W\star B-B\star W=0\,, \tag{4.3}$$

$$dS+W\star S+S\star W=0\,, \tag{4.4}$$

$$S\star B-B\star S=0\,, \tag{4.5}$$

$$S\star S=\mathrm{i}(\mathrm{d}z^{\alpha}\,\mathrm{d}z_\alpha+\mathrm{d}\bar z^{\dot\alpha}\,\mathrm{d}\bar z_{\dot\alpha}+\mathrm{d}z^{\alpha}\,\mathrm{d}z_\alpha F(B)\star k\star\kappa + \mathrm{d}\bar z^{\dot\alpha}\,\mathrm{d}\bar z_{\dot\alpha}\bar F(B)\star\bar k\star\bar\kappa)\,, \tag{4.6}$$

where $W=\mathrm{d}x^{n}W_n(Z;Y;K|x)$ and $S=\mathrm{d}z^{\alpha}s_\alpha(Z;Y;K|x)+\mathrm{d}\bar z^{\dot\alpha}\,\bar s_{\dot\alpha}(Z;Y;K|x)$ describe 1-form connections in the space-time with coordinates x and in the noncommutative space with coordinates Z. The 0-form $B(Z;Y;K|x)$ serves as a generating function for the curvatures of higher-spin gauge fields and for lower-spin fields. $f(B)$ is an arbitrary star-product function of the 0-form B:

$$f(B)=\sum_{n=1}^{\infty}f_n\underbrace{B\star\ldots\star B}_{n}\,.$$

The Klein operators $K=(k,\bar k)$ generate chirality transformations

$$k\star f(A)=f(\tilde A)\star k\,,\quad \bar k\star f(A)=f(-\tilde A)\star\bar k\,,$$
$$A=(A_\alpha,\bar A_{\dot\alpha}):\quad \tilde A=(-A_\alpha,\bar A_{\dot\alpha})\,,$$

which act not only on the functions of Y and Z, as the operators κ and $\bar\kappa$ do, but also on the differentials of noncommutative coordinates $\mathrm{d}Z$. It should be noted that $k\bar k$ is the generator of total boson–fermion parity.

Equations (4.2)–(4.6) are invariant under the gauge transformations

$$\delta W=\varepsilon\star W-W\star\varepsilon\,,\quad \delta S=\varepsilon\star S-S\star\varepsilon\,,$$
$$\delta B=\varepsilon\star B-B\star\varepsilon\,,$$

where the gauge parameter $\varepsilon=\varepsilon(Z;Y;K|x)$ is an arbitrary function of its arguments.

A remarkable feature of equations (4.2)–(4.6) is that all those equations that contain derivatives with respect to space-time coordinates via exterior differential d, i.e., equations (4.2)–(4.4), have the form of zero-curvature equations and covariant constancy equations. It is not hard to write down their explicit local solution in the pure gauge form. As a result, it turns out that all the information about solutions of the nonlinear system of higher-spin equations is encoded in equations (4.5) and (4.6), which describe the expression for the curvature of the noncommutative space of the variables Z in terms of the 0-form B. These equations admit an interesting interpretation: they describe a two-dimensional quantum hyperboloid of radius $B(x)$ in the noncommutative space of Y_A and Z_A.

On the other hand, solving equations (4.5) and (4.6) order-by-order and substituting the result into equations (4.2)–(4.4) gives the unfolded form of massless equations [32] with all nonlinear corrections. Although unfolded equations have the form of first-order equations, because the fields W, S, and B contain an infinite number of auxiliary fields, interaction terms contain fields of all spins, along with all their derivatives.

In contrast to most of the known problems of classical field theory, nonlinear higher-spin equations contain no low-energy expansion parameter. Indeed, the dimensionless combination composed from the derivative and space–time curvature ρD_ν, where ρ is a typical radius scale of the background spacetime, while D_ν is the background covariant derivative, cannot be regarded as small because, when acting on one tensor or another, $\rho^2[D_\mu, D_\nu]$ turns out to be a dimensionless matrix of order one.

In other words, the higher-spin equations (4.2)–(4.6) describe interaction vertices with all degrees of derivatives of dynamic fields, which can make a competing contribution. The structure of interactions is determined by the higher-spin symmetries. Thus, on the one hand, higher-spin symmetries lead to the nonlocality of the interacting higher-spin theory, while, on the other hand, they fully determine the structure of this nonlocality. The nonlocal character of nonlinear higher-spin equations does not allow using for their analysis many standard means of field theory and general relativity (GR), such as, e.g., low-energy expansion or geodesic motion, demanding the development of alternative approaches.

5. Recent progress and prospects

At present, higher-spin theory is going through the stage of impetuous development. Let us list here some of the latest results and avenues of investigations, in most cases confining ourselves merely to references to recent publications where one can find a more comprehensive review of the available literature.

Nonlinear equations (4.2)–(4.6) for symmetric higher-spin fields in four dimensions were generalized to any number of dimensions in Ref. [37].

Extension of the higher-spin theory to gauge fields of any symmetry type is not yet completed, even at the level of free fields. One surprising phenomenon related to this problem is that the very notions of a free field in Minkowski and AdS spaces differ for massless fields of any symmetry type: in most cases, an irreducible field in the AdS space reduces in the flat limit to a number of elementary fields in Minkowski space [38, 39]. During recent years, much attention has been paid to the analysis of free fields with an arbitrary type of symmetry (see, e.g., papers [40–51] and references therein).

An interesting area is related to the study of conformal higher-spin fields [33, 34, 52–56]. Although in most cases these systems turn out to be nonunitary, their study is of considerable interest because they allow analyzing unitary field-theoretical models as conformal models with spontaneously broken conformal symmetry, which not only leads to technical simplifications but also may help to find fundamental symmetries of the theory.

One more area of research is related to the construction of cubic interaction vertices of massive and massless fields of arbitrary spin for any number of dimensions, both in Minkowski and in AdS spaces [57–71]. Of great interest is work on the derivation of scattering amplitudes of higher-spin fields from string theory [72–74].

Considerable efforts are aimed at the development of the general theory of unfolded equations and clarification of their relation with other approaches to dynamical systems and applications [34, 49 – 51, 75 – 80].

A distinguished position is occupied by the problem of finding exact solutions to complete nonlinear higher-spin equations, which essentially differs from most known problems of classical field theory in that the equations under consideration possess no low-energy expansion parameter. At present, very few exact solutions of nonlinear higher-spin equations are known in three and four dimensions [81–84]. One of the most interesting ones is a spherically symmetric exact solution of the four-dimensional higher-spin theory [85], which in the weak field regime behaves as the black hole solution of GR. It is a very interesting problem to analyze strong-field phenomena related to this solution.

One more important and interesting avenue of investigations is related to the Sp(8)-invariant description of four-dimensional massless fields in a ten-dimensional space $x_{\alpha\dot{\alpha}} \to X_{AB} = X_{BA}$ $(A, B = 1, 2, 3, 4)$ [34, 87–90]. Possessing a number of remarkable properties, this formulation allows, in particular, new insight into such a fundamental concept underlying Einstein's approach to spacetime as a local event, i.e., a point of spacetime.

One of the most unusual features of the theory of higher-spin gauge fields is that they admit a nontrivial interaction only in a curved space such as AdS space [24]. This property, which seemed strange at the first stage, later on acquired deep meaning in the context of the AdS/CFT-correspondence conjecture [25–27]. A possible interpretation of higher-spin theories in terms of AdS/CFT correspondence has been discussed by various authors. In the context of the four-dimensional higher-spin theory described in this paper, Klebanov and Polyakov [91] (see also paper [92]) put forward a hypothesis for its duality to the three-dimensional O(N)-sigma model in the limit $N \to \infty$. An explicit verification of this hypothesis turned out to be quite laborious and was performed only recently [93, 94].

Apart from the work on AdS_4/CFT_3 correspondence, there are a number of interesting papers on establishing AdS_3/CFT_2 correspondence between three-dimensional higher-spin theories and two-dimensional conformal theories [95–98], and even on the analysis of the AdS_{d+1}/CFT_d correspondence for higher-spin theories for any number of dimensions [99, 100]. At the free-field level, important results in this area were also obtained by Metsaev [101, 102].

Despite the considerable progress achieved over recent years, a number of interesting questions in higher-spin theory remain to be solved. We can mention the construction of nonlinear equations for mixed-symmetry fields, the construction of a complete nonlinear action in higher-spin theory,[4] a deeper understanding of higher-spin geometry, an accurate

[4] Interesting suggestions proposed recently in the papers [103–105], which generalize the old remark in the paper [32], unlikely close this problem.

definition of the notion of (non)locality in higher-spin theory, clarification of the relation with string theory, and many others.

In conclusion, I would like to reproduce a statement by Vitaly Lazarevich Ginzburg made about five years ago. In his speech to newcoming students at the Chair of Problems of Physics and Astrophysics at MIPT, Ginzburg mentioned his passion for higher-spin theory in a somewhat unexpected context, saying that anyone has to realistically estimate the limits of their abilities, in time leaving behind too hard problems, as he himself at the time quit his work on the higher-spin theory (see also Ref. [5]). This is the edifying example of the sober assessment, not so much of his own abilities, but of the state of science at the time the decision was taken. Indeed, at the time Vitaly Lazarevich was talking about, there remained a quarter of a century till the discovery of supergravity, leading to the perception of the fundamental role of the principle of gauge invariance in the higher-spin theory. Before this had happened, the chances of real progress in the theory were as little as the chances of constructing the theory of electroweak interactions before the development of Yang–Mills theory.

Turning out to be remarkably deep and promising, the higher-spin theory is now going through a true renaissance, probably leading to a new understanding of a number of fundamental physical concepts. Still, knowing too little about the higher-spin theory as a whole, we already know enough to claim that today is probably the best time for research on this extremely interesting and quickly developing area.

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References

1. Dirac P A M *Proc. R. Soc. Lond. A* **155** 447 (1936)
2. Fierz M, Pauli W *Proc. R. Soc. Lond. A* **173** 211 (1939)
3. Freedman D Z, van Nieuwenhuizen P, Ferrara S *Phys. Rev. D* **13** 3214 (1976)
4. Ginzburg V L *O Fizike i Astrofizike* (On Physics and Astrophysics) 3rd ed. (Moscow: Byuro Kvantum, 1995) p. 321 [Translated into English: *The Physics of a Lifetime* (Berlin: Springer-Verlag, 2001) p. 318]
5. Ginzburg V L "Opyt nauchnoi avtobiografii" ("A scientific autobiography: an attempt"), in *O Sverkhprovodimosti i Sverkhtekuchesti. Avtobiografiya* (On Supercoductivity and Superfluidity. A Scientific Autobiography) (Moscow: Izd. Fiz.-Mat. Lit., 2006) p. 190 [Translated into English (Berlin: Springer-Verlag, 2009) p. 183]
6. Ginzburg V L "O Efime Samoiloviche Fradkine i ob uravneniyakh dlya chastits s vysshimi spinami" ("About Efim Samoilovich Fradkin and the equations for higher-spin particles"), Preprint No. 330 (Moscow: Lebedev Physical Institute, 1985) [Translated into English: "About Fradkin and the equations for higher-spin particles", in Quantum Field Theory and Quantum Statistics: Essay in Honor of the Sixtieth Birthday of E S Fradkin Vol. 2 (Eds I A Batalin, C J Isham, G A Vilkovisky) (Bristol: Adam Hilger, 1987) p. 15]
7. Ginzburg V L *Zh. Eksp. Teor. Fiz.* **12** 425 (1942); Ginsburg V *J. Phys. USSR* **7** 115 (1943)
8. Davydov A S *Zh. Eksp. Teor. Fiz.* **13** 313 (1943)
9. Rarita W, Schwinger J *Phys. Rev.* **60** 61 (1941)
10. Ginzburg V L "K teorii elementarnykh chastits" ("On the theory of elementary particles"), Doctoral Thesis (Kazan: Lebedev Physical Institute, 1941)
11. Ginsburg V L *J. Phys. USSR* **8** 33 (1944)
12. Ginzburg V L *Trudy Fiz. Inst. Akad. Nauk SSSR* **3** (2) 193 (1946)
13. Ginsburg V L *Dokl. Akad. Nauk SSSR* **37** 191 (1942) [*C.R. Acad. Sci. URSS* **37** 166 (1942)]
14. Fradkin E S *Zh. Eksp. Teor. Fiz.* **20** 27, 211 (1950)
15. Ginzburg V L, Tamm I E *Zh. Eksp. Teor. Fiz.* **17** 227 (1947)
16. Gross D J *Phys. Rev. Lett.* **60** 1229 (1988)
17. Fronsdal C *Phys. Rev. D* **18** 3624 (1978)
18. Coleman S, Mandula J *Phys. Rev.* **159** 1251 (1967)
19. Aragone C, Deser S *Phys. Lett. B* **86** 161 (1979)
20. Berends F A, Burgers G J H, Van Dam H *Z. Phys. C* **24** 247 (1984)
21. Berends F A, Burgers G J H, Van Dam H *Nucl. Phys. B* **260** 295 (1985)
22. Berends F A, Burgers G J H, Van Dam H *Nucl. Phys. B* **271** 429 (1986)
23. Bengtsson A K H, Bengtsson I, Brink L *Nucl. Phys. B* **227** 31, 41 (1983)
24. Fradkin E S, Vasiliev M A *Phys. Lett. B* **189** 89 (1987)
25. Maldacena J *Adv. Theor. Math. Phys.* **2** 231 (1998); *Int. J. Theor. Phys.* **38** 1113 (1999); hep-th/9711200
26. Gubser S S, Klebanov I R, Polyakov A M *Phys. Lett. B* **428** 105 (1998); hep-th/9802109
27. Witten E *Adv. Theor. Math. Phys.* **2** 253 (1998); hep-th/9802150
28. Vasiliev M A *Yad. Fiz.* **32** 855 (1980) [*Sov. J. Nucl. Phys.* **32** 439 (1980)]
29. Vasiliev M A *Fortsch. Phys.* **35** 741 (1987)
30. Lopatin V E, Vasiliev M A *Mod. Phys. Lett. A* **3** 257 (1988)
31. Fradkin E S, Vasiliev M A *Ann. Physics* **177** 63 (1987)
32. Vasiliev M A *Ann. Physics* **190** 59 (1989)
33. Shaynkman O V, Tipunin I Yu, Vasiliev M A *Rev. Math. Phys.* **18** 823 (2006); hep-th/0401086
34. Vasiliev M A *Nucl. Phys. B* **793** 469 (2008); arXiv:0707.1085
35. Vasiliev M A *Phys. Lett. B* **243** 378 (1990)
36. Vasiliev M A *Phys. Lett. B* **285** 225 (1992)
37. Vasiliev M A *Phys. Lett. B* **567** 139 (2003); hep-th/0304049
38. Metsaev R R *Phys. Lett. B* **354** 78 (1995)
39. Brink L, Metsaev R R, Vasiliev M A *Nucl. Phys. B* **586** 183 (2000); hep-th/0005136
40. Labastida J M F *Phys. Rev. Lett.* **58** 531 (1987)
41. Labastida J M F *Nucl. Phys. B* **322** 185 (1989)
42. Bekaert X, Boulanger N *Commun. Math. Phys.* **245** 27 (2004); hep-th/0208058
43. Buchbinder I L, Krykhtin V A, Takata H *Phys. Lett. B* **656** 253 (2007); arXiv:0707.2181
44. Alkalaev K B, Shaynkman O V, Vasiliev M A *Nucl. Phys. B* **692** 363 (2004); hep-th/0311164
45. Alkalaev K B, Shaynkman O V, Vasiliev M A *JHEP* (08) 069 (2005); hep-th/0501108
46. Campoleoni A et al. *Nucl. Phys. B* **815** 289 (2009); arXiv:0810.4350; arXiv:0904.4447
47. Skvortsov E D *JHEP* (07) 004 (2008); arXiv:0801.2268
48. Skvortsov E D *Nucl. Phys. B* **808** 569 (2009); arXiv:0807.0903
49. Boulanger N, Iazeolla C, Sundell P *JHEP* (07) 013 (2009); arXiv:0812.3615
50. Boulanger N, Iazeolla C, Sundell P *JHEP* (07) 014 (2009); arXiv:0812.4438
51. Skvortsov E D *JHEP* (01) 106 (2010); arXiv:0910.3334
52. Fradkin E S, Tseytlin A A *Phys. Rep.* **119** 233 (1985)
53. Segal A Y *Nucl. Phys. B* **664** 59 (2003); hep-th/0207212
54. Metsaev R R, arXiv:0709.4392; arXiv:0707.4437
55. Marnelius R, arXiv:0906.2084
56. Vasiliev M A *Nucl. Phys. B* **829** 176 (2010); arXiv:0909.5226
57. Vasiliev M A *Nucl. Phys. B* **616** 106 (2001); hep-th/0106200
58. Alkalaev K B, Vasiliev M A *Nucl. Phys. B* **655** 57 (2003); hep-th/0206068
59. Alkalaev K B, arXiv:1011.6109
60. Zinoviev Yu M *Class. Quantum. Grav.* **26** 035022 (2009); arXiv:0805.2226
61. Zinoviev Yu M *JHEP* (03) 082 (2011); arXiv:1012.2706
62. Zinoviev Yu M *JHEP* (08) 084 (2010); arXiv:1007.0158
63. Bekaert X, Boulanger N, Cnockaert S *JHEP* (01) 052 (2006); hep-th/0508048
64. Boulanger N, Leclercq S, Cnockaert S *Phys. Rev. D* **73** 065019 (2006); hep-th/0509118
65. Boulanger N, Leclercq S *JHEP* (11) 034 (2006); hep-th/0609221

66. Metsaev R R *Nucl. Phys. B* **759** 147 (2006); hep-th/0512342
67. Metsaev R R *Phys. Rev. D* **77** 025032 (2008); hep-th/0612279
68. Fotopoulos A, Tsulaia M *Int. J. Mod. Phys. A* **24** 1 (2009); arXiv:0805.1346
69. Boulanger N, Leclercq S, Sundell P *JHEP* (08) 056 (2008); arXiv:0805.2764
70. Manvelyan R, Mkrtchyan K, Rühl W *Phys. Lett. B* **696** 410 (2011); arXiv:1009.1054
71. Bekaert X, Boulanger N, Leclercq S *J. Phys. A Math. Theor.* **43** 185401 (2010); arXiv:1002.0289
72. Sagnotti A, Taronna M *Nucl. Phys. B* **842** 299 (2011); arXiv:1006.5242
73. Fotopoulos A, Tsulaia M *JHEP* (11) 086 (2010); arXiv:1009.0727
74. Polyakov D *Int. J. Mod. Phys. A* **25** 4623 (2010); arXiv:1005.5512
75. Shaynkman O V, Vasiliev M A *Teor. Mat. Fiz.* **123** 323 (2000) [*Theor. Math. Phys.* **123** 683 (2000)]; hep-th/0003123
76. Vasiliev M A *Int. J. Geom. Meth. Mod. Phys.* **3** 37 (2006); hep-th/0504090
77. Barnich G et al. *Commun. Math. Phys.* **260** 147 (2005); hep-th/0406192
78. Barnich G, Grigoriev M, hep-th/0504119
79. Kaparulin D S, Lyakhovich S L, Sharapov A A, arXiv:1012.2567
80. Ponomarev D S, Vasiliev M A, arXiv:1012.2903
81. Prokushkin S F, Vasiliev M A *Nucl. Phys. B* **545** 385 (1999); hep-th/9806236
82. Sezgin E, Sundell P *JHEP* (07) 055 (2002); hep-th/0205132
83. Sezgin E, Sundell P *Nucl. Phys. B* **762** 1 (2007); hep-th/0508158
84. Iazeolla C, Sezgin E, Sundell P *Nucl. Phys. B* **791** 231 (2008); arXiv:0706.2983
85. Didenko V E, Vasiliev M A *Phys. Lett. B* **682** 305 (2009); arXiv:0906.3898
86. Fronsdal C "Massless particles, ortosymplectic symmetry and another type of Kaluza-Klein theory", Preprint UCLA/85/TEP/10 (1985); in *Essays on Supersymmetry* (Mathematical Physics Studies, Vol. 8, Ed. C Fronsdal) (Dordrecht: Reidel, 1986) p. 164
87. Bandos I, Lukierski J, Sorokin D *Phys. Rev. D* **61** 045002 (2000); hep-th/9904109
88. Vasiliev M A *Phys. Rev. D* **66** 066006 (2002); hep-th/0106149
89. Vasiliev M A, hep-th/0111119
90. Gelfond O A, Vasiliev M A *JHEP* (03) 125 (2009); arXiv:0801.2191
91. Klebanov I R, Polyakov A M *Phys. Lett. B* **550** 213 (2002); hep-th/0210114
92. Sezgin E, Sundell P *Nucl. Phys. B* **644** 303 (2002); "Erratum" *Nucl. Phys. B* **660** 403 (2003); hep-th/0205131
93. Giombi S, Yin X *JHEP* (09) 115 (2010); arXiv:0912.3462
94. Giombi S, Yin X *JHEP* (04) 086 (2011); arXiv:1004.3736
95. Henneaux M, Rey S-J *JHEP* (12) 007 (2010); arXiv:1008.4579
96. Campoleoni A et al. *JHEP* (11) 007 (2010); arXiv:1008.4744
97. Gaberdiel M R, Gopakumar R *Phys. Rev. D* **83** 066007 (2011); arXiv:1011.2986
98. Gaberdiel M R, Hartman T *JHEP* (05) 031 (2011); arXiv:1101.2910
99. de Mello Koch R et al. *Phys. Rev. D* **83** 025006 (2011); arXiv:1008.0633
100. Douglas M R, Mazzucato L, Razamat S S *Phys. Rev. D* **83** 071701 (2011); arXiv:1011.4926
101. Metsaev R R *Phys. Rev. D* **81** 106002 (2010); arXiv:0907.4678
102. Metsaev R R *Phys. Lett. B* **682** 455 (2010); arXiv:0907.2207
103. Boulanger N, Sundell P, arXiv:1102.2219
104. Sezgin E, Sundell P, arXiv:1103.2360
105. Doroud N, Smolin L, arXiv:1102.3297

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V L Ginzburg and the development of experimental work on high-temperature superconductivity at LPI: 'iron superconductors'

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1. Introduction

One day in 2006, one of the authors of this paper (VMP) received a surprise phone call with an exciting proposal. The caller was V L Ginzburg, and the proposal was to undertake research into high-temperature superconductivity (HTSC) to develop superconductors with the critical temperature above room temperature: a worthwhile effort, Ginzburg convincingly explained, because it was of exceptional practical importance and because no theoretical reason was known to forbid room-temperature superconductivity (RTSC).

What does changing the subject mean for an experimentalist? First, the scale of the proposed research ruled out small group work and required the effort of most, if not all, of the laboratory, thus necessitating that the personnel be freshly trained and undergraduate programs be set up to prepare specialists in the new field. Second, the project needed to be financed and equipment and materials had to be purchased. Finally, it was necessary to find funds for refitting the building for different experimental work and to develop a redesign project for the existing building, as a whole and in parts, to optimize the operation of the new equipment. It was not until after three years [1] of these types of concerns that the first experiments were carried out to synthesize and study

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