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Dedicated to Prof. Dumitru Barbu Ion's 70th Anniversary

CHERENKOV EFFECTS

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Abstract. Cherenkov effect is well known in ordinary matter. It is widely studied and applied. The speculations about such effect in the hadronic matter were proposed. Some preliminary experimental indications were found from time to time. However, only recently the observations at RHIC provided more definite and quantitative data. Their interpretation still needs to be more elaborated. This is one of the fields where D.B. Ion contributed intensively.

Key words: Cherenkov gluons, nuclei.

Cherenkov photons are emitted due to the wellknown collective coherent effect. Their origin is the wave radiation by a charge moving with speed v exceeding the phase velocity of light c_w. If z-axis is chosen along the charge propagation, then emission in an infinite medium at rest is directed along the cone with the polar angle θ defined by the condition

$$\cos\theta = \frac{c_w}{v}. \tag{1}$$

For Cherenkov photons $c_w = c/n$ where n is the refractive index. This is the collective effect determined by the presence of the medium. The wave front has a conical shape with an opening angle θ_f with respect to the direction of the charged particle motion given by $\theta_f = \frac{\pi}{2} - \theta$. Photons are emitted perpendicular to the wave front and fill the rings in the plane transverse to the charge direction. Rings of light in Cherenkov detectors are used to measure v if the refractive index n is known. Emission of Cherenkov photons is due to the polarization of atoms induced by a beam of charged particles. It is a consequence of electromagnetic forces acting in the medium. The refractive index of the medium n should exceed 1 for condition $|\cos\theta| < 1$ to be satisfied because

$$\cos\theta = \frac{1}{\beta n}, \tag{2}$$

where β (≈ 1 for relativistic particles) is the ratio of the velocities of the particle and (in-vacuum) light.

Experimentally, it was first observed by Cherenkov in 1934 [1] as famous Cherenkov rings whose radius is determined by Eq. (2). Its theoretical explanation was given by Tamm and Frank in 1937 [2] (see also [3]). In 1958 they got the Nobel Prize for this discovery.

Are there analogues of these effects for strong interactions?

Many indications in favor of it exist but further studies are necessary.

In old days before the quark model and QCD appeared, nucleons and pions were considered as elementary entities with pions being the quanta of radiation. Namely in this way the ideas about nuclear Cherenkov effect were first promoted [4–12]. No discussion of nuclear refractive index analogous to its electromagnetic counterpart was attempted at that time. It was *ad hoc* assumed that the necessary condition can be somehow satisfied. The purpose was to explain main mechanism of particle production by this effect. It has failed. Moreover, the pseudoscalar nature of pions did not correspond to vector photons and could not provide the proper rings.

Only with appearence of quantum chromodynamics it became possible to find the corresponding counterparts to electrons and photons with quarks and gluons acting as partons in high energy interactions. Almost massless quarks with spin 1/2 and massless vector gluons recall electrons and photons but color forces between them with self-interaction of gluons lead to such new properties as asymptotic freedom and confinement.

The intuitive picture which comes to mind is to consider the impinging partner in *hh*, *hA*, *AA* collisions as a bunch of partons passing through a hadronic medium. A target hadron or a nucleus can be treated as a nuclear slab with a definite *nuclear* refractive index. The analogue to Cherenkov photons would be Cherenkov gluons emitted by a parton entering this hadronic medium. The notion of Cherenkov gluons was proposed long time ago [16, 17] and experimental indications in favor of this effect appearing from time to time are quite extensive [18–33]. For more recent theoretical papers see [34–39]. New experimental data will be discussed in more detail below.

There exists the general relation (see, *e.g.*, [40]) between the refractive index and the forward scattering amplitude $F(E, 0^o)$:

$$\Delta n = \mathrm{Re}n - 1 = \frac{8\pi N_s \mathrm{Re}F(E, 0^o)}{E^2}. \tag{3}$$

Here E is the photon (gluon) energy, N_s is the density of the scattering centers in the medium. We shall use this relation as a starting point for all results on Cherenkov gluons. The necessary condition for Cherenkov radiation is

$$\Delta n > 0 \quad \text{or} \quad \mathrm{Re}F(E, 0^o) > 0. \tag{4}$$

If these inequalities are satisfied, Cherenkov photons (gluons) are emitted along the cone defined by Eq. (2).

The forward scattering amplitude for gluons is infinite. To define the refractive index in the absence of the theory of nuclear media (for a simplified approach see [36]) I prefer to rely on our knowledge about hadronic reactions translated in partonic language to develop phenomenological models.

There are two common features for all hadron-hadron collisions. First, the prominent resonances are formed at rather low energies. They are described by the Breit-Wigner amplitudes which have the positive real part in their low-mass wings. In hadronic medium, there should be some modes (quarks, gluons or their preconfined bound states, condensates, blobs of hot matter...?) which can get excited by the gluon field of the impinging parton and radiate coherently if $n > 1$. The necessary condition (4) for the Cherenkov effect is satisfied for those gluons colliding with these internal modes whose energies are suitable for production of the states within these wings. Thus, the resonance amplitude is chosen for $F(E, 0^o)$ at comparatively low energies.

Second, it follows both from experiment and from dispersion relations that the real parts of hadronic amplitudes (and, consequently, Δn) become positive at very high energies as well. They are usually negative at intermediate energies. Their common feature is the rather high energy threshold above which the real parts of amplitudes become positive for all processes studied.

One can expect that these general features also hold for gluons as carriers of strong interaction forces. Then the gluonic Cherenkov effects can be observable in the two (low and high energy) regions.

Summarizing, the scenario, we have in mind, is as follows. Any parton, either belonging to a colliding nucleus or already scattered in the medium, can emit a gluon which traverses the nuclear medium. On its way, the gluon collides with some internal modes. Therefore it affects the medium as an "effective" wave which accounts also for the waves emitted by other scattering centers. Beside incoherent scattering, there are processes which can be described as the refraction of the initial wave along the path of the coherent wave (see, *e.g.*, [40]). The Cherenkov effect is the induced coherent radiation by a set of scattering centers placed on the way of propagation of the gluon. That is why the forward scattering amplitude plays such a crucial role in formation of the refractive index. At low energies its excess over 1 is related to the resonance peaks as dictated by the Breit-Wigner shapes of the amplitudes. In experiment, usual resonances are formed during the color neutralization process. However, only those gluons whose energies are within the left-wing resonance region of $n > 1$ give rise also to the collective Cherenkov effect proportional to Δn. At high energies these excitations should lead to Cherenkov jets. In both energy regions the coherent Cherenkov emission proceeds at angles determined by Eq. (2) where n can depend on energy.

Let us first discuss the comparatively low-energy contributions to Cherenkov effect due to resonances. In classical electrodynamics, it is the dipole excitation and polarization of atoms by the electromagnetic field of charged beams moving in the medium which results in the Breit-Wigner shape of the amplitude $F(E, 0^o)$. The real part of the forward scattering amplitude is positive in the low-mass wing of any Breit-Wigner resonance. Therefore, atoms behaving as oscillators provide the indices of refraction larger than 1 within their low-energy wings (see, *e.g.*, Fig. 31-5 in vol. 1 of Feynman lectures [41]). This is responsible for Cherenkov effect.

There are numerous resonances created during hadronic collisions. The hadronic Cherenkov effect can be pronounced only in the special narrow energy bands of corresponding wings of resonances. The attempts to define these bands were done in [12–15] without referring to the parton structure of particles.

Recent RHIC experiments [42, 43] have shown the two-bump shape of the azimuthal angle distribution (now with *z*-axis chosen along the collision axis) of particles with rather low transverse momenta near the away-side jets in central heavy-ion collisions. There is no such structure in pp-collisions. The difference has been attributed to “in-medium” effects. These features are clearly seen in Fig. 1 (the upper part for pp, lower one for Au-Au).

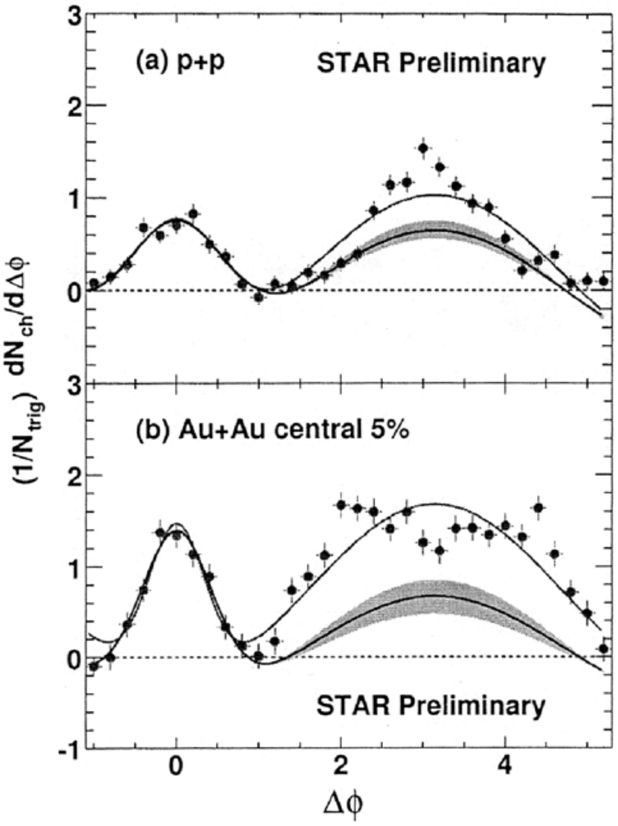

Fig. 1 – The Δϕ-distribution of particles produced by trigger and companion jets at RHIC [42] shows two peaks in *pp* and three peaks in AuAu-collisions.

One easily notices the remarkable difference between particle distributions in the direction opposite to the trigger jet maximum positioned at $\Delta\phi = 0$. Both trigger and companion high-p_T jets have been created in central Au-Au collisions at $\sqrt{s} = 200$ GeV at the periphery of a nucleus. They move in opposite directions if produced in head-on collisions of partons with equal energies. The trigger parton immediately escapes the nucleus and, therefore, is detected as the "in-vacuum" jet. The companion (away-side) jet traverses the whole nucleus before it comes out. It is modified by "in-medium" effects.

These features can be interpreted in the following way. Beside normal jet fragmentation, its initiating parton can emit Cherenkov gluons which produce a ring of hadrons in the plane perpendicular to the away-side jet axis. Ring's plane is perpendicular both to the trigger momentum and to the collision plane in which momenta of the colliding particles and the trigger are placed. The two-bump structure results due to the one-dimensional projection of the ring on the azimuthal plane. The analogous two-bump structure was shown by Cherenkov in his earlier papers [1] (see also Fig. 1.8 in [44]). It is clear that projection of a ring on its diameter in the azimuthal plane is not the best one to reveal its properties. The shapes of two- and three-particle correlations studied at RHIC [45] are its less direct indications although they have the ring-like structure themselves.

From the distance between the peaks defined in angular ($\theta = D$ in PHENIX notation) variables in Fig. 1 one gets according to Eq. (2) the nuclear refractive index. Its value is found to be quite large $n = 3$ compared to usual electromagnetic values for gases close to 1. If interpreted in terms of the Breit-Wigner resonances, as explained below, it results in the large density of partons in the created quark-gluon system with about 20 partons within the volume of a single nucleon [37]. It agrees with its estimates from v_2 and hydrodynamics. This value is also related to the energy loss of gluons estimated in [37] as $dE/dx \approx 1$ GeV/fm. The height of the peaks determines the width of the ring which in its turn defines the free path length of Cherenkov gluons [37] which happens to be long enough $R_f \sim 7$ fm. Thus they hadronize, probably, close to the surface of the initial volume.

These estimates are obtained [37] as follows. If the hadronization of gluons is a soft process then the gluon energy closely corresponds to the energy of the produced resonance. It implies that in this particular experiment Cherenkov gluons can be emitted only with energies within the lower wings of hadronic resonances. Their amplitude is of the Breit-Wigner shape. Using the BW-amplitudes one can get above estimates.

Another specific feature of low-energy Cherenkov effect is that it leads to the somewhat unusual particle content within the ring. Apart from the ordinary Breit-Wigner shape of the cross section for resonance production, the dilepton mass spectrum would acquire the additional term proportional to Δn (that is typical for Cherenkov effects) at masses below the resonance peak [39]. Therefore its excess (*e.g.*, near the ρ-meson[1]) can be described as shown in Fig. 2.

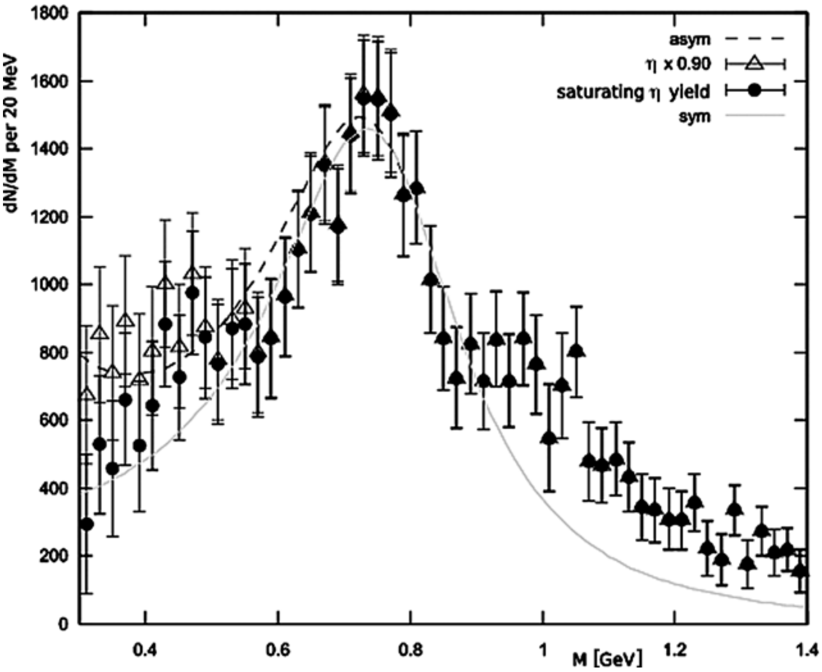

Fig. 2 – Excess dilepton mass spectrum in semi-central In-In collisions at 158 AGeV (dots are NA60 data) compared to the in-medium ρ-meson peak with additional Cherenkov effect (the dashed line).

The prediction of asymmetrical in-medium widening of **any** resonance at its low-mass side due to Cherenkov gluons is universal. This universality is definitely supported by experiment. Very clear signals of the excess on the low-mass sides of ρ, ω and ϕ mesons have been seen in KEK [51,52]. This effect for ω-meson is also studied by CBELSA/TAPS-collaborartion [54]. Slight asymmetry of ϕ-meson near 0.9–1 GeV is noticeable in the Fig. 2 shown above but the error bars are large there. We did not try to fit it just to deal with as small number of parameters as possible. There are some indications from PHENIX at RHIC (see Fig. 6 in [53]) on this effect for *J*/ψ-meson. It is astonishing that this effect has been observed in a wide interval of initial energies. The relative share of Cherenkov effects, described by the parameter *w* above, can depend on energy.

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[1] Only ρ-mesons are considered here because the most precise experimental data are available [46] about them. To include other mesons, one should evaluate the corresponding sum of similar expressions. Other experimental data can be found in [47–55].

At much higher energies one can expect better alignement of the momenta of initial partons. This would favor the direct observation of emitted by them rings in non-trigger experiments. The first cosmic ray event [18] with ring structure gives some hope that at LHC energies the initial partons are really more aligned and this effect can be found. Two rings more densely populated by particles than their surroundings were noticed. It is demonstrated in Fig. 3 where the number of produced particles is plotted as a function of the distance from the collision point. It clearly shows two maxima. This event has been registered in the detector with nuclear and X-ray emulsions during the balloon flight at the altitude about 30 km. It was initiated by a primary with energy about 10^{16} eV close to LHC energies.

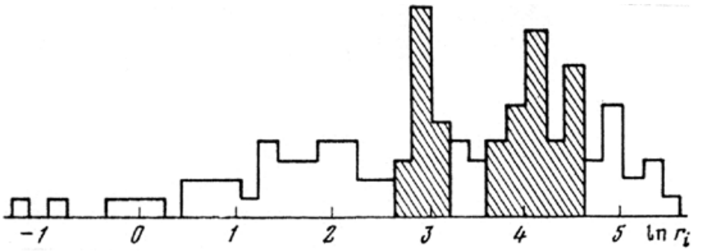

Fig. 3 – The dependence of the number of produced hadrons on the distance from the collision point in the cosmic ray event.

The ring-like structure can be revealed by the event-by-event wavelet analysis [56, 28].

One of the most intriguing problems is that the RHIC and cosmic ray data were fitted with very different values of the refractive index equal to 3 and close to 1, correspondingly. This could be interpreted as due to the difference in values of x (the parton share of energy) and Q^2 (the transverse momenta). It is well known that the region of large x and Q^2 corresponds to the dilute partonic system. At low x and Q^2 the density of partons is much higher.

At RHIC one deals with rather low x and Q^2. One would expect the large density of partons in this region and, therefore, high n. It is interesting to note that the two-bump structure disappears in RHIC data at higher p_t where the parton density must get lower. It corresponds to smaller n and θ, *i.e.* bumps merge in the main away-side peak.

In the cosmic ray event one observes effect due to leading partons with large x. Also, the experimentalists pointed out that the transverse momenta in this event are quite large. In this region one would expect for low parton density and small n.

Thus the same medium can be probably seen as a liquid or a gas depending on the parton energy and transferred momenta. This statement can be experimentally verified by using triggers positioned at different angles to the collision axis and considering different transverse momenta. In that way, the hadronic Cherenkov effect can be used as a tool to scan $(1/x, Q^2)$-plane and plot on it the parton densities corresponding to its different regions.

Thus both theoretical and experimental studies are necessary to clarify the problems of hadronic Cherenkov radiation and get more knowledge on properties of nuclear media.

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REFERENCES

1. P. A. Cherenkov, Doklady AN SSSR **2**, 451 (1934); **3**, 413 (1936).
2. I. E. Tamm, I. M. Frank, Doklady AN SSSR **14**, 109 (1937).
3. I. E. Tamm, J. Phys. USSR **1**, 439 (1939).
4. W. Wada, Phys. Rev. **75**, 981 (1949).
5. D. D. Ivanenko, V. A. Gurgenidze, Doklady AN SSSR **67**, 997 (1949).
6. D. I. Blokhintsev, V. L. Indenbom, ZhETF **20**, 1123 (1950).
7. G. Yekutieli, Nuovo Cim. **13**, 446, 1306 (1959).
8. W. Czyz, T. Ericson, S. L. Glashow, Nucl. Phys. **13**, 516 (1959).
9. W. Czyz, S. L. Glashow, Nucl. Phys. **20**, 309 (1960).
10. P. Smrz, Nucl. Phys. **35**, 165 (1962).
11. D. B. Ion, F. G. Nichitiu, Nucl. Phys. **B29**, 547 (1971).
12. D. F. Zaretskii, V. V. Lomonosov, Sov. J. Nucl. Phys. **26**, 639 (1977).
13. D. B. Ion, W. Stocker, Phys. Lett. **B273**, 20 (1991); **B346**, 172 (1995); Phys. Rev. **C52** 3332 (1995).
14. D. B. Ion, E. K. Sarkisyan, Rom. J. Phys. **49**, 25 (2004); hep-ph/0302114.
15. D. B. Ion, *Selected papers on mesonic and gamma generalized Cherenkov-like effects in nuclear and hadronic media*, 2002.
16. I. M. Dremin, Pisma v ZhETF **30**, 152 (1979); JETP Lett. **30**, 140 (1979).
17. I. M. Dremin, Yad. Fiz. **33**, 1357 (1981); Sov. J. Nucl. Phys. **33**, 726 (1981).
18. A. V. Apanasenko, N. A. Dobrotin, I. M. Dremin, K. A. Kotelnikov, Pisma v ZhETF **30**, 157 (1979); JETP Lett. **30**, 145 (1979).
19. K. I. Alexeeva *et al.*, Izv. AN SSSR **26**, 572 (1962); J. Phys. Soc. Japan **17**, A-II (1962).
20. N. V. Maslennikova *et al.*, Izv. AN SSSR **36**, 1696 (1972).
21. N. Arata, Nuovo Cim. **43A**, 455 (1978).
22. E. A. Marutyan *et al.*, Yad. Fiz. **29**, 1566 (1979).
23. M. Adamus *et al.* (NA22), Phys. Lett. **B185**, 200 (1987).
24. I. M. Dremin *et al.*, Mod. Phys. Lett. **A5**, 1743 (1990); Yad. Fiz. **52**, 842 (1990); Sov. J. Nucl. Phys. **52**, 840 (1990).
25. M. I. Adamovich *et al.*, J. Phys. **C21**, 2035 (1993).
26. A. El-Naghy *et al.*, Phys. Lett. **B299**, 370 (1993).
27. N. M. Agababyan *et al.* (NA22), Phys. Lett. **B389**, 397 (1996).
28. N. M. Astafyeva, I. M. Dremin, K. A. Kotelnikov, Mod. Phys. Lett. **A12**, 1185 (1997).
29. S. Wang *et al.*, Phys. Lett. **B427**, 385 (1998).
30. M. I. Adamovich *et al.*, Eur. Phys. J. **A5**, 429 (1999).
31. G. L. Gogiberidze *et al.*, Phys. Lett. **B430**, 368 (1998), **B471**, 257 (1999); Yad. Fiz. **64**, 147 (2001); Phys. Atom Nucl. **64**, 143 (2001); Nucl Phys. Proc. Suppl. **92**, 75 (2001).

32. I. M. Dremin *et al.*, Phys. Lett. **B499**, 97 (2001).
33. S. Vokal *et al.*, hep-ex/0412017; 0501025.
34. I. M. Dremin, Nucl. Phys. **A767**, 233 (2006).
35. A. Majumder, X. N. Wang, Phys. Rev. **C73**, 051901 (2006).
36. V. Koch, A. Majumder, X. N. Wang, Phys. Rev. Lett. **96**, 172302 (2006).
37. I. M. Dremin, Nucl. Phys. **A785**, 369 (2007).
38. I. M. Dremin, J. Phys. **G34** (2007) N9.
39. I. M. Dremin, V. A. Nechitailo, hep-ph/0704.1081
40. M. Goldberger, K. Watson, *Collision Theory* (John Wiley and Sons Inc., 1964) Ch. 11, sect. 3, sect. 4.
41. R. P. Feynman, R. B. Leighton, M. Sands, *The Feynman Lectures in Physics* (Addison-Wesley PC Inc., 1963) **1**, *31*.
42. J. Adams *et al.*, (STAR), Phys. Rev. Lett. **95**, 152301 (2005).
43. S. S. Adler *et al.*, (PHENIX), Phys. Rev. Lett. **97**, 052301 (2006).
44. J. V. Jelley, *Cherenkov radiation and its applications* (Pergamon Press, 1958), p. 13.
45. J. G. Ulery (STAR), Nucl. Phys. **A783**, 511 (2007);
    C. A. Pruneau (STAR), nucl-ex/0703009; 07030010.
46. R. Arnaldi *et al.*, (NA60), Phys. Rev. Lett. **96**, 162302 (2006);
    S. Damjanovic *et al.*, (NA60), Eur. Phys. J. **C49**, 235 (2007), nucl-ex/0609026 and Nucl. Phys. **A783**, 327 (2007), nucl-ex/0701015.
47. G. Agakichiev *et al.*, (CERES), Phys. Rev. Lett. **C41**, 1272 (1995);
    Phys. Lett. **B422**, 405 (1998); Eur. Phys. J. **C41**, 475 (2005).
48. D. Adamova *et al.*, (CERES), Phys. Rev Lett. **91**, 042301 (2003); **96**, 152301 (2006); nucl-ex/0611022.
49. S. Damjanovic *et al.*, (NA60), Phys. Rev. Lett. **96**, 162302 (2006).
50. D. Trnka *et al.*, Phys. Rev. Lett. **94**, 192303 (2005).
51. M. Naruki *et al.*, (KEK), Phys. Rev. Lett. **96**, 092301 (2006), nucl-ex/0504016.
52. R. Muto *et al.*, (KEK), Phys. Rev. Lett. **98**, 042501 (2007), nucl-ex/0511019.
53. A. Kozlov (PHENIX), nucl-ex/0611025.
54. M. Kotulla (CBELSA/TAPS), nucl-ex/0609012.
55. I. Tserruya, Nucl. Phys. **A774**, 415 (2006).
56. I. M. Dremin, O. V. Ivanov, V. A. Nechitailo, UFN **171**, 465 (2001), Physics-Uspekhi **44**, 447 (2001).