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Mirror particles and mirror matter: 50 years of speculation and searching

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Contents

Abstract. This review describes the history of the discovery of the violation of the spatial parity P, the charge conjugation parity C, and the combined parity CP. The hypothesis of the existence of mirror particles was intended by its authors to restore the symmetry between left and right. The review presents the emergence and evolution of the concepts of 'mirror particles' and 'mirror matter' and can serve as a concise travel guide to 'mirror-land.' An important part of the review is the list of about 200 references with their titles.

1. Introduction

The terms 'mirror particles,' 'mirror matter,' and 'mirror world' currently refer to the hypothetical hidden sector of particles and interactions that compensate the mirror asymmetry of the weak interactions of ordinary particles. Mirror particles are regarded as a possible component of invisible dark matter. The history of mirror particles is a history of the intertwining of parity violation and parity degeneracy, rigorous and broken mirror symmetry, dark matter in the universe, atomic, nuclear and high-energy physics, cosmology, and astrophysics.

2. 1950s. Violation of P and C. Conservation of PC

In the middle of the 1950s, the so-called $\theta\tau$ puzzle became the most challenging problem of elementary particle physics. At that time, the decays $K^+ \to 2\pi$ and $K^+ \to 3\pi$ were assigned to two different mesons, θ^+ and τ^+, having opposite P-parities. But the masses and lifetimes of θ^+ and τ^+ were suspiciously close. Therefore, Lee and Yang put forward the idea of parity degeneracy [1].

However, at the Rochester conference in April of 1956, Feynman, referring to Block, asked the crucial question: could it be that parity is not conserved?

Here are a few excerpts from the proceedings [2]:

"J.R. Oppenheimer presiding:

There are the five objects K_{π_3}, K_{π_2}, K_{μ_2}, K_{μ_3}, K_{e_3}. They have equal, or nearly equal, masses and identical, or apparently identical, lifetimes. One tries to discover whether in fact one is dealing with five, four, three, two, or one particle...."

"Yang's introductory talk followed:

... the situation is that Dalitz's argument strongly suggests that it is not likely that $K^+_{\pi_3}\,(\equiv \tau^+)$ and $K^+_{\pi_2}\,(\equiv \theta^+)$ are the same particles".

"Dalitz discussed the $\tau\theta$ problem ... 600 events ... when plotted on the 'Dalitz diagram,' give a remarkably uniform distribution.... This would point to a τ-meson of spin-parity 0^-...".

"...Feynman brought up Block's question:

Could it be that the θ and τ are different parity states of the same particle which has no definite parity, i.e. that parity is not conserved...?"

"Yang stated that he and Lee looked into this matter without arriving at any definite conclusions."

Feynman presumably meant a special mechanism of parity violation through the mixing of degenerate scalar and pseudoscalar mesons.

It is interesting that neither Dalitz nor Michel, who also participated in the discussion, mentioned the possibility of parity violation.

A few months later, Lee and Yang suggested that parity is not conserved in weak decays and proposed experiments to search for pseudoscalar correlations of spin and momentum **sp** [3]. (Their famous paper was received by *Physical Review* on June 22, circulated as a preprint, and appeared in the

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journal on October 1, 1956.) At the end of this paper, in order to save the left – right symmetry in a more general sense, the existence of hypothetical right-handed protons, p_R, was considered, although the term 'mirror particles' was not used and p_R and p_L were assumed to interact "with the same electromagnetic field and perhaps the same pion field."

Much later I learned that already in 1952 Michel [4] considered parity-violating interactions and pseudoscalar correlations between momenta of several particles in multiparticle processes. Wick, Wightman, and Wigner considered pseudoscalar amplitudes [5]. Purcell and Ramsey suggested testing parity conservation experimentally by measuring the electric dipole moment of the neutron [6]. However, they did not realize (as Landau did subsequently) that the electric dipole moment violates the time-reversal invariance as well. Berestetsky and Pomeranchuk published a note [7] on the beta-decay of the neutron, in which they mentioned a remark by Landau that actually ten four-fermion couplings exist "if pseudo-spinors are used in addition to spinors."

As is well known, the experiments proposed by Lee and Yang were performed half a year later and found large left – right asymmetries in the β-decay of ^{60}Co [8] and in $\pi \to \mu \to e$ decays [9, 10].

Before the results of these experiments were published, Ioffe and Rudik had submitted a short paper to *ZhETF* in which they argued that the existence of a short-lived C-even K_1^0-meson and long-lived C-odd K_2^0-meson proved that C-parity was conserved and hence violation of P-parity would mean (due to the CPT theorem) violation of T-parity (time reversal invariance). This led them to the conclusion that P-odd asymmetries are impossible because they are T-even.

I vividly recall how ITEP theorists discussed these arguments with Landau after one of the traditional ITEP seminars in November 1956. (At that time, the name ITEP did not exist; the institute was called TTL, Thermo-Technical Laboratory.) The discussion took place in the room no. 9, where at that time young theorists worked and where my desk was.

At that time, Landau considered the P-parity violation impossible because space is mirror symmetric. This is analogous to the conservation of momentum and angular momentum, because space is homogeneous and isotropic. Of course, the analogy is not complete, because shifts and rotations are continuous, whereas reflections are discrete.

Half a year earlier, the Lebedev Institute hosted the first Moscow conference on elementary particles in which American physicists participated [11, 12]. I recall that Landau laughed sarcastically at Gell-Mann (the youngest of the Americans at the conference, but already very famous), when the latter, during his seminar at the Institute of Physical Problems, mentioned that parity violation could be one of the solutions to the θτ problem.[1]

At about the same time, Landau reacted similarly to an unpublished note by Shapiro in which a Wu-type experiment was suggested. I learned about it three years later, when Shapiro moved from Moscow State University to ITEP and showed me his unpublished note. (Later, Shapiro gave this note to the director of ITEP Alikhanov, and it was lost. There was no copying machine at ITEP.) I remember that there was an incorrect statement in this note: the value of energy is different in left- and right-handed coordinates if P is violated.[2]

But let me return to the discussion in room 9. During the discussion, I pointed out that short- and long-lived kaons might exist not due to the C-invariance, as had been proposed by Gell-Mann and Pais a year before [16], but due to the (albeit approximate) T-invariance, and hence CP-invariance. In that case, **sp** asymmetries and the decay $K_2^0 \to 3\pi^0$ would be allowed.

As a consequence of this discussion, Ioffe and Rudik decided to insert my comments into their paper and urged me to become a coauthor of an essential revision of their paper.[3] At first I refused, but conceded after Ioffe literally went down on one knee in front of me. (This took place in the same room no. 9.) Our article [18] was noticed by Yang and Lee, who, with Oehme [19], independently but later came to the same conclusions (see references to [18] in their Nobel lectures [20, 21]).

Another consequence of the discussion was that Landau abruptly changed his attitude to parity nonconservation and put forward the idea of strict CP-conservation [22] (see also [23]). At the end of this paper, he wrote: "I would like to express my deep appreciation to L Okun, B Ioffe and A Rudik for discussions from which the idea of this paper emerged." According to his idea, a mirror-reflected process cannot exist in Nature and becomes physical only after changing particles into corresponding antiparticles.[4]

An excellent example of CP-conjugated particles was presented by Landau [25] in his theory of massless longitudinally polarized neutrinos: the spin of ν is oriented opposite to its momentum, while the spin of $\bar{\nu}$ is oriented along its momentum; in other words, ν is left-handed and $\bar{\nu}$ is right-handed. In *JETP*, paper [25] immediately followed [22]. Both papers [22, 25] were later published as a single paper in English [26]. Longitudinal neutrinos were independently considered by Salam [27] and by Lee and Yang [28]. The longitudinal neutrinos lighted up the road to the theory of the universal weak $V-A$ interaction [29, 30]. According to this theory, in the relativistic limit $(v/c \to 1)$, all elementary fermions become left-handed in interactions of weak charged currents and their antiparticles become right-handed. Only a few years ago the discovery of neutrino oscillations made it clear that neutrinos are not massless and hence the theory of longitudinal neutrinos is valid only approximately, although in many cases with very high accuracy.

It is worth mentioning the idea of a possible existence of baryonic photons coupled to the baryonic charge [31]. This article became an inspiration for the further search for leptonic photons, paraphotons, and mirror photons (see Sections 3, 5, and 6).

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[1] Gell-Mann repeated his talk twice: at the Institute for Physical Problems and at the Lebedev Institute, in Tamm's office. I was carefully taking notes at both of them. He stopped for a moment and asked me with a smile: "What happens if you find at home that the two records contradict each other?" In the 1980s, Telegdi published very interesting reports on the history of parity violation [13, 14]. In Ref. [14], he wrote: "Murray Gell-Mann emphasized to me ... that I.S. Shapiro most strenuously objected to the parity violation idea when M.G.M. presented the latter in 1956 in the Landau seminar as one of the possible solutions to the τ – θ puzzle." As I have already mentioned, I remember the objections by Landau, but I do not recall that they were also raised by Shapiro at the same seminar. (See author's note to the English proofs, p. 384.)

[2] Further exposition of this statement is contained in [15].

[3] The scheme in which P and T are violated but C is conserved, was discussed at length in [17] even after it was proven false by experiment.

[4] See also [24].

3. 1960s. CP-violation

I liked the idea of strict CP-conservation very much. But on the other hand, I could not understand why the coefficients in the Lagrangian could not be complex. Thus, in the lectures at ITEP [32], weak interactions of hadrons were described based on the composite model of hadrons involving the CP-conservation assumption. In lectures in Dubna [33] and in book [34], I insisted that experimental tests of CP-invariance were one of the highest priorities. A group of Dubna experimentalists led by Okonov searched for CP-forbidden decays $K_2^0 \to \pi^+\pi^-$ and established the upper bound for their branching ratio as approximately 2×10^{-3} (they did not find two-body decays among 600 three-body decays) [35]. Unfortunately, they were stopped at this stage by their lab director. The group was unlucky: two years later, several dozens two-body decays with the branching ratio almost reached in [35] were discovered by the Princeton group [36].

The discovery of the $K_2 \to 2\pi$ decay by Christenson et al. [36] put an end to Landau's idea of strict CP-conservation, according to which antiparticles look exactly like mirror images of particles. To avoid this conclusion, Nishijima and Saffouri [37] put forward the hypothesis of a 'shadow universe' to explain the two-pion decays without CP-violation. According to [37], the decays to two pions observed in [36] were decays not of CP-odd K_2^0 but of a new hypothetical long-lived CP-even 'shadow' K_1^0-meson through its transition into an ordinary K_1^0. But it was soon shown in [38] that this mechanism contradicts the results of neutrino experiments, because shadow K_1^0-mesons would penetrate through the shielding and decay into two pions in the neutrino detector, while such events were not observed.

In the next paper, Kobzarev, Okun, and Pomeranchuk [39] postulated CPA-symmetry (A from Alice) and the existence of hypothetical mirror particles and of a mirror world. [The modern terminology, in which mirror matter refers only to the duplication of all our particles (not some of them) was *in statu nascendi*, and therefore the 'mirror world' and 'mirror particles' were used in [39] practically as synonyms. It is noteworthy that the Standard Model did not exist at that time.] According to [39], mirror particles cannot participate in ordinary strong and electromagnetic interactions with ordinary particles. In this respect, they are radically different from the right-handed protons considered by Lee and Yang [3]. The hidden mirror sector must have its own strong and electromagnetic interactions. This means that mirror particles, like ordinary ones, must form mirror atoms, molecules, and, under favorable conditions, invisible mirror stars, planets, and even mirror life. Moreover, this invisible mirror world can coexist with our world in the same space. [5]

I recall a weekend hike with Igor Kobzarev in a forest near Moscow, from Firsanovka station for Leningrad-bound trains to Nakhabino station for Riga-bound trains, when I suddenly 'saw' an invisible train crossing a clearing on invisible rails, invisible and inaudible. It was argued in our paper [39] that such a situation is impossible. A mirror train needs a mirror globe, but a mirror globe would gravitationally perturb the trajectory of our globe. Gravitational coupling between two worlds seemed indispensable because in the absence of any interaction with our matter, the mirror matter was doomed to become purely fictitious. In addition to graviton exchanges, neutrino exchanges were also allowed in [39], although we did not give any specific discussion of how this could be made consistent with the $V-A$ theory of weak interactions. The coupling of two worlds via neutral kaons was considered in [43].

Mirror particles were discussed at the Fourth European Conference on Elementary Particles (September 1967) [44] and at the Moscow conference on CP-violation (January 1968) (see [45]).

Perhaps it is worth mentioning a paper on muonic photons [46], although it had no direct relation to mirror matter. It considered an additional hypothetical photon and transitions between it and the ordinary photon through a muonic loop. This gives the effective coupling $\epsilon F_{\alpha\beta} F'_{\alpha\beta}$, where F is our field and F' is the new one, while ϵ is a dimensionless constant. Because of this coupling, which is presently called 'kinetic mixing,' the muonic neutrino acquires a tiny electric charge ϵe (see also [66, 86 – 89, 147 – 153, 231 – 236]).

In [47], the gravitational dipole moment of a proton was examined and it was shown to be forbidden in the framework of the general theory of relativity. The gravitational interaction of so-called sterile neutrino was considered in [48].

As is well known, in the mainstream of particle physics, quarks and electroweak theory with spontaneous symmetry breaking were suggested in the 1960s. An important article by Sakharov [49] was published, linking CP-violation with the baryonic asymmetry of the universe and, ultimately, with our existence.

4. 1970s. 'Minimum.' Exotic vacua

In the 1970s, charm, beauty, and the τ-lepton were discovered and QCD was formulated, but there was a minimum of articles on mirror particles. I am aware of only one such paper, by Pavšič [50]. A relation between mirror symmetry and the structure of a particle was attempted in it: the author claimed that mirror nucleons are unconditionally necessary because the baryons are composite, while mirror leptons are necessary only if leptons also have an internal structure. This differs from the standard concept of mirror matter. In 2001, Pavšič posted his paper [50] in an electronic archive with a note: "An early proposal of 'Mirror Matter' published in 1974" [51].

Also in the 1970s, the spontaneous breaking of gauge symmetries was brought to the cosmological model of the hot universe [52 – 54] and the first articles were published on spontaneous violation of the CP-symmetry [55], on the domain structure of the vacuum [56, 57], and on the metastable vacuum [58]. According to [56, 57], vacuum domains are a consequence of spontaneous violation of the CP invariance. They were then to appear during cooling of the universe after the big bang. Thus, space itself could be not mirror symmetric (recall Landau's arguments). The metastable vacuum was dubbed the false vacuum three years later (see Refs [59 – 61]).

5. 1980s. Revival

A revival of interest in mirror particles occurred in the 1980s. In papers [62 – 70], various aspects of the hidden sector of particles and interactions were considered. The existence of new long-range forces and of new x and y particles was suggested in [62]. According to [62], y-particles have no

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[5] We did not know of the pioneering articles on dark matter by Oort [40] and Zwicky [41, 42].

direct interactions with the ordinary ones, while x-particles serve as connectors: they are coupled to both ordinary and y-particles. In Refs [63, 64], gluon-like θ-bosons with a large confinement radius were introduced; they could form unbreakable strings with lengths measured in kilometers. The role of θ-bosons in the early universe was discussed in [65]. In Refs [66], mirror hadrons and neutral meson connectors between the ordinary and the mirror worlds were discussed. The existence of paraphotons was suggested in [67]. Their mixing could lead to oscillations of the ordinary photons, discussed in [67]. Tiny charges of particles that are usually considered neutral (atoms and neutrinos) were analyzed in [68]. A review of hypothetical phenomena was presented in the rapporteur talk "Beyond the Standard Model" [69]. Among other subjects, photon oscillations and left – right symmetric models were discussed there, but no mirror particles were considered.

In 1986, Ellis visited ITEP; together with Voloshin, we wrote review [70], whose significant part was dedicated to mirror particles. At the last moment, seeing the review as too speculative, I decided not to submit it to the Soviet review journal *Uspekhi Fiz. Nauk*, and it was published only as an ITEP preprint [70].

Voloshin continued the quest for mirror particles. He induced the ARGUS (A Russian – German – United States – Swedish) collaboration at DESY to search for decays $\Upsilon(2S) \to \pi^+\pi^-\Upsilon(1S)$, in which $\Upsilon(1S)$ due to transitions to its mirror counterpart decays into 'nothing.' The upper bound for the branching ratio of this invisible channel was established: $\mathrm{BR} \leqslant 2.3\%$ at 90% CL [71, 72]. The search for invisible decay products of the ϕ-meson was carried out in [73].

An experimental group at ITEP measured the upper end of the electron spectrum in tritium β-decay and announced that the mass of the electron neutrino is 30 eV (this result was not confirmed later on). This prompted Zeldovich and Khlopov to publish their review [74]. Alongside other scenarios, they considered the possibility of the neutrino mass occurring due to transitions between our left-handed neutrino and the right-handed mirror neutrino, serving as a bridge to the mirror world.

A model in which connectors between the two worlds are the so-called hybrids (particles with electroweak quantum numbers of ordinary quarks, and QCD quantum numbers of mirror quarks and their mirror counterparts) was considered in [75]. Bound states with fractional charges — fractons — occur in this model.

Schwarz and Tyupkin [76] suggested the unification of mirror and ordinary particles using the SO(20) group. In this model, mirror cosmic strings appeared. After circling such a string, an ordinary particle is transformed into a mirror particle and vice versa (see also [77, 78]).

Further cosmological and astrophysical manifestations of mirror particles were discussed in [79 – 85]. In particular, Alice strings were considered in [79, 82].

Glashow and collaborators became interested in the mirror universe and photon oscillations [86, 87, 90]. In Ref. [87], he suggested explaining the experimental anomaly in orthopositronium decays, observed at that time, by transitions between orthopositronium and mirror orthopositronium. (See [105, 148, 150] for the later development of this suggestion)

Tiny ordinary electric charges of mirror particles, which otherwise have no ordinary charge but have a mirror electric charge, appear due to the mixing of ordinary and mirror photons [88, 89] (see also [240]).

6. 1991 – 2006. 'Maximum.' From cosmology and astrophysics to LHC

A flood of mirror particles articles occurred after 1990. The Australian physicist Foot became a great enthusiast of mirror particles and published dozens of articles on this subject. One can appreciate the range of his interests by looking at the titles of references [91 – 132] and his book [133]. In Ref. [91], a mirror-symmetric version of the standard gauge model was considered, in particular, the mixing interaction of ordinary and mirror Higgs bosons was analyzed. We note that this renormalizable model forbids strong transitions of three quarks into three mirror quarks, as well as of two gluons into two mirror gluons, because such transitions are nonrenormalizable. Therefore, an experimental discovery of the transition of a neutron into the mirror neutron, $\mathrm{n} \leftrightarrow \mathrm{n}'$ or $\Upsilon \leftrightarrow \Upsilon'$ would disprove this theoretical model.

The fantastic new idea of grains of mirror matter embedded in ordinary matter due to the interaction caused by the mixing of ordinary and mirror photons deserves mention [114, 118, 121]. Many of Foot's coauthors — Volkas, Ignatiev, Mitra, Gninenko, Silagadze — also published their own papers on mirror particles [134 – 159] (see also [151]). A few of these papers were also devoted to mirror grains [145, 147, 156 – 159].

An impressive contribution to the field of mirror particles was made by Berezhiani, who published over 15 papers together with his coauthors [160 – 176] (see also [177 – 182]).

Most of the papers cited in this section are based on strict mirror symmetry. They ascribe the observed macroscopic disparity between mirror and ordinary particles to the inflationary stage of the universe (see [143, 166]).

Mohapatra published about 15 papers (many of them with coauthors) on various aspects of astrophysics in the framework of broken mirror symmetry [183 – 196].

The search [197 – 201] for gravitational microlenses produced by separate stars in the halos of galaxies — the so-called MACHOs (MAssive Compact Halo Objects) — has led to the discovery of an excess of MACHOs in the direction of the Large Magellanic Cloud [200, 201]. Even before this discovery, theorists had indicated [154, 162, 202] that some of the MACHOs could be mirror stars. This interpretation was developed further in [203, 204]. Although the discovery of MACHOs has been questioned [205, 206] (see the discussion in [207, 208]), many astrophysicists believe that the observed stellar dark matter cannot consist of ordinary baryons [209, 210].

Since the publication of papers by Oort [40] and Zwicky [41, 42], two alternative explanations for the anomalously high velocities of stars and galaxies (the so-called 'virial paradox') have existed: (1) invisible dark matter, (2) anomalously strong gravity at large distances. Recent observations [211, 212] of colliding clusters of galaxies seem to settle the ambiguity in favor of dark matter. Dark matter, which manifests itself through the effect of gravitational lensing, is segregated from the luminous parts of clusters in such collisions. If this dark matter is mirror matter, then the mirror stars in it must be more prominent compared to mirror gas than ordinary stars compared to ordinary gas (Blinnikov and Silagadze, private communications).

The correlation of gamma-ray bursts with the distribution of dark matter in galaxies might suggest that these bursts are produced by explosions of mirror stars, accompanied by emission of mirror neutrinos [213 – 215] or of mirror axions [165, 167, 181] (see also [182]).

Supernova constraints on sterile neutrino production are given in [216]. Cosmic mirror strings as sources of cosmic rays of ultra-high energies were considered in [217] (see also [218 – 220]). Various aspects of mirror astrophysics were discussed in articles [221, 222] and books [223, 224]. New gauge symmetry of the type of weak SU(2) was proposed in [225] and critically analyzed in [226 – 230]. Leptonic (muonic) photons were discussed in the 1990s in [231 – 236]. Upper bounds for invisible decays of B^0 mesons and η and η' mesons were established in [237, 238]. The upper bound for the branching ratio of invisible decays of the $\Upsilon(1S)$ meson $B < 2.5 \times 10^{-3}$ was established by the Belle collaboration [239].

Various 'mirror matters' were considered in [240 – 246]; proposals for dark matter search were formulated in [247 – 249].

In 2004, a physical start was made of special ring accumulator of positrons LEPTA (Low-energy particle toroidal accumulator), one of the goals being the search for mirror orthopositronium [250 – 255].

A very interesting discussion of invisible decay channels of the Higgs bosons that can be generated at the Large Hadron Collider at CERN can be found in [141, 256 – 258] (see also [259]). The invisible decays occur because of the mixing of ordinary and mirror Higgs bosons. Higgs bosons may be discovered in the near future.

7. Concluding remarks

We compare mirror symmetry with supersymmetry. The former cannot compete with the latter in the depth of its concepts and mathematics. But it can compete in the breadth and diversity of its phenomenological predictions. Without a doubt, mirror matter is much richer than the dark matter of supersymmetry.

The preliminary version of this review was prepared for a talk at the ITEP Workshop on the Future of Heavy Flavor Physics, July 24 – 25, 2006 (http://www.itep.ru/eng/belle-meeting) and published on June 19 as hep-ph/0606202v1. The final version (v2) was prepared for *Physics – Uspekhi* during the summer of 2006.

As a result, the number of references has doubled. It could have risen even higher. If you google for "mirror particles" (do not forget the quotation marks!), about a thousand links are found. (Typing "mirror world" or "mirror universe" returns about 200,000 links devoted mainly to "Star Trek" television episodes.) A search in Wikipedia is suggested in some of the links. But the Wikipedia articles on mirror matter may be misleading. Instead of Google, it is better to use Google Scholar, where the number of links for 'mirror universe' is about a hundred, while for 'mirror particle' it is a few hundred. The extra articles do not deal with those mirror particles that are the subject of this review. They are 'mirror' in a different sense. For instance, the terms 'mirror families' or 'mirror fermions' refer to hypothetical families of very heavy fermions with reversed isotopic quantum numbers, which are assumed to interact with ordinary photons and gluons.

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Author's note to the English proofs

After the Russian version of this article was published, I received a letter from S S Gershtein containing the following passage concerning footnote 1 at the beginning of the article:

"I remember well what I am describing. Many interesting foreigners came to the 1956 conference. Once during the conference I saw many people following I.E. along the corridor past the FIAN library. I was told that I.E. had invited Gell-Mann in order to hear the latest news from him. G.-M. started speaking about the tau – theta problem and said that Feynman even thought of parity nonconservation as a possibility. I.E. asked: R.P. Feynman? Yes, R.P., replied G.-M. At that point, I.S. Shapiro stood up and started (as we later joked) teaching diamat to G.-M., saying that Nature must have conservation laws. I remember that G.-M. became angry and rather sharply replied that "one has to analyze the phenomena of Nature, and not to impose laws on it.""

[Comments. I.E.: Igor Evgenievich Tamm, FIAN: Lebedev Institute, diamat: dialectical materialism. If one takes this testimony at its face value, one has to conclude that the note was written by I.S. Shapiro after he learned about Feynman's remark.]

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