ОБЪЕДИНЕННЫЙ ИНСТИТУТ ЯДЕРНЫХ ИССЛЕДОВАНИЙ,
Лаборатория теоретической физики им. Н.Н. Боголюбова

Совещание по прецизионной физике и фундаментальным физическим константам

Тезисы докладов

Workshop on Precision Physics and Fundamental Physical Constants

Book of Abstracts

Дубна, 1–5 декабря 2014

Организационный комитет

Сопредседатели:

С.Г. Каршенбойм (ГАО РАН), В.И. Коробов (ОИЯИ)

Члены Организационного комитета:

А.В. Малых (ОИЯИ), уч. секретарь
А.Б. Арбузов (ОИЯИ), С.Н. Багаев (ИЛФ СО РАН), Д. Бакалов (ИЯИЯЭ БАН), Д.А. Варшалович (ФТИ РАН), М. Гнатич (P.J. Šafárik University Kŏsice & ОИЯИ), С. Дубничка (IP SAS Братислава), В.Г. Иванов (ГАО РАН), И.Н. Мешков (ОИЯИ), С.Н. Неделько (ОИЯИ), К. Пахуцки (ун-т Варшавы), Р.Н. Фаустов, (ВЦ РАН), Д. Хорват (Wigner Research Centre for Physics, IPNP, Будапешт), И.Б. Хриплович (ИЯФ СО РАН), С.И. Эйдельман (ИЯФ СО РАН)

Совещание по прецизионной физике и фундаментальным физическим константам (Workshop on Precision Physics and Fundamental Physical Constants) проводится Лабораторией теоретической физики им. Н.Н. Боголюбова ОИЯИ совместно с Рабочей группой РНК КОДАТА по фундаментальным физическим константам.

Совещание организуется при поддержке Particle Data Group (PDG).

Совещание проводится при поддержке Российского фонда фундаментальных исследований (грант 14-02-20361-г), фонда некоммерческих программ Дмитрия Зимина "Династия" № ДП-КФ-026/14

————————

The workshop on Precision Physics and Fundamental Physical Constants is jointly organized by the Joint Institute for Nuclear Research and the Russian National CODATA Task Group on fundamental constants.

The workshop is endorsed by the CODATA Task group on fundamental constants and Particle Data Group (PDG)

The workshop is supported in part by the Russian Foundation for Basic Research under grant № 14-02-20361, Dynasty foundation № ДП-КФ-026/14.

Contents

Quantum electrodynamical corrections to the quadratic Zeeman effect

Valentin Agababaev[a,b], Dmitry Glazov[a,b]

[a] *Department of Physics, St. Petersburg State University, Oulianovskaya 1, Petrodvorets, 198504 St. Petersburg, Russia*

[b] *State Scientific Centre "Institute for Theoretical and Experimental Physics" of National Research Centre "Kurchatov Institute", B. Cheremushkinskaya st. 25, 117218 Moscow, Russia*

Simultaneous experimental and theoretical study of the g-factor of light hydrogen-like ions provided the best up-to-date determination of the electron mass [1]. First ppb-precision measurements for lithium-like system has been accomplished recently [2]. Corresponding investigations for heavy hydrogen-like and boron-like ions will lead to independent determination of the fine structure constant [3, 4]. As an important step towards this goal, ARTEMIS experiment presently implemented at GSI aims at high-precision measurement of the Zeeman splitting in boron-like argon for both ground ($2P_{1/2}$) and first excited ($2P_{3/2}$) states. Apart from the g-factors of these states it will be sensitive to the non-linear contributions in magnetic field [5]. In particular, the relative contributions of the second and third order in magnetic field amount to 10^{-4} and 10^{-8}, respectively, at the field of 7 Tesla. The latest theoretical results for the second- and third-order effects in boron-like argon are given in Ref. [6]. In the present contribution the QED corrections to the quadratic Zeeman effect are considered. Simple non-relativistic result is obtained with an effective Hamiltonian [7] employing the anomalous magnetic moment. A part of the corresponding bound-state QED diagrams is calculated.

---

[1] S. Sturm *et al.*, Nature **506**, 467 (2014).

[2] A. Wagner *et al.* Phys. Rev. Lett. **110**, 033003 (2013).

[3] V. M. Shabaev *et al.*, Phys. Rev. Lett. **96**, 253002 (2006).

[4] A. V. Volotka and G. Plunien, Phys. Rev. Lett. **113**, 023002 (2014).

[5] D. von Lindenfels *et al.*, Phys. Rev. A. **87**, 023412 (2013).

[6] D. A. Glazov *et al.*, Phys. Scr. **T156**, 014014 (2013).

[7] R. A. Hegstrom, Phys. Rev. A **7**, 451 (1973).

Continuous wavelet transform for gauge theories

M.V.Altaisky

Space Research Institute RAS, Profsoyuznaya 84/32, Moscow, 117997, Russia

Wavelet transform has been attracting attention as a tool for regularization of gauge theories since the first paper of Federbush [1], where integral representation of the gauge fields by means of wavelet transform was suggested. In present paper we analyze different trends in application of wavelet transform for regularization of gauge theories in continuous formalism [2, 3, 4] and also in simulation on a lattice.

---

[1] P.Federbush, Prog. Theor. Phys. **94** (1995) 1135.

[2] M.V.Altaisky, Phys. Rev. D 81 (2010) 125003.

[3] S. Albeverio and M.V.Altaisky, New Advances in Physics **5** (2011) 1.

[4] M.V.Altaisky and N.E.Kaputkina, Phys. Rev. D **88** (2013) 025015.

Method for production of highly charged ions with polarized nuclei and zero total electron angular momentum

A.A. Bondarevskaya[a], E.A. Mistonova[a], K.N. Lyashchenko[a], O.Yu. Andreev[a], A. Surzhykov[b,c,d], L.N. Labzowsky[a,e], G. Plunien[f], D. Liesen[b,c], F. Bosch[c], Th. Stöhlker[c,d,g]

[a] *Department of Physics, St. Petersburg State University, 198504, St. Petersburg, Petergof, Russia*
[b] *Fakultät für Physik und Astronomie, Ruprecht-Karls-Universität Heidelberg, D-69120, Heidelberg, Germany*
[c] *GSI Helmholzzentrum für Schwerionenforschung, D-64291 Darmstadt, Germany*
[d] *Helmholtz-Institut Jena, D-07743 Jena, Germany*
[e] *Petersburg Nuclear Physics Institute, 188300, St. Petersburg, Gatchina, Russia*
[f] *Institut für Theoretische Physik, Technische Universität Dresden, D-01062, Dresden, Germany*
[g] *Institut für Optik und Quantenelektronik, Friedrich-Schiller-Universität Jena, D-07743 Jena, Germany*

During the last decades, experiments with spin-polarized particles became of primary importance in the low-energy fundamental physics. Except for highly charged ions (HCI), the techniques for polarizing beams of electrons, protons, and muons have been well developed by now. However, during the last years several experiments using just polarized HCI for tests of the fundamental symmetries like the parity non-conservation and for the search of a nuclear and an electron electric dipole moment have been proposed ([1]-[4]).

We present a new method for polarizing the nuclei of He-like heavy ions with zero total electron angular momentum in storage rings for high-energy ions based on capture of polarized electrons by H-like ions. A detailed analysis for $^{151}_{63}$Eu-ions with nuclear spin I = 5/2 predicts a nuclear polarization degree of about 47% already after one passage through a target containing 100% polarized electrons. Almost 50% of the polarized He-like ions are predicted to be in states with zero total electron angular momentum. Such ions were recently considered as most promising candidates in experiments at storage rings for the search for violations of the fundamental symmetries and for a nuclear and an electron electric dipole moment.

———————————

[1] L. N. Labzowsky, A. V. Nefiodov, G. Plunien, G. Soff, R. Marrus, and D. Liesen, Phys. Rev. A **63**, 054105 (2001).

[2] A. Bondarevskaya, A. Prozorov, L. Labzowsky, G. Plunien, D. Liesen, and F. Bosch, Phys. Rep. **507**, 1 (2011).

[3] I. B. Khriplovich, Phys. Lett. B **444**, 98 (1998); Hyperfine Inter. **127**, 365 (2000).

[4] A. Prozorov, L. Labzowsky, D. Liesen, and F. Bosch, Phys. Lett. B **574**, 180 (2003).

Аномальный магнитный момент мюона вне массовой поверхности

А.Б. Арбузов[a,b], Т.В. Копылова[b]

[a] *ЛТФ ОИЯИ, Дубна, 141980 Россия*

[b] *Кафедра высшей математики, Университет Дубна, 141980 Дубна, Россия*

В докладе рассматривается [1] ранее не учтенный вклад в измеряемую величину аномального магнитного момента мюона за счет коллективных взаимодействий мюонов внутри пучка в условиях эксперимента, вызывающих эффективный сход частиц со своей массовой поверхности. Для количественного описания рассматриваемого эффекта используется результат однопетлевых вычислений форм-факторов заряженного фермиона [2], полученный в следующей кинематике: $k^2 = 0$, $p^2 = -m^2$, $(p+k)^2 + m^2 = 2pk = \kappa m^2$, где k — импульс фотона; p и $p+k$ - импульсы мюона, только один из которых находится на массовой поверхности, метрика $(-,+,+,+)$. Малый безразмерный параметр κ описывает степень схода с массовой поверхности, $\kappa < 0$, $|\kappa| \ll 1$. Для аномального магнитного момента в однопетлевом приближении мы получили

$$a_\mu^{(1,\kappa)} = \frac{\alpha}{2\pi}\Big[1 + \Big(\frac{1}{4} + \frac{\ln|\kappa|}{2}\Big)\kappa + \mathcal{O}(\kappa^2)\Big], \tag{1}$$

где ведущий член, $\frac{\alpha}{2\pi}$, воспроизводит результат Ю. Швингера [3]. Имеющуюся на сегодняшний день разницу между экспериментальными данными и теоретическими предсказаниями можно объяснить за счет рассмотренного эффекта, если $\kappa \approx -3.5 \cdot 10^{-7}$, что соответствует среднему сходу с массовой поверхности порядка $m|\kappa| \sim 35$ эВ. В заключение отметим, что планируемые новые эксперименты по измерению аномального магнитного момента мюона [4, 5] будут иметь отличные от эксперимента E821 характеристики пучка и, соответственно, могут получить систематический сдвиг в измеряемом значении.

Авторы благодарны за полезные обсуждения проф. И.Ф. Гинзбургу, С.Г. Каршенбойму и Э.А. Кураеву. А.Б.А. также благодарит фонд Династия за финансовую поддержку.

———————————

[1] A.B. Arbuzov and T.V. Kopylova, PEPAN Lett. **11** (2014) 339.

[2] A.I. Akhiezer, V.B. Berestetskii, *Elements of Quantum Electrodynamics*, Oldbourne Press, 1964.

[3] J.S. Schwinger, Phys. Rev. **73** (1948) 416.

[4] B.L. Roberts Chin. Phys. C. **34** (2010) 741.

[5] T. Mibe [J-PARC g-2 Collaboration], Nucl. Phys. Proc. Suppl. **218** (2011) 242.

Progress in the theoretical background of high precision experimental tests of fundamental physics

Dimitar Bakalov[a],

[a] *INRNE, Bulgarian Academy of sciences*

Significant progress has been achieved recently in the theoretical foundation of two experimental projects aimed at testing the fundamental characteristics of matter.

1. An experiment for the measurement of the hyperfine splitting in the ground state of muonic hydrogen, first proposed more than 20 years ago, has recently been started. This became possible thanks to (a) the development of pulsed narrow-band tunable NIR lasers delivering up to 5 mJ per pulse at 50 Hz; (b) the availability of high intensity pulsed muon sources at ISIS (RAL, UK); (c) the progress in the theory of low-energy processes involving muonic atoms which allowed for finding the optimal experimental conditions and obtain high efficiency of the measurements [1, 2]. Among the expected results are: the hyperfine splitting in $(\mu^- p)_{1s}$ accurate to 10^{-5}, the Zemach radius of the proton with accuracy better than 1%, statistically significant comparison of the Zemach radii obtained by spectroscopy of ordinary and muonic hydrogen [3].

2. The possibility to build a clock based on the hyperfine spectrum of a hydrogen molecular ion, and with precision that exceeds the precision of present day atomic clocks, has been recently demonstrated, making use of the "composite frequency" method, developed in [4]. On the ground of the high accuracy *ab initio* calculations of the Zeeman [5, 6] and (dc and ac) Stark effects [7] in the molecular ions HD^+ and H_2^+, it has been shown that the overall systematic shift of appropriate linear combinations of the frequencies of individual hyperfine transitions due to external fields is very strongly suppressed. Among other, clocks with such a high precision will allow for setting more stringent limits on the time variability of fundamental physical constants.

———————————

[1] A. Adamczak *et al.*, Nucl. Instr. Meth. **B281** (2012) 72.

[2] D. Bakalov *et al.*, to appear in Phys. Lett. A (2014).

[3] D. Bakalov *et al.*, Phys. Rev. **A68** (2003) 052503.

[4] S. Schiller *et al.*, Phys. Rev. Lett. **1** (2011) 1.

[5] D. Bakalov *et al.*, J. Phys. B: At. Mol. Opt. Phys. **44** (2011) 025003.

[6] D. Bakalov *et al.*, Appl. Phys. **B114** (2014) 213.

[7] S. Schiller *et al.*, Phys. Rev. **A89**, (2014)052521.

Two-loop electroweak contribution to the matching of α_s in the Standard Model

A.V. Bednyakov[a]

[a] *Joint Institute for Nuclear Research*

The effective renormalizable theory describing electromagnetic and strong interactions of quarks of five light flavors ($n_f = 5$ QCD×QED) is considered as a low-energy limit of the full Standard Model. Two-loop relation between the running strong coupling constants α_s defined in either theories is found by simultaneous decoupling of electroweak gauge and Higgs bosons in addition to the top quark. The relation potentially allows one to confront "low-energy" determination of α_s with a high-energy one with increased accuracy. Numerical impact of new $\mathcal{O}(\alpha_s \alpha)$ terms is studied at the electroweak scale. It is shown that the corresponding contribution, although being suppressed with respect to $\mathcal{O}(\alpha_s^2)$ terms, is an order of magnitude larger than the three-loop QCD corrections $\mathcal{O}(\alpha_s^3)$ usually taken into account in four-loop renormalization group evolution of α_s. The dependence on the matching scale is also analyzed numerically.

The talk is based on Ref. [1].

———————————

[1] A. V. Bednyakov, arXiv:1410.7603 [hep-ph].

Electric dipole moment of electron and P,T-odd electron-nucleus interaction in highly charged ions

A. A. Bondarevskaya[a], D. V. Chubukov[a], O. Yu. Andreev[a], E. A. Mistonova[a], L. N. Labzowsky[a,b], G. Plunien[c], D. Liesen[d,e], F. Bosch[d]

[a] *St. Petersburg State University, Petrodvorets, Russia*
[b] *Petersburg Nuclear Physics Institute, Gatchina, Russia*
[c] *Institut für Theoretische Physik, Technische Universität Dresden, Dresden, Germany*
[d] *GSI Helmholzzentrum für Schwerionenforschung GmbH, Darmstadt, Germany*
[e] *Fakultät für Physik und Astronomie, Ruprecht-Karls-Universität Heidelberg, Germany*

The search for fundamental symmetry violation in low-energy physics presents one of the most important problems in present theoretical physics. In this connection in particular it is interesting to study the electric dipole moment (EDM) of elementary particles (e.g. electron as in this report) as well as the EDM of closed many-particle systems because the presence of EDM violates both space parity (P-odd effects) and time-invariance parity (T-odd effects). Currently, the Standard Model (SM) predicts an EDM of the electron of $d_e < 10^{-38}$ e cm (e is the electron charge) [1]. However, within various extensions of the SM [2] the electron EDM can be enhanced up to a value close to the bounds obtained in recent accurate experiments with heavy diatomic molecule ThO [5]. So discovery and studying of this effect will allow to find a new physics beyond SM.

The search for the electron EDM in closed systems (atoms, ions, molecules) has one important difference compared to that for free particles. In any experiment with any particular closed system it cannot be distinguished between the electron EDM effect and the interfering P,T-odd scalar-pseudoscalar electron-nucleus interaction effect. The equivalence of these two effects was first stated in [3]. The main goal of the present report is to demonstrate that these effects can be well distinguished in a series of experiments with H-like and Li-like highly charged ions (HCI) in storage rings (both electrostatic and magnetic ones). A proposal is based upon the different dependence of these effects on the nuclear charge Z.

———————————

[1] M. Pospelov and I. Khriplovich, Sov. Nucl. Phys. **53** (1991) 638 [Yad. Fiz. **53** (1991) 1030].

[2] J. Engel, M.J. Ramsey-Musolf, U. van Kolck, Progr. in Particle and Nucl. Phys. **71** (2013) 21.

[3] The ACME collaboration, Science 343 (2014) 26.

[4] V.G. Gorshkov, L.N. Labzowsky and A.N. Moskalev, ZhETF **76** (1979) 414 [Sov. Phys. JETP **49** (1979) 209].

Non-destructive Diagnostics of Antihydrogen by the Characteristic Spectra of Microwave Ionization

Yu.V. Dumin[a,b]

[a]*Sternberg Astronomical Institute of Lomonosov Moscow State University, Russia*
[b]*Space Research Institute of Russian Academy of Sciences, Moscow, Russia*

The antihydrogen atoms, used for studying the fundamental laws of nature [1], are typically produced in the highly-excited (Rydberg) states by the three-body recombination of positrons and antiprotons. The commonly-used experimental procedure for diagnostics of the population of Rydberg atoms/antiatoms is their ionization by the DC electric field with gradually increasing amplitude and counting the number of the released electrons/positrons as function of the applied voltage. Unfortunately, such an approach results in the complete destruction of the original Rydberg sample. This is not a serious problem in the experiments with ordinary matter but becomes very expensive in the case of antimatter.

The aim of the present report is to discuss a possible method for non-destructive (or partially-destructive) diagnostics of the Rydberg systems, based on the characteristic spectra of their ionization by microwave (MW) irradiation. The principal idea of such an approach comes from the experiments with ordinary matter [2], where a few well-expressed subharmonics of the ionization yield were detected under MW irradiation of the laser-excited Rydberg atoms with "artificially reduced" ionization thresholds. However, it was unclear in advance if the above-mentioned spectra will survive in the case of the recombination-produced Rydberg atoms, because of a considerable difference in their typical angular momenta and the respective electron-cloud shapes.

Fortunately, the numerical simulation performed in our study have shown that, under the appropriate choice of irradiation parameters, the subharmonics of the ionization yield can be clearly identified even in the case of purely "circular" electron orbits ($l \approx n$). Besides, depending on the MW amplitude and pulse duration, it is possible to get either a single well-expressed ionization maximum (if it is desirable to minimize the number of destroyed atoms) or a set of few ionization peaks (if a more careful diagnostics is necessary).

In summary, we expect that the proposed method may be a valuable tool in the future experiments with antihydrogen. Besides, the independent test of feasibility of this approach can be obtained from the experiments with microwave irradiation of the recombining ordinary ultracold plasmas [3].

---

[1] E. S. Reich, Nature **468** (2010) 355.

[2] H. Maeda & T. F. Gallagher, Phys. Rev. Lett. **93** (2004) 193002.

[3] R. S. Fletcher, X. L. Zhang, & S. L. Rolston, Phys. Rev. Lett. **96** (2006) 105003.

Ti:sapphire femtosecond frequency comb for optical frequency metrology in the NIR region

S. Fedorov,[a,b] D. Sukachev,[a] N. Kolachevky[a]

[a] *P.N. Lebedev Physical Institute, 119991 Moscow, Leninsky prospekt 53, Russia*
[b]*Moscow Institute of Physics and Technology, 141700 Dolgoprudny, Russia*

In the early 2000s there was a breakthrough in the field of optical frequency metrology due to invention of a novel way of comparison between optical and radio frequencies [1]. Femtosecond frequency combs became a precise, simple and robust link between optical clocks and primary RF frequency standards used in the definition of SI second.

A femtosecond comb spectrum consists of equally spaced "teeth"at frequencies f_n. These frequencies are separated by the femtosecond laser repetition rate f_r and shifted as a whole by the carrier-envelope offset frequency f_{CEO}

$$f_n = nf_r + f_{CEO} \tag{2}$$

where n is a number of the order of 10^6. Since both f_r and f_{CEO} typically have values between 0.1 and 10 GHz, the total spectrum may cover more than octave in the optical and NIR ranges.

Here we present recent results on the realization of a frequency comb based on a Ti:Sa femtosecond laser oscillator. We demonstrate the comb spectrum broadening to more than octave in a photonic crystal fiber (Fig. 1.a), detection of f_{CEO} using nonlinear f-$2f$ interferometer technique [2] and stabilization of f_{CEO} to an external rf frequency source by controlling pump laser power. The achieved signal to noise ratio in detected f_{CEO} is about 50 dB (Fig. 1.b). We plan to use the stabilized frequency comb for precision measurements of clock transition in laser cooled Thulium (1140 nm), clock transition spectroscopy in Aluminum ion (1070 nm) and spectroscopy of atomic hydrogen (972 nm).

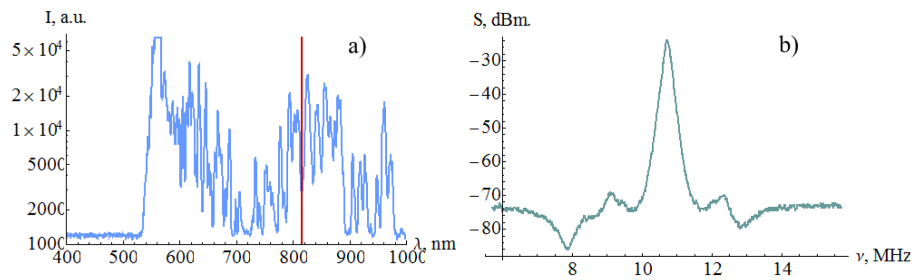


Рис. 1: a) part of supercontinuum generated in a photonic crystal optical fiber detected by a silicon CCD detector b) carrier-envelope offset f_{CEO} beat signal

———————————

[1] Th. Udem, R. Holzwarth, T. W. Haensch., Nature **416** (2002) 233.

[2] D. J. Jones *et al.*, Science **288** (2000) 635.

Preliminary results of the hadronic cross sections measurements with the CMD-3 detector at electron-positron collider VEPP-2000

G.V.Fedotovich
on behalf of the CMD-3 collaboration

BINP, Novosibirsk, Russia

CMD-3 detector during the last three seasons has collected the integrated luminosity about 60 pb^{-1} at the e^+e^- VEPP-2000 collider. The integrated luminosity was measured using two well-known QED process: $e^+e^- \to e^+e^-$, $e^+e^- \to \gamma\gamma$. These processes have the large cross sections and events can be selected purely without background due to a simple signature in the detector. The half of the data has been collected below the phi-meson mass. The stability of the beam energy has controlled with accuracy 0.1 MeV, using Compton laser light back scattering techniques. The other half of the statistics was taken in the energy range from 1 to 2 GeV. The preliminary results of various hadronic cross sections measurements are presented. The first study of dynamics of multi hadrons production is performed.

Variability of the Gravitational Constant – Forty-Three Years Later

Plamen P. Fiziev[a], Ts. Ya. Fizieva[b]

[a] *BLTP JINR Dubna*
[b] *Independent Researcher*

The values of the gravitational constant G resulting from the latest experiments each with comparatively small uncertainties but in disagreement with each other and with earlier measurements with comparable uncertainties led to an even larger expansion of the a priori assigned uncertainties of the data for G, see [1] and the Table below. We consider the obvious contradiction between the experimentally observed data with high precision and analyze some hypotheses about the possible explanation of this mystery.

Special attention is paid to the variation of Earth gravitational field and its relation with the model of minimal dilatonic gravity (MDG) [2]. The hypothesis that the massive Nambu-Goldsone dilaton can explain the variability of the gravitational constant was formulated for the first time by Fujii [3], as early as in 1971. It was extensively investigated experimentally in 80-ties and 90-ties of the last century without convincing results.

We present here the modern development of MDG model [2] and its new predictions, based on the Preliminary Reference Earth Model (PREM) [4].

G $\times 10^{-11} m^3 kg^{-1} s^{-2}$	Uncertainty	G $\times 10^{-11} m^3 kg^{-1} s^{-2}$	Uncertainty
6.672 48(43)	6.4×10^{-5}	6.673 87(27)	4×10^{-5}
6.672 9(5)	7.5×10^{-5}	6.672 28(87)	1.3×10^{-4}
6.673 98(70)	1.0×10^{-4}	6.674 25(12)	1.9×10^{-5}
6.674 255(92)	1.4×10^{-5}	6.673 49(18)	2.7×10^{-5}
6.675 59(27)	4.0×10^{-5}	6.672 34(14)	2.1×10^{-5}
6.674 22(98	1.5×10^{-4}	6.67545(18)	1.48×10^{-4}

———————————

[1] P. J. Mohr, B. N. Taylor, and D. B. Newell, Rev. Mod. Phys. **84** 1527 (2012).

[2] O'Hanlon, Phys. Rev. Lett. **29** 137 (1972); P. P. Fiziev, Mod. Phys. Lett. A **15** 1077 (2000); Plamen P. Fiziev, arXiv:gr-qc/0202074; P. Fiziev, Georgieva D., Phys. Rev. D **67** 064016 (2003); P. P. Fiziev, Phys. Rev. D **87** 0044053 (2013); Plamen P. Fiziev, Frontiers of Fundamental Physics 14, PoS (FFP14) 080 (2014), arXiv:1411.0242.

[3] Fujii, Y., Nature (London), Phys. Sci. 2**34** 5 (1971); Fujii, Y., Phys. Rev. D **9** 874 (1972); F. D. Stacey, G. J. Tuck, G. I. Moore, S. C. Holding, B. D. Goodwin, R. Zhou, Rev. Mod. Phys. **59** 157 (1987); Y. Fujii, K. Maeda, *The Scalar-Tensor Theory of Gravitation, Cambridge Monographs on Mathematical Physics*, Cambridge 2003.

[4] A. M. Dziewonski, D. L. Anderson, Physics of the Earth and Planetary Interiors **25** 297 (1981).

On the structure of the physical vacuum

A. S. Gevorkyan[a,b]

[a]*Institute for Informatics and Automation Problems, NAS of Armenia*
[b]*Institute for Chemical Physics, NAS of Armenia*

In the representation of the quantum field theory (QFT), the physical vacuum is the infinite set of all fluctuating virtual energetic particles and fields in the R^4 space-time of Minkowski. The experimental facts such as the Lamb shift of energy levels of the hydrogen atom, Casimir and Unruh effects etc., are important proofs of QFT predictions. In conjunction with this a natural question arises, namely, what is the structure of the *physical vacuum* (PV) at equilibrium, when there is no external influence on it? It is obvious that to study such problems we need to develop a nonperturbative QFT [1]. In this work we consider the propagation of electromagnetic fields in free PV in the framework of Langevin-Maxwell type stochastic differential equations. For the sake of simplicity we have assumed, that the random sources of energetic particles and fields satisfy the correlation conditions of the white noise. The last allows in particular to derive the equation for distribution of vacuum fields and, respectively to construct nonperturbative closed theory for the physical vacuum taking into account the influence of the external electromagnetic fields. As it is proved, in the limit of a statistical equilibrium the physical vacuum after some simplifications is described in the $6D$ space-time, where $4D$ is the Minkowski space-time, while the additional $2D$ is the compact space on which physical vacuum is in quantized states. In other words, the PV without any external influence has a *structure*. It is shown, that at the absence of the external fields the integral representation for refractive indexes, as one would expect are identically equal to units. When the physical vacuum is under the influence of the external electromagnetic fields, the quantized states are deformed, that leads to changes of the values of refractive indexes even at small external fields. This indicates the existence of a new mechanism of photon-photon scattering which differs from the mechanism described by the well-known Feynman diagrams of the fourth order. Note, that at propagation of electromagnetic fields in the vacuum the last is polarized. This leads to change of the refractive indices of the physical vacuum, that directly influences on a propagation of photon from another source, this is the meaning of the new mechanism of photon-photon interaction. At last, it is necessary to note, that the mentioned mechanism of photon-photon scattering is due to the nonlinear properties of the quantum vacuum which, as it was shown experimentally, is manifested also at small external fields. The new properties of the physical vacuum can fundamentally change our understanding of the structure of the quantum vacuum and give new opportunities for a space-time engineering with far-reaching practical applications.

———————————

[1] A. S. Gevorkyan *et al.*, Physics of Atomic Nuclei, **74**, No. 6 (2011) 901.

[2] A. S. Gevorkyan *et al.*, AIP Conference Proceedings No. 1232, (2010) 267.

New data on the Higgs boson by CMS

Dezső Horváth (on behalf of the CMS Collaboration)
Wigner Research Centre for Physics, Budapest, Hungary
and *Institute of Nuclear Research (Atomki), Debrecen, Hungary*

The 40 years old standard model, the theory of particle physics, seems to describe all experimental data very well. All of its elementary particles were identified and studied apart from the Higgs boson until 2012. For decades many experiments were built and operated searching for it, and finally, the two main experiments of the Large Hadron Collider at CERN, ATLAS and CMS in 2012 observed a new particle with properties close to those predicted for the Higgs boson. The discovery of the Higgs boson proves the validity of the Brout-Englert-Higgs mechanism of spontaneous symmetry breaking and François Englert and Peter Higgs were awarded the 2013 Nobel Prize in Physics.

In spite of the general quantitative agreement of its predictions with experiment the standard model (SM) has serious theoretical shortcomings. It cannot account for neutrino oscillations, cannot solve the hierarchy problem (the unnaturally high corrections to the mass of the Higgs boson), there is no place in it for the dark matter and it cannot explain the lack of antimatter galaxies in the universe. Its gauge couplings are converging but not to the same point at high energies and it cannot include gravity as a gauge interaction. Most of these problems are solved within the frameworks of SM extensions, the most popular of them being supersymmetry. The latter predicts several deviations from the SM, especially in the Higgs sector, where it expects at least 5 Higgs bosons, three neutral and two charged ones.

Studying the observed Higgs boson may uncover new physics beyond the SM, and thus it is one of the most important programs for the experiments of the Large Hadron Collider. We summarize the activity of CMS to measure the mass and other properties of the 125 GeV Higgs boson, the new data on its decay properties as compared to the SM predictions, and also attempts to check for other Higgs bosons at different masses. Thus far every data agrees with the SM, no deviation is found.

[1] S. Chatrchyan *et al.* [CMS Collaboration], Phys. Lett. B **716** (2012) 30.

[2] S. Chatrchyan *et al.* [CMS Collaboration], Phys. Rev. Lett. **110** (2013) 081803.

[3] S. Chatrchyan *et al.* [CMS Collaboration], Phys. Rev. D **89** (2014) 092007.

[4] S. Chatrchyan *et al.* [CMS Collaboration], JHEP **1401** (2014) 096.

[5] S. Chatrchyan *et al.* [CMS Collaboration], Nature Phys. **10** (2014) 557.

[6] V. Khachatryan *et al.* [CMS Collaboration], arXiv:1407.0558 [hep-ex].

[7] CMS Collaboration [CMS Collaboration], CMS-PAS-HIG-14-009.

Determination of the proton charge radius

Savely Karshenboim

Pulkovo Onservatory
Max-Planck-Institut für Quantenoptik, Garching

I will discuss determination of the proton charge and magnetic radius by means of atomic spectroscopy. In particular, I will discuss data on ordinary hydrogen and deuterium and on muonic hydrogen.

Progress in deep laser cooling of Strontium at VNIIFTRI

K. Khabarova[a,c], S. Strelkin[a,b], A. Galyshev[a,b], O. Berdasov[a,b], A. Gribov[a,b], N. Kolachevsky[a,b,c], S. Sluysarev[a,b]

[a] *VSUE VNIIFTRI, Mendeleevo, Moscow Region, Russia*
[b] *National Research Nuclear University MEPhI, Moscow, Kashirskoye sh. 31, Russia*
[c] *P.N. Lebedev Physical Institute, Moscow, Leninsky prospekt 53, Russia*

Today strontium optical lattice clock is one of the most stable source of frequencies approaching eighteenth digit in fractional stability [1]. Such impressive progress makes strontium optical clock a strong candidate for re-definition of second and open new perspectives for fundamental tests and applications. Our group at VNIIFTRI works on development of Sr-87 lattice clock targeting fractional inaccuracy of frequency at 10^{-16} level.

In this presentation we will discuss current progress of past few years: efficient first stage laser cooling at 461 nm, second stage laser cooling at 689 nm and development of stabilized lasers for the second stage cooling and clock transition spectroscopy. Using highly stabilized laser at 689 nm [2] we recently demonstrated deep second stage laser cooling at the "broadband" and "single mode" regimes for Sr-88 isotope. Achieved temperatures of 2-3 μK (see fig. 1) should be sufficient for efficient loading in an optical dipole trap at the magis wavelength of 813 nm. After test experiments with Sr-88 we plan to switch to less abundant Sr-87 isotope for spectroscopy of the clock transition at 698 nm.

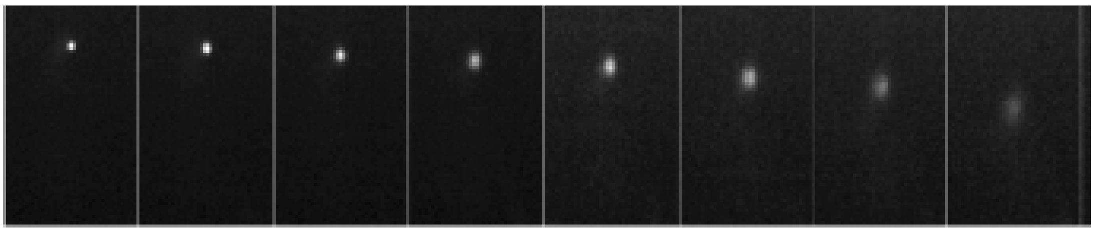


Рис. 1: Ballistic flight of Sr-88 cloud after cycle of second stage cooling. Images are captured after 1, 10, 20, 25, 30, 35, 40 and 50 ms after switching off the MOT.

[1] B.J. Bloom et al., Nature 506, 71 (2014).

[2] K. Khabarova et al., Quantum Electronics 42, 1021 (2012).

Constraints on axion-nucleon coupling constants from measurements of the Casimir interaction

G. L. Klimchitskaya

Department of Astrophysics, Central Astronomical Observatory at Pulkovo of the Russian Academy of Sciences, St.Petersburg, 196140, Russia;
Institute of Physics, Nanotechnology and Telecommunications, St.Petersburg State Polytechnical University, St.Petersburg, 195251, Russia

Axion is a light pseudoscalar particle, which was introduced in QCD in order to avoid strong CP violation and large electric dipole moment of a neutron. Axion and different types of axion-like particles suggested in many extensions of the Standard Model provide an elegant solution for the problem of dark matter in astrophysics and cosmology. There are many attempts to find axions in different laboratory experiments and astrophysical observations (see [1,2] for a review). Up to the moment, however, only more or less strong constraints on the mass and coupling constants of an axion and axion-like particles to photons, leptons and nucleons have been obtained. Specifically, laboratory constraints on the couplings of axions to a proton and a neutron are the most weak ones.

In this talk we collect the recently obtained [3-6] constraints on axion to nucleon coupling constants, which follow from different experiments on measuring the Casimir interaction. We consider the constraints derived from measuring the Casimir-Polder force between Rb atoms and a SiO_2 plate, from measurements of the gradient of the Casimir force between surfaces of a sphere and a plate coated by both nonmagnetic (Au) and magnetic (Ni) metals using different laboratory setups, and from measurements of the Casimir force between sinusoidally corrugated surfaces coated with Au. These constraints are compared with those following from some other laboratory experiments for masses of axion-like particles from 10^{-10} to 20 eV. The possibility to obtain even stronger constraints on axion to nucleon coupling constants from the Casimir effect is proposed.

---

[1] K. Baker *et al.*, Ann. Phys. (Berlin) **525** (2013) A93.

[2] J. Beringer *et al.* (Particle Data Group), Phys. Rev. D **86** (2012) 010001.

[3] V. B. Bezerra, G. L. Klimchitskaya, V. M. Mostepanenko, and C. Romero, Phys. Rev. D **89** (2014) 035010.

[4] V. B. Bezerra, G. L. Klimchitskaya, V. M. Mostepanenko, and C. Romero, Phys. Rev. D **89** (2014) 075002.

[5] V. B. Bezerra, G. L. Klimchitskaya, V. M. Mostepanenko, and C. Romero, Eur. Phys. J. C **74** (2014) 2859.

[6] V. B. Bezerra, G. L. Klimchitskaya, V. M. Mostepanenko, and C. Romero, Phys. Rev. D **90** (2014) 055013.

Spectroscopy of laser cooled Thulium atom

N. Kolachevsky[a,b], K. Khabarova[a,b], D. Sukachev[a,b], G. Vishnjakova[a,b], E. Kalganova[a,b], S. Fedorov[a], A. Golovisin[a,b], V. Sorokin[a,b]

[a] *P.N. Lebedev Physical Institute of Russian Academy of Sciences*
119991 Moscow, Leninsky prospekt 53, Russia
[b] *Russian Quantum Center, ul. Novaya 100, Skolkovo, Moscow region, Russia*

After successful demonstration of laser cooling of Thulium [1] we continue spectroscopic studies of this rare-earth element cooled to μK range. Our current experiments focus on loading Tm in an optical lattice and spectroscopy of transition at 1.14 μm between the fine-structure components $J = 7/2$ and $J = 5/2$ of the ground state. We propose this magnetic-dipole transition as a favorable candidate for application in optical lattice clock [2].

Recently we demonstrated second stage laser cooling and optical trapping of Tm in a dipole trap at 530 nm (fig. 1). Also for the first time we observed clock transition at 1.14 μm using a stabilized diode laser. Calculations show that dynamic polarizabilities of two clock states ($J = 7/2$, $5/2$) cancel each other to less than 3 % in a broad infrared range which significantly suppress black body radiation shifts compared to alkali-earth atoms.

In this talk we will discuss the progress achieved to date, demonstrate results of clock transition spectroscopy and discuss some metrological properties of proposed candidate transition.

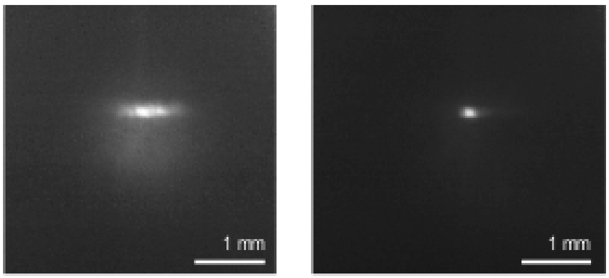


Рис. 1: Images of laser-cooled Thulium atoms trapped in an optical dipole trap at 530.6 nm. Left: axial trapping in a single focused laser beam. Right: trapping in a 1D optical lattice.

———————————

[1] D. Sukachev et al., Phys. Rev. A 82, 011405 (2010).

[2] N.N. Kolachevsky, Usp. Phys. Nauk 54, 863-870 (2011).

Search for fine-structure constant variation in Ni II

E. A. Konovalova

Petersburg Nuclear Physics Institute, Gatchina, Russia

The Ni II absorption lines are observed in quasars by astrophysicists. Nickel is one of the few elements with high sensitivity to α-variation, whose lines are detected at high redshifts. This makes it a sensitive probe for α-variation on the cosmological timescale. We calculated the dependence of the transition frequencies on the fine-structure constant (q-factors) for Ni II [1]. The electronic structure of Ni II ion was treated within the configuration interaction (CI) method using Dirac-Coulomb Hamiltonian. The results of calculations for transition frequencies and sensitivity coefficients are presented in Table 1.

State	Experiment		Theory		q-factor	
	ω	g	ω	$g_{\rm calc}$	this work	Ref. [2]
$^4D_{7/2}$	51558	1.420	49002	1.423	−2490 (150)	−2415
$^2G_{7/2}$	56371*	0.940	53972	0.923	−250 (300)	−124
$^4F_{3/2}$	56425	0.412	54140	0.420	−140 (150)	
$^2F_{7/2}$	57081*	1.154	54817	1.134	−790 (300)	−700(250)
$^2D_{5/2}$	57420*	1.116	55315	1.100	−1500 (150)	−1400(250)
$^2F_{5/2}$	58493*	0.946	56376	0.966	−100 (150)	−20(250)
$^2D_{3/2}$	58706*	0.795	56770	0.799	−370 (150)	
$^4P_{5/2}$	66571*	1.480	66169	1.506	−2210 (150)	
$^4P_{3/2}$	66580	1.550	66173	1.592	−2290 (250)	
$^2F_{5/2}$	67695	0.960	67512	0.943	−1900 (150)	
$^2F_{7/2}$	68131*	1.200	67921	1.186	−1600 (200)	
$^2D_{3/2}$	68154*	1.020	68080	1.033	−1090 (250)	
$^2D_{5/2}$	68736*	1.264	68753	1.242	−410 (150)	
$^4D_{7/2}$	70778	1.385	70704	1.383	−750 (200)	

Таблица 1: The results of calculated sensitivity coefficients and transition frequencies (q-factors, ω are given in $\rm cm^{-1}$). Asterisks mark the lines of astrophysical interest. Experimental frequencies and g-factors are taken from *http://physics.nist.gov/PhysRefData/ASD/index.html*.

———————————

[1] E. A. Konovalova, M. G. Kozlov, and R. T. Imanbaeva, Phys. Rev. A **90** (2014) 042512.

[2] V. A. Dzuba, V. V. Flambaum, M. G. Kozlov, and M. Marchenko, Phys. Rev. A **66** (2002) 022501.

Измерение релаксации распределения зарядов на поверхности плавленого кварца под действием электростатического поля

Д.В. Копцов, Л.Г. Прохоров

Физический факультет, МГУ им. М.В. Ломоносова

Экспериментальное обнаружение гравитационных волн, предсказанных общей теорией относительности Эйнштейна, является одной из актуальных задач современной физики. Решению этой задачи посвящены проекты по поиску гравитационных волн Advanced LIGO [1], GEO600 [2], Advanced VIRGO [3]. Данные проекты основаны на интерферометре Майкельсона с резонаторами Фабри-Перо в плечах, длина которых изменяется под действием гравитационной волны. Один из блоков настройки интерферометра включает в себя электростатические актюаторы ESD - систему гребенчатых электродов, расположенную вблизи пробных масс - зеркал интерферометра [4]. При подаче на них управляющего напряжения создается неоднородное электростатическое поле, в которое втягивается пробная масса, изменяя длину плеча.

Поскольку изменение длин плеч под действием гравитационных волн от предполагаемых космических источников очень мало, шум смещения пробной массы не должен превышать 10^{-20} м/Гц$^{-1/2}$ на частотах около 100Гц [1]. Один из источников шума смещения связан с перераспределением электрических зарядов на пробной массе под действием поля ESD. Исследование этого дополнительного шума является актуальным для проекта Advanced LIGO.

В данной работе предложен и реализован метод экспериментального исследования процессов перераспределения зарядов на поверхности образца из плавленого кварца под действием электростатического поля системы гребенчатых электродов. Разработана установка, состоящая из монолитного крутильного осциллятора из плавленого кварца, системы гребенчатых электродов и интерферометра Майкельсона для измерения колебаний осциллятора.

Исследовано перераспределение зарядов на поверхности пластины осциллятора и продемонстрирован его релаксационный характер. Экспериментальный результат подтверждается численным расчетом. Поскольку перераспределение зарядов - случайный процесс, оно является источником дополнительного шума. По результатам измерений дана верхняя граница спектральной плотности шума.

[1] G. M. Harry, Class Quantum Grav **27** (2010) 084006.

[2] H. Grote, Class. Quantum Grav **27** (2010) 084003.

[3] Advanced Virgo Baseline Design, https://tds.ego-gw.it/itf/tds/file.php?callFile=VIR-0027A-09.pdf

[4] S. M. Aston *et al.*, Class. Quantum Grav **29** (2012) 235004.

Ro-vibrational spectroscopy of the hydrogen molecular ion and antiprotonic helium

Vladimir Korobov

Joint Institute for Nuclear Research, Dubna

In our recent work [1] we have calculated the relativistic Bethe logarithm contribution at order $m\alpha^7$ in the two Coulomb center approximation. These results then have been used for improved calculations of the transition energies for the hydrogen isotope molecular ions and antiprotonic helium atoms. The general formula for the one-loop self-energy contribution at the $m\alpha^7$ order has been obtained in [2]. Including other theoretical contributions in a nonrecoil limit at order $m\alpha^7$, such as one-loop vacuum polarization, the Wichman-Kroll contribution, the complete two-loop contribution, etc, and the leading term of the $m\alpha^8$ order one gets transition energies for the vibrational fundamental transition $(v = 0, L = 0) \rightarrow (1, 0)$ in the hydrogen molecular ion with the relative theoretical uncertainty of $\sim 7 \cdot 10^{-12}$ that corresponds to a fractional precision of $1.5 \cdot 10^{-11}$ in determination of the electron-to-proton mass ratio, m_p/m_e. The proton rms charge radius uncertainty as is defined in the CODATA10 adjustment contributes to the fractional uncertainty at the level of $\sim 4 \cdot 10^{-12}$ for the transition frequency. While the muon hydrogen "charge radius"moves the spectral line blue shifted by 3 KHz that corresponds to a relative shift of $5 \cdot 10^{-11}$.

---

[1] V.I. Korobov, L. Hilico, and J.-Ph. Karr, Phys. Rev. A **87**, 062506 (2013).

[2] V.I. Korobov, L. Hilico, and J.-Ph. Karr, Phys. Rev. Lett. **112**, 103003 (2014); V.I. Korobov, L. Hilico, and J.-Ph. Karr, Phys. Rev. A **89**, 032511 (2014).

Optical transitions in highly charged ions

M. G. Kozlov[a,b], M. S. Safronova[c,d], V. A. Dzuba[e], V. V. Flambaum[e], U. I. Safronova[f,g], and S. G. Porsev[a,c]

Petersburg Nuclear Physics Institute, Gatchina 188300
Petersburg Electrotechnical University "LETI", Prof. Popov Str. 5, St. Petersburg 197376
[c]University of Delaware, Newark, Delaware, USA,
[d]Joint Quantum Institute, NIST and the University of Maryland, College Park, Maryland, USA,
[e]The University of New South Wales, Sydney, Australia,
[f]University of Nevada, Reno, Nevada, USA,
[g]University of Notre Dame, Notre Dame, Indiana, USA

It has been pointed out in [1, 2] that highly charged ions (HCI) can have very narrow lines in the optical range. This happens because the energy of different atomic shells has different dependence on the nuclear charge Z along the isoelectronic series. As a result the levels of different configurations can come close to crossing for a particular value of Z. Transition rates can be very small because of the high multipolarity ($M1$, $E2$, etc.). Such lines have very high sensitivity to α-variation [1, 2] and can be used for exceptionally accurate optical clocks [3].

We use CI+AO (configuration interaction plus all-order) method [4] to identify 10 particularly promising ions and calculate for them transition frequencies, coefficients of sensitivity to α-variation, and lifetimes [5, 6].

[1] J. C. Berengut, V. A. Dzuba, V. V. Flambaum, Phys. Rev. Lett. **105** (2010) 120801, `arXiv:1007.1068`.

[2] J. C. Berengut, V. A. Dzuba, V. V. Flambaum, Phys. Rev. A **84** (2011) 054501.

[3] A. Derevianko, V. A. Dzuba, V. V. Flambaum, Phys. Rev. Lett. **109** (2012) 180801.

[4] M. S. Safronova, M. G. Kozlov, W. R. Johnson, and D. Jiang, Phys. Rev. A **80**, 012516 (2009), `arXiv: 0905.2578`.

[5] M. S. Safronova, V. A. Dzuba, V. V. Flambaum, U. I. Safronova, S. G. Porsev, and M. G. Kozlov, Phys. Rev. Lett. **113**, 030801 (2014), `arXiv:1405.4271`.

[6] M. S. Safronova, V. A. Dzuba, V. V. Flambaum, U. I. Safronova, S. G. Porsev, and M. G. Kozlov, Phys. Rev. A **90**, 042513 (2014), `arXiv:1407.8272`.

On the use of $^{207}Pb^{19}F$ in the search for temporal variation of the fundamental constants

A.D. Kudashov[a,b], L.V. Skripnikov[a,b], A.N. Petrov[a,b], A.V. Titov[a,b], N.S. Mosyagin[a,b]

[a]*Saint Petersburg State University, Saint Petersburg*
[b]*Petersburg Nuclear Physics Institute, Gatchina*

The issue of the fundamental constants' variation entered modern physics with Paul Dirac pointing out the possible temporal variation of the gravitational constant [1]. Among other fundamental parameters, that have been drawing researchers' attention, are the fine-structure constant (α) and the $m_q/\Lambda_{\rm QCD}$ ratio, where m_q is the light quark mass and $\Lambda_{\rm QCD}$ is the scale of quantum chromodynamics (QCD) [2, 3]. The investigation of these phenomena can lead to deeper understanding of cosmology and physics beyond the Standard model of electroweak interactions, prompting further attempts at discovering the variations of fundamental constants in laboratory conditions. Recently, the ^{207}Pb^{19}F radical was put forward as a possible candidate for such experiments [4].

Proven experimentally is the existence of closely-spaced ($\omega = 266, 285$ MHz) opposite-parity levels in the ground-state electronic term of ^{207}Pb^{19}F [5]. This quasidegeneracy is due to mutual cancellation of Ω-type doubling and magnetic hyperfine interaction. The dependences on α and $m_q/\Lambda_{\rm QCD}$ of these two energy-shifting contributions being significantly different, the transition frequency ω gains additional sensitivity to variations of these fundamental constants [4]. And to further increase the chances of a positive experimental outcome, one might look for even smaller transition frequencies between opposite-parity vibrational levels belonging to the ground electronic state.

Using relativistic *ab initio* methods we have calculated a variety of transitions between opposite-parity levels in ^{207}Pb^{19}F electronic ground state vibrational manifold and assessed their sensitivity to α and $m_q/\Lambda_{\rm QCD}$ variation, searching for the optimal transition to test the variation of the fundamental constants.

The authors acknowledge Saint Petersburg State University for a research grant No. 0.38.652.2013. The work is supported by RFBR Grants No. 13-02-01406 and 13-03-01307. L.V.S. is also supported by the grant of the President of RF No. MK-5877.2014.2.

———————————

[1] P.A.M. Dirac, Nature (London) **139**, 323 (1937).

[2] J.K. Webb *et al.*, Phys. Rev. Lett. **107**, 191101 (2011).

[3] V.V. Flambaum and R.B. Wiringa, Phys. Rev. C **79**, 034302 (2009).

[4] V.V. Flambaum, Y.V. Stadnik, M.G. Kozlov, and A.N. Petrov, Phys. Rev. A **88**, 052124 (2013).

[5] L.D. Alphei, J.-U. Grabow, A.N. Petrov *et al.*, Phys. Rev. A **83**, 040501(R) (2011).

Ω-doubling and a limit for the enhancement of the electron EDM effect in diatomic molecules

D.V. Chubukov[a] and L. N. Labzowsky[a,b]

[a]*St. Petersburg State University, Petrodvorets, Russia*
[b]*Petersburg Nuclear Physics Institute, Gatchina, Russia*

A theoretical and experimental search for the P- and P,T- odd effects (P is the space parity, T is the time reflection) in heavy heteronuclear diatomic molecules with open electron shells on the basis of the Standard Model started with the works [1]-[3]. In [1] the P-odd effect was discussed, in [2] the P,T-odd effect due to the presence of the electron Electric Dipole Moment (EDM) was investigated and in [3] a study of the P,T-odd electron-nucleus scalar interaction in such molecules was performed and it was found that the effect of this interaction cannot be distinguished from the electron EDM effect in any experiment with particular molecule.

All these effects are strongly enhanced in such molecules due to the Λ-doubling (Ω-doubling) of the ground or low metastable energy levels. Here Λ is a projection of the orbital electron momentum on the molecular axis, Ω is total (including spin) projection which replaces Λ for relativistic electron in heavy molecule. In principle, the larger Ω for particular molecule in the ground (metastable) state, the stronger is the P- and P,T-odd effects enhancement. However, there exists a saturation effect. Both electron EDM and P,T-odd electron-nucleus interaction effects are observed in an external electric field and the enhancement of both effects grows with the field strength until some critical field value. In the recent accurate experiments with molecules YbF [4] ($\Omega = 1/2$) and ThO [5] ($\Omega = 1$) which gave the upper bounds for the electron EDM and P,T-odd electron-nucleus interaction constants much lower than before the enhancement coefficients were about 10^{14}. Here we understand the enhancement coefficient as the ratio of the "effective"field acting on the electron ($26 \cdot 10^9$ V/cm for YbF and $84 \cdot 10^9$ V/cm for ThO) to the saturation field (10^{-3} V/cm for both molecules).

In our present work we argue that 10^{14} is the maximum possible value of the enhancement for any heteronuclear diatomic molecule with any ground (metastable)-state Ω value. Our argumentation we support with an estimate of enhancement in the metastable $\Omega = 2$ state of ThO molecule.

————————————

[1] L.N. Labzowsky, Sov.Phys. JETP **48** (1978) 434.

[2] O.P. Sushkov and V.V. Flambaum, Sov. Phys. JETP **48** (1978) 608.

[3] V.G. Gorshkov, L.N. Labzowsky and A.N. Moskalev, Sov. Phys. JETP **49**(1979) 209.

[4] J.J. Hudson, D.M. Kara, I.J. Smallman, B.E. Sauer, M.R. Tarbutt and E.A. Hinds, Nature **473** (2011) 493.

[5] The ACME collaboration, Science **343** (2014) 269.

Local tests of spatial variations of m_e/m_p

S.A. Levshakov[a]

[a]*Ioffe Physical-Technical Institute*

The Einstein equivalence principle in terms of local position invariance will be discussed. Current limits and expected future constraints on the fractional changes in the electron-to-proton mass ratio, $\mu = m_e/m_p$, in the Milky Way and at high redshifts will be presented.

Calculation of differential cross section for dielectronic recombination with one-electron uranium

K.N. Lashchenko[1], O.Yu. Andreev[1]

[1]*Faculty of Physics, St. Petersburg State University, ul. Ulyanovskaya 1, Petergof, St. Petersburg, 198504, Russia*

Calculation of the dielectronic recombination with one-electron uranium within the framework of QED is presented. We consider process where the initial state is presented by a one-electron ion of uranium being in the ground state and by an incident electron. The energy of the initial state is close to the energies of double-excited states ($(2s, 2s)$, $(2s, 2p)$, $(2p, 2p)$). The final state is given by a two-electron ion in one of the single-excited states ($(1s, 2s)$, $(1s, 2p)$) and by emitted photon. The process of dielectronic recombination is a resonant process. The resonances in the cross section correspond to the double excited states. In the resonant area the dielectronic recombination gives the main contribution to the cross section.

The calculation is performed with employment of the line-profile approach [1,2]. The one-photon exchange correction for the low-lying states is taken into account in all orders of the QED perturbation theory. The electron self-energy and vacuum polarization corrections are considered in the first order of the perturbation theory.

We present results of the calculation of the total and differential cross section. The polarization properties are also considered and the Stokes parameters are presented. The contribution of the Breit interaction to the cross section and to the Stokes parameters is investigated. The results are compared with available experimental and theoretical data.

———————————

[1] O. Yu. Andreev, L. N. Labzowsky, G. Plunien, D. A. Solovyev Phys. Rep. **455** (2008) 135.

[2] O. Yu. Andreev, L. N. Labzowsky, A. V. Prigorovsky Phys. Rev. A **80** (2009) 042514.

Renormdynamics of Coupling Constants and Masses

Nugzar Makhaldiani[a]

[a] *JINR, Dubna, Russia*

In the Standard Model of Particle Physics (SM), the values of the coupling constants and masses of particles depends on the scale according to the Renormdynamic motion equations. In a Fundamental Theory the values of the Fundamental Physical Constants also will be defined from the solutions of the corresponding renormdynamic motion equations. In SM, minimal supersymmetric extension of the SM, standard pion-nucleon field theory and other models is shown how to define the values of coupling constants and masses.

————————————

[1] N. V. Makhaldiani, Phys. At. Nucl. **76** (2013) 1169.

QED calculation of the ground-state energy of Be-like ions

A. V. Malyshev[a], A. V. Volotka[a,b], D. A. Glazov[a,b,c],
I. I. Tupitsyn[a], V. M. Shabaev[a], G. Plunien[b]

[a] *Department of Physics, St. Petersburg State University, St. Petersburg, Russia*
[b] *Institut für Theoretische Physik, Technische Universität Dresden, Dresden, Germany*
[c] *State Scientific Centre "Institute for Theoretical and Experimental Physics" of National Research Centre "Kurchatov Institute", Moscow, Russia*

The *ab initio* QED calculations of the ground-state binding energies of Be-like ions are performed for the wide range of the nuclear charge number $Z = 18 - 96$ [1]. To formulate the QED perturbation theory the two-time Green function method is employed [2]. Instead of the usual Furry picture, where only the nucleus is considered as a source of the external field, here we add also some screening potential to the zeroth-order Hamiltonian. The perturbation theory is constructed in powers of the difference between the full QED interaction Hamiltonian and the screening potential. This approach accelerates the convergence of the perturbative series. As the main screening potential the local Dirac-Fock potential is used [3]. The calculations with other potentials (Kohn-Sham, Perdew-Zunger) allow to estimate the uncertainty of our results.

The calculations incorporate the first two orders of the rigorous QED perturbation theory. The third and higher orders of the interelectronic interaction are calculated within the Breit approximation by means of the configuration-interaction Dirac-Fock-Sturm method [4, 5]. In addition, the effects of nuclear recoil and nuclear polarization are taken into account. As a result, the most precise theoretical predictions for the ground-state binding energies in Be-like ions have been obtained.

Investigations of highly charged berylliumlike ions (along with investigations of H-, He- and Li-like systems) may serve for tests of QED at strong fields. Furthermore, such precise calculations might be useful for the tasks of mass spectrometry [6].

---

[1] A. V. Malyshev *et al.*, arXiv:1410.1961 [physics.atom-ph].

[2] V. M. Shabaev, Phys. Rep. **356** (2002) 119.

[3] V. M. Shabaev *et al*, Phys. Rev. A **72** (2005) 062105.

[4] V. F. Bratzev *et al*, Izv. Acad. Nauk SSSR, Ser. Fiz. **41**, 2655 (1977), [Bull. Acad. Sci. USSR: Phys. Ser. **41**, 173 (1997)].

[5] I. I. Tupitsyn, V. M. Shabaev, *et al.*, Phys. Rev. A **68** (2003) 022511.

[6] E. G. Myers, Int. J. Mass Spectrom. **349-350** (2013) 107.

Nuclear charge radii: experiment, data and systematics

Krassimira Marinova

Laboratory of Nuclear Reactions, Joint Institute for Nuclear Research, 141980 Dubna, Moscow region

Nuclear ground state properties including charge radii, spins and moments can be determined by applying atomic physics techniques such as laser spectroscopy. The *rms* nuclear charge radii, together with other nuclear ground state properties, represent key information on nuclear matter. They indicate pronounced nuclear structure effects, e.g. shell closures and onset of deformation. The most precise determination of the charge radii — exactly of radii changes — along an isotopic sequence is based on measurements of isotope shifts in the atomic spectra. Tunable laser systems with their high available laser intensity ($\geq$ 10 mW/cm2) and extremely small line width ($\sim$1 MHz) are an important prerequisite for development of very precise and sensitive optical methods. The general principle of the optical method for extraction of nuclear parameters will be described briefly. It is explained why extreme resolving power exceeding 10^6 can be reached by modern laser spectroscopic methods and how it reflects on the accuracy of the measured *rms* nuclear radii. The conditions necessary for the study of unstable nuclei, the status and trends of laser spectroscopy on radioactive nuclei are discussed.

The absolute values of nuclear charge radii can be derived by muonic spectra and electronic scattering experiments. These methods, applicable to a limited number of stable isotopes, are sensitive to different properties of the nuclear ground-state charge distributions. For this reason, a combination of data from different experimental methods generally yields more detailed and accurate knowledge of the nuclear radii than is available from any single method alone. Combining both types of experimental data — radii changes and absolute radii — an updated set of absolute nuclear charge radii values for 956 isotopes of 92 elements from $_1$H to $_{96}$Cm has been obtained [1]. Two different algorithms of combined analysis are used [2, 3]. Such a procedure reduces possible systematic errors arising from the differing approach of the evaluators [4]. The data obtained are not simple compilation of individual measurements, but constitute a self-consistent set of rms R-values giving a global survey of nuclear charge radii over the whole nuclide chart. Remarkable correlations of the nuclear charge radii with other nuclear observables have been recognized in isotopic as well as in isotonic behavior. The latter gives a convincing experimental confirmation that the applied combined analysis results in correct charge radii values.

---

[1] K. Marinova and I. Angeli, `https://www-nds.iaea.org/radii/` (2014).

[2] E.G. Nadjakov *et al.*, At. Data Nucl. Data Tables **56**, 113 (1994).

[3] I. Angeli, At. Data Nucl. Data Tables **87**, 185 (2004).

[4] I. Angeli and K.P. Marinova, At. Data Nucl. Data Tables **99**, 69 (2013).

Лэмбовский сдвиг в ионах мюонного гелия $(\mu\, {}^{3,4}_{2}He)^+$

А. А. Крутов[a], А. П. Мартыненко[a,b], Г. А. Мартыненко[a], Р. Н. Фаустов[c]

[a]*Самарский государственный университет*
[b]*Самарский государственный аэрокосмический университет имени С.П. Королева*
[c]*Вычислительный центр РАН имени А.А. Дородницина*

В работах [1] были измерены частоты переходов между уровнями $2P$ и $2S$ в мюонном водороде $\nu(2S^{F=1}_{1/2} - 2P^{F=2}_{3/2}) = 49881.35(65)$ ГГц и $\nu(2S^{F=0}_{1/2} - 2P^{F=1}_{3/2}) = 54611.16(1.05)$ ГГц, которые позволили получить более точное значение зарядового радиуса протона r_p= 0.84087 $(26)_{exp}$ $(29)_{th}$ = 0.84087 (39) фм. Оно отличается на 7σ от значения рекомендованного CODATA [2]. Если причина этого расхождения связана с нарушением мюон-электронной универсальности, то спектроскопические исследования ионов мюонного гелия должны это обнаружить. Теоретические исследования тонкой структуры спектра ионов мюонного гелия были выполнены в течение многих лет (см., например, [3, 4, 5, 6]) как на основе уравнения Дирака, так и в рамках трехмерного квазипотенциального метода. В этих работах были получены как основные вклады в спектр энергии, так и ряд наиболее важных поправок, связанных прежде всего с электронной поляризацией вакуума. В данной работе нами проведен новый аналитический и численный расчет поправок порядка α^5 и α^6 в лэмбовском сдвиге $(2S_{1/2} - 2P_{1/2})$ в двух ионах мюонного гелия $(\mu^4_2He)^+$ и $(\mu^3_2He)^+$, которые определяются релятивистскими эффектами, эффектами поляризации вакуума, структуры ядра и отдачи. Были получены полные значения лэмбовского сдвига в этих атомах с точностью 0.001 мэВ.

[1] A. Antognini *et al.*, Science **339** (2013) 417; Ann. Phys. **331** (2013) 127.

[2] P.J. Mohr, B.N. Taylor and D.B. Newwell, Rev. Mod. Phys. **84** (2012) 1527.

[3] E. Borie, Ann. Phys. **327** (2012) 733.

[4] J.L. Friar, Ann. Phys. **122** (1979) 151; PRC **88** (2013) 034003; J.L. Friar, J. Martorell and D.W.L. Sprung, Phys. Rev. A **56** (1997) 4579.

[5] E.Yu. Korzinin, V.G. Ivanov and S.G. Karshenboim, PRD **88** (2013) 125019; S.G. Karshenboim, V.G. Ivanov, E.Yu. Korzinin, and V.A. Shelyuto, PRA **81** (2010) 060501.

[6] A.P. Martynenko, Phys. Rev. A **76** (2007) 012505.

Controllable narrowing of magnetic Feshbach resonances in atomic traps

Vladimir S. Melezhik[a]

[a]*Bogoliubov Laboratory of Theoretical Physics, Joint Institute for Nuclear Research, Dubna Moscow Region 141980, Russian Federation*

By using our computational technique for ultracold scattering in low-dimensions [1,2] we have developed and analyzed a theoretical model which yields the shifts and widths of Feshbach resonances in atomic waveguides [3]. This model permits quantitative investigation of Feshbach resonances with different tensorial structure and having broad, narrow and overlapping character. We have calculated the shifts and widths of s-, d-, and g-wave magnetic Feshbach resonances of Cs atoms emerging in harmonic waveguides as confinement-induced resonances $T(B_r) = 0$ at the field strengths B_r and resonant enhancement $T(B^*) = 1$ of the transmission $T(B)$ at zeros $a(B^*) = 0$ of the free-space scattering length a. We have found the linear dependence of the width $\Gamma = \Delta k a_\perp^2/a_{bg}$ of the resonance at the magnetic field B^* on the longitudinal atomic momentum k and quadratic dependence on the waveguide width $a_\perp$ (here $\Delta = B^* - B_{r0}$ is the width of the Feshbach resonance at B_{r0} and a_{bg} is the background scattering length in free-space).

The found effect could potentially be used experimentally. Actually, one can control the width $\Gamma = \Delta k a_\perp^2/a_{bg}$ of the resonance by varying the trap width $a_\perp$. From the other side, by measuring the width Γ one can extract from the obtained formulae the longitudinal colliding energy E ($k = \sqrt{2mE/\hbar}$) and estimate the temperature of the atomic cloud in the trap.

We have also found that the relationship $a = 0.68a_\perp$ for the position of the confinement-induced resonance in a harmonic waveguide (where $T(B_r) = 0$) is fulfilled with high accuracy for the Feshbach resonances of different tensorial structure which holds in spite of the fact that this property was originally obtained in the framework of the s-wave single-channel pseudopotential approach [4]. Note, that this property was recently experimentally confirmed for d-wave Feshbach resonances in a gas of Cs atoms transformed in atomic traps into confinement-induced resonances [5].

[1] V.S. Melezhik, Multi-Channel Computations in Low-Dimensional Few-Body Physics, Lecture Notes in Computer Science 7125, (Springer 2012) p.94; arXiv:1110.3919.

[2] V.S. Melezhik, Phys. Atom. Nucl. **76** (2013) 139.

[3] S. Saeidian, V.S. Melezhik , and P. Schmelcher, Phys. Rev. **A76** (2012) 62713.

[4] M. Olshanii, Phys. Rev. Lett. **81** (1998) 938.

[5] E. Haller, M.J. Mark, R. Hart, J.G. Danzl, L. Reichsöllner, V. Melezhik, P. Schmelcher, and H.C. Nägerl, Phys. Rev. Lett. **104** (2010) 153203.

New precision experiments on the Casimir force sharpen problems in foundations of quantum statistical physics

V. M. Mostepanenko

Department of Astrophysics, Central Astronomical Observatory at Pulkovo of the Russian Academy of Sciences, St.Petersburg, 196140, Russia;
Institute of Physics, Nanotechnology and Telecommunications, St.Petersburg State Polytechnical University, St.Petersburg, 195251, Russia

The Casimir force acting between uncharged closely spaced bodies in vacuum is a quantum phenomenon originating from the zero-point and thermal fluctuations. It is of the same nature as the van der Waals force, but acts at larger separations where the relativistic retardation becomes important. During the last fifteen years a lot of precision measurements of the Casimir force between metallic and dielectric test bodies at short separations has been performed [1,2]. In the comparison between experiment and fundamental Lifshitz theory it was unexpectedly found that for metallic test bodies the data are in agreement with theoretical predictions only if the relaxation properties of conduction electrons are omitted in computations. For dielectric test bodies the data were found to be in agreement with theory only if the dc conductivity of materials is disregarded (see [1,2] for review). At the same time, theoretically it was found that if the contributions of relaxation of conduction electrons for metals and dc conductivity for dielectrics are taken into account, the obtained Casimir entropy goes to nonzero quantities depending on the parameters of a system when the temperature vanishes in violation of the third law of thermodynamics (the Nernst heat theorem).

In this talk we review the most recent experiments on measuring the Casimir interaction in configurations with magnetic surfaces [3-5]. The results of these experiments demonstrate independence of any unaccounted systematic error or background effect. This leads to the conclusion that some of the basic concepts of quantum statistical physics behind the Lifshitz theory should be reconsidered.

---

[1] M. Bordag, G. L. Klimchitskaya, U. Mohideen, and V. M. Mostepanenko, *Advances in the Casimir Effect* (Oxford University Press, Oxford, 2009).

[2] G. L. Klimchitskaya, U. Mohideen, and V. M. Mostepanenko, Rev. Mod. Phys. **81** (2009) 1827.

[3] A. A. Banishev, C.-C. Chang, G. L. Klimchitskaya, V. M. Mostepanenko, and U. Mohideen, Phys. Rev. B **85** (2012) 195422.

[4] A. A. Banishev, G. L. Klimchitskaya, V. M. Mostepanenko, and U. Mohideen, Phys. Rev. Lett. **110** (2013) 137401; Phys. Rev. B **88** (2013) 155410.

[5] R. S. Decca, Talk at the Symposium "Materials Relevance in Fluctuation-Induced Interactions Cancun, Mexico, 2014.

Constraints from Oklo reactor analysis on parameters of BSBM model of varying α

Onegin M.S.[ab]

[a]*Petersburg Nuclear Physics Institute*
[b]*Khlopin Radium Institute*

New severe constraints on the variation of the fine structure constant have been obtained from reactor Oklo analysis in work [1]:

$$-0.7 \cdot 10^{-8} < \delta\alpha/\alpha < 1.0 \cdot 10^{-8}$$

We investigate here how these constraints confine the parameter of BSBM model [2] of varying α. This theory combines Bekenstein extension of electrodynamics with varying alpha to include gravitational effects of new scalar field ψ. It respects covariance, gauge invariance, causality and has only two free parameters: the fraction of electromagnetic energy ζ_m in the total energy of matter including dark matter as well as the dimensional parameter l which is having sense of fundamental length. Integrating the coupled system of equations from the Big Bang up to the present time and taking into account the Oklo limits we have obtained the following margin on the combination of the parameters of BSBM model:

$$|\zeta_m(\frac{l}{l_{pl}})^2| < 6 \cdot 10^{-7},$$

where $l_{pl} = (\frac{G\hbar}{c^3})^{\frac{1}{2}} \approx 1.6 \cdot 10^{-33}$ cm is a Plank length. The natural value of the parameter ζ_m for ordinary matter is about 10^{-4} and could be as large as about $|\zeta_{CDM}| = 1$ for cold dark matter [2]. As a result it is followed from our analysis that the fundamental length l of BSBM theory should be considerably smaller than the Plank length to fulfill the Oklo constraints on α variation.

---

[1] M. S. Onegin *et al.*, Mod. Phys. Lett. A **27** (2012) 1250232.

[2] H. B. Sandvik *et al.*, Phys. Rev. Lett. **88** (2002) 031302.

Higher-order constraints on precision of the time-frequency metrology of atoms in optical lattices

V.D. Ovsiannikov[a], V.G. Palchikov[b]

[a] *Voronezh State University, Voronezh, Russia*
[b] *VNIIFTRI, Mendeleevo, Moscow Region, Russia*

Numerical estimates of nonlinear, anharmonic and multipole effects on precision of the time-frequency standard of atoms trapped in an optical-lattice standing wave of a magic wavelength (MWL) demonstrate strong influence of the atom-lattice interaction on the clock-level shifts.

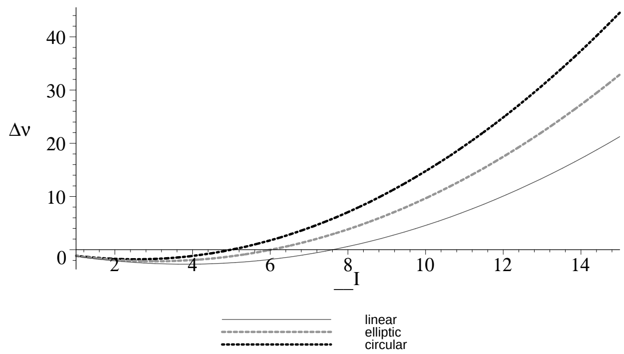
The dependence of the lattice-induced shift of the clock frequency on the lattice-laser intensity I up to quadratic terms may be written as

$$\Delta\nu = c_{1/2}I^{1/2} + c_1 I + c_{3/2}I^{3/2} + c_2 I^2, \qquad (3)$$

where the intensity-independent coefficients c are the functions of the lattice-wave polarization and the quantum number of vibrations in the lattice traps. In addition, the coefficients are strongly dependent on the definition of the MWL. Three different strategies for determining the MWL are proposed for minimizing and taking into account the influence of indicated effects in order to reduce the uncertainties of the clock frequency measurements to the level of $10^{-17} \div 10^{-18}$:

1. Equalization of the clock-level shifts in a traveling wave.
2. Equalization of the clock-level shifts in a standing wave.
3. Equalization of the clock-level dipole polarizabilities.

The dependence of the lattice-induced shifts (3) (in mHz) on the intensity I (in kW/cm^2) of the clock frequency in Sr atoms, trapped to their lowest vibration states, are presented in the figure for the lattice-wave linear, elliptic and circular polarization at the MWL determined in a standing wave (where $c_{1/2} = 0$).



Similar dependencies have been also determined for Yb and Hg atoms and may be used for reducing the clock-frequency fractional uncertainties to the level of $10^{-17} \div 10^{-18}$.

Electric dipole moment search in molecular beam of thorium monoxide: Zeeman interaction in ThO $H^3\Delta_1$

A.N. Petrov[a,b], L.V. Skripnikov[a,b], A.V. Titov[a,b]

[a]*Petersburg Nuclear Physics Institute, Gatchina, Leningrad district 188300, Russia*
[b]*Dept. of Physics, Saint Petersburg State University, Petrodvoretz 198504, Russia*

One of the most intriguing fundamental problems of modern physics is the search for a permanent electric dipole moment (EDM) of elementary particles. The most sensitive probes of the electron EDM are precision measurements of spin precession, in which the energy level shifts caused by interaction of a valence electron (or electrons) with a large effective internal electric $\mathcal{E}_{\rm eff}$ field is determined. The most rigid upper bound on the electron EDM, $|d_{\rm e}| < 8.7\times10^{-29}$ $e{\cdot}$cm (90% confidence), is attained in the experiments on pulsed molecular beam of thorium monoxide (ThO) molecules in the metastable electronic $H^3\Delta_1$ state [5]. Polar molecules have a number of advantages over atoms for electron EDM searches, including a larger $\mathcal{E}_{\rm eff}$, and resistance to a number of important systematics. Some molecules, for example ThO [5], have additional advantages due to the existence of closely-spaced levels of opposite parity, called Ω-doublets. Molecules with Ω-doublets can typically be polarized in modest laboratory electric fields ($1-100$ V/cm), and, in addition, the eEDM measurement can be carried out in different Ω-doublets where the molecular dipole is either aligned or anti-aligned with the external laboratory field, which heavily suppresses many effects related to magnetic fields or geometeric phases but doubles the electron EDM signature. However, the upper and lower Ω-doublet states have slightly different magnetic g-factors. Therefore systematic effects related to magnetic field imperfections and geometric phases can still mimic the eEDM signal. The difference of g-factors, Δg, depends on the lab electric field and these systematics can be further suppressed by operating the experiment at an electric field where the Δg is minimized. It is clear that understanding the g-factor dependence on electric fields is important for understanding possible systematic effects in polar molecule-based electron EDM searches. We have considered g-factors of the Ω-doublets of the ThO in $J=1,2$ rotational levels in the external electric field. We have found that Δg for $J=2$ can be made zero for particular electric field and much smaller than that for $J=1$ for other electric fields values [2]. The small value of Δg means that the $H, J=2$ state should be even more robust against a number of systematic errors compared to $H, J=1$.

This work is supported by the SPbU Fundamental Science Research grant from Federal Budget No. 0.38.652.2013, RFBR Grant No. 13-02-01406. L.S. is also grateful to the President of RF grant No. MK-5877.2014.2.

---

[1] J. Baron,*et al.*, (The ACME Collaboration), Science **343**, (2014) 269.

[2] A.N. Petrov, L.V. Skripnikov, A.V. Titov, N.R. Hutzler, P.W. Hess, B.R. O'Leary, B. Spaun, D. DeMille, G. Gabrielse, and J.M. Doyle, PRA **89** (2014) 062505

Linear Paul trap for confinement of Al^+ and Mg^+ ions

T. Shpakovsky,[a,c] K. Khabarova,[a,b,c] V. Sorokin,[a,c] I. Zalivako,[a] N. Kolachevsky[a,b]

[a] *P.N. Lebedev Physical Institute, 119991 Moscow, Leninsky prospekt 53, Russia*
[b] *VSUE VNIIFTRI, Mendeleevo, Moscow Region, Russia*
[c] *Russian Quantum Center, ul. Novaya 100, Skolkovo, Moscow region, Russia*

Today one of the most precise frequency sources is an optical $^{27}Al^+$ single-ion clock based on the $^1S_0 \rightarrow {}^3P_0$ clock transition with a natural line width of 8 mHz. Extremely low sensitivity of this transition to BBR shift allowed to demonstrate frequency instability of 8.3×10^{-18} [1] thus opening new perspectives for precision metrology, tests of fundamental theories and gravimetry.

To achieve ultimate characteristics of an optical standard one should reach deep laser cooling of ions. Though, the laser cooling transition at 165 nm in Al^+ in not accessible by existing narrow line cw lasers. For deep ground state cooling of an Al^+ ion, an additional laser cooled Mg^+ ion is used (method of sympathetic cooling). Cooling transition $^3S_{1/2} \rightarrow {}^3P_{3/2}$ in Mg^+ has a wavelength of 279.6 nm, which is easily accessible by the fourth harmonic of a semiconductor laser [2]. According to [3] a Mg^+ is also used for reading quantum information about excitation of the clock transition (the method of quantum logic).

In frames of cooperation between National Russian Metrology Institute (VNIIFTRI) and P.N. Lebedev institute we started a project aimed for study of clock transition in single Al^+ ion. Current progress in development of the linear quadrupole ion trap (fig. 1), and laser sources for cooling and interrogation of the ions is presented in this report.

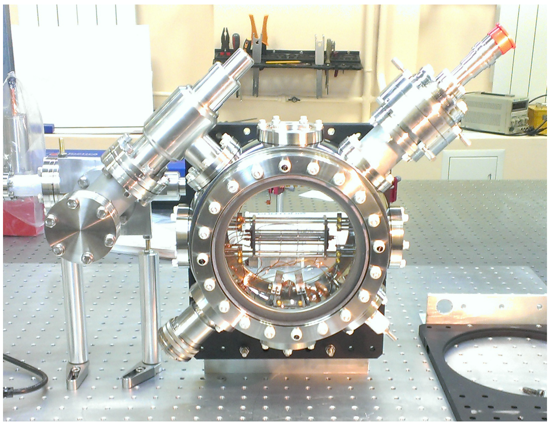


Рис. 1: Linear quadrupole Paul trap for simultaneous confinement of aluminum and magnesium ions

———————————

[1] C. W. Chou, D. B. Hume, et al., Phys. Rev. Lett., 104, 070802 (2010).

[2] M. Herrmann, V. Batteiger, S. Knunz, et al., Phys. Rev. Lett., 102, 013006 (2009).

[3] P. O. Schmidt, T. Rosenband, C. Langer, et al., Science 309, 749 (2005).

Experimental bounds for spacetime torsion

Yuri N. Obukhov[a], Alexander J. Silenko[b,c], Oleg V. Teryaev[b]

[a]*Nuclear Safety Institute, RAS, Moscow, Russia*
[b]*Joint Institute for Nuclear Research, Dubna, Russia*
[c]*Research Institute for Nuclear Problems, BSU, Minsk, Belarus*

Mathematical methods developed in relativistic quantum mechanics [1] are used for description of a Dirac fermion in strong gravitational fields with a spacetime torsion [2]. The general Hermitian Dirac Hamiltonian is derived and is transformed to the Foldy-Wouthuysen representation. General dynamics of the particle spin is determined. The problem of anomalous gravitomagnetic and gravitoelectric moments is considered. New strong bounds on the possible background spacetime torsion for the minimally coupled Dirac fermion are established. The results obtained are based on the recently fulfilled experiments [3]. They are consistent with the earlier estimates of the torsion derived from the Hughes-Drever type experiments [4] and with the experimental limits found in the framework of the search of the Lorentz symmetry violations [3,5].

---

[1] A. J. Silenko, J. Math. Phys. **44** (2003) 2952; Phys. Rev. A **77** (2008) 012116; Part. Nuclei Lett. **10** (2013) 144.

[2] Yu. N. Obukhov, A. J. Silenko, and O. V. Teryaev, arXiv:1410.6197 [hep-th].

[3] F. Allmendinger *et al.*, Phys. Rev. Lett. **112** (2014) 110801.

[4] C. Lämmerzahl, Phys. Lett. A **228** (1997) 223.

[5] V. A. Kostelecký, N. Russell, and J. D. Tasson, Phys. Rev. Lett. **100** (2008) 111102.

Theoretical study of ThO for the electron electric dipole moment search

L.V. Skripnikov[a,b], A.N. Petrov[a,b], A.V. Titov[a,b]

[a] *Petersburg Nuclear Physics Institute, Gatchina, Leningrad district 188300, Russia*
[b] *Dept. of Physics, Saint Petersburg State University, Saint Petersburg, Petrodvoretz 198504, Russia*

Search for permanent electric dipole moment (EDM) of electron is one of the most intriguing fundamental problems of modern physics. A nonzero value of EDM implies manifestation of interactions which are not symmetric with respect to both spatial (P) and time (T) inversions. The observation of the electron EDM at a level significantly greater than 10^{-38} e·cm would indicate the presence of a New physics beyond the Standard model. Popular extensions of the Standard model predict the magnitude of the electron EDM at the level of $10^{-26} - 10^{-29}$ e·cm [1]. In 70^{th} it was shown that diatomic molecules containing heavy atoms are very promising for such experiments. In the systems one can achieve very strong effective electric field ($E_{\rm eff}$) acting on unpaired electrons which leads to the enhanced effect. However, a feature of all these experiments is that the interpretation of their results in terms of electron EDM requires knowledge of the magnitude of the internal effective electric field, which cannot be measured experimentally.

We report a progress of the two-step method [2] developed by our group for calculation of properties such as $E_{\rm eff}$, hyperfine structure constants, etc. in diatomic molecules and atoms. This approach includes relativistic correlation calculation of valence electronic structure using generalized relativistic effective core potential approach followed by the non-variational restoration of four-component electronic structure in the vicinity of heavy atom. Results of the calculations of the effective electric field, g-factor and other parameters of the $^3\Delta_1$ state of ThO molecule [3, 4] are given. Combination of the calculated $E_{\rm eff}$(ThO) with the spin precession measurement of ThO performed by ACME collaboration [5] leads to the most rigid limit on electron EDM: less than 9×10^{-29} e·cm. The limit is an order of magnitude better than the previous best limit.

This work is supported by the SPbU Fundamental Science Research grant from Federal Budget No. 0.38.652.2013, RFBR Grant No. 13-02-01406. L.S. is also grateful to the President of RF grant no MK-5877.2014.2.

———————————

[1] E. D. Commins, Adv. At. Mol. Opt. Phys. 40 (1998) 1.

[2] A. V. Titov, N. S. Mosyagin, A. N. Petrov *et al.*, Progr. Theor. Chem. Phys. B 15 (2006) 253.

[3] L. V. Skripnikov, A. N. Petrov, and A. V. Titov, J. Chem. Phys. 139 (2013) 221103.

[4] L. V. Skripnikov, and A. V. Titov, arXiv:1410.2485 (2014).

[5] J. Baron *et al.*, (The ACME Collaboration), Science 343, (2014) 269.

Searches for dark matter in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS experiment at the LHC

Lidia Smirnova

M.V. Lomonosov Moscow State University, Moscow, Russia

Although the presence of dark matter in the Universe is well established, little is known of its particle nature or its nongravitational interactions. One of the best motivated candidates for such particle is a weakly interacting massive particle (WIMP). At the Large Hadron Collider (LHC), one can search for WIMPs (denoted as χ) that are pair produced in pp collisions. The WIMPs are invisible to the detectors, but the events can be detected if there is associated initial-state radiation of a SM particle.

Searches are presented for WIMP pairs, produced in pp collisions at center mass energy 8 TeV and registered with the ATLAS detector at the LHC with integrated luminosity 20.3 $\text{fb}^{-}1$.

There are three types of searches: for dark matter pair production in association with a W or Z boson, recorded as a hadronic jet [1], for production of dark matter particles recoiling against a leptonically decaying Z boson to two oppositely charged electrons or muons [2], for dark matter pair production in association with bottom or top quarks [3] and with presence of large missing transverse momentum in all types of events.

In each analysis the data are found to be consistent with the Standard Model expectations. The following limits from each of analysis are found, correspondingly.

Limits are set on the mass scale in the effective field theories that describe the interaction of dark matter and standard model particles, and on the cross section of Higgs production and decay to invisible particles.

Limits are set on the mass scale of the contact interaction as a function of the dark matter particle mass using an effective field theory description of the interaction of dark matter with quarks or with Z bosons. Limits are also set on the coupling and mediator mass of a model in which the interaction is mediated by a scalar particle.

Limits on the dark-matterïnucleon cross-section for spin-independent and spin-dependent interactions are established. These limits are particularly strong for low-mass dark matter. Using a simplified model, constraints are set on the mass of dark matter and of a coloured mediator suitable to explain a possible signal of annihilating dark matter.

---

[1] ATLAS Collaboration, Phys. Rev. Lett. **112**, 041802 (2014)

[2] ATLAS Collaboration, Phys. Rev. D **90**, 012004 (2014)

[3] ATLAS Collaboration, arXiv:1410.4031, submitted to Eur. Phys. J. C, CERN-PH-EP-2014-229

Hydrogen and Antihydrogen spectra in presence of external fields

D. Solovyev[a] and L. Labzowsky[a,b]

[a]*Department of Physics, St. Petersburg State University, Petrodvorets, Oulianovskaya 1, 198504, St. Petersburg, Russia*

[b]*Petersburg Nuclear Physics Institute, 188300, Gatchina, St. Petersburg, Russia*

First, a theoretical comparison of the hydrogen (H) and antihydrogen ($\bar{H}$) atoms in an external magnetic field is made. The 21 cm absorption line is the subject of discussion. It is shown that the difference of radiation polarization in this line in an external magnetic field can be used for the search of antihydrogen atom in the universe [1].

Second, we analyze the effect of the Rydberg ns states mixing for the hydrogen atom in the presence of an external electric field. In presence of an external electric field the additional terms arise in the differential transition probability. This leads to the difference in the spectroscopic properties of H and $\bar{H}$ atoms [2].

Third, it is shown that forbidden by the selection rules $E1$ decay is allowed in the presence of an electric field. The linear in the field term vanishes after the integration over photon emission directions and does not contribute to the total decay rate. However, the quadratic in the field term leads to the essential change of the level width in very weak electric field for the highly excited states. The results were obtained analytically and can be applied to any excited state of hydrogen atom [3].

[1] D. Solovyev and L. Labzowsky, Prog. Theor. Exp. Phys., **2014** (2014) 111E01.

[2] D. Solovyev, V. Sharipov, L. Labzowsky and G. Plunien, J. Phys. B, **43** (2010) 074005.

[3] D. Solovyev, *Rydberg states mixing in presence of an external electric field: comparison of the hydrogen and anti-hydrogen spectra*, to be published.

Сверхтонкая структура S- и P-состояний мюонного дейтерия

А. П. Мартыненко[a,b], Г. А. Мартыненко[a], В. В. Сорокин[a], Р. Н. Фаустов[c]

[a]*Самарский государственный университет*
[b]*Самарский государственный аэрокосмический университет имени С.П. Королева*
[c]*Вычислительный центр РАН имени А.А. Дородницина*

В последние годы экспериментальной коллаборацией CREMA (Charge Radius Experiment with Muonic Atoms) достигнут существенный прогресс при изучении энергетической структуры мюонного водорода. Измерение частоты перехода ($2P_{3/2}^{F=2} - 2S_{1/2}^{F=1}$) в мюонном водороде позволило получить на порядок более точное значение зарядового радиуса протона $r_p = 0.84087(39)$ фм, которое отличается на 7 стандартных отклонений от значения рекомендованного CODATA [1, 2]. Измерение частоты перехода $2P_{3/2}^{F=1} - 2S_{1/2}^{F=0}$ для $2S$-состояния позволило найти сверхтонкое расщепление $2S$-уровня, величину радиуса Земаха $r_Z = 1.082(37)$ фм и значение магнитного радиуса протона $r_M = 0.87(6)$ фм. Данные по прецизионным измерениям уровней энергии в мюонном дейтерии, ионах мюонного гелия уже получены и находятся на стадии обработки. Они позволят определить зарядовые радиусы этих ядер с точностью 0.0005 фм, стимулируют новые теоретические расчеты эффектов структуры и поляризуемости ядра, а также поиск путей разрешения "загадки радиуса протона которые лежат за рамками Стандартной Модели.

В настоящей работе нами проведен аналитический и численный расчет поправок порядка α^5 и α^6 сверхтонком расщеплении S- и P-состояний в атоме мюонного дейтерия в рамках квазипотенциального метода в квантовой электродинамике. В работе рассматриваются такие эффекты поляризации вакуума, отдачи, структуры ядра, которые имеют важное значение для достижения высокой точности расчета. Результаты работы уточняют вычисления в [3] за счет учета новых вкладов. Полученные нами численные значения сверхтонких расщеплений [4] можно использовать для сравнения с экспериментальными данными CREMA.

———————————

[1] A. Antognini *et al.*, Science **339** (2013) 417; Ann. Phys. **331** (2013) 127.

[2] P.J. Mohr, B.N. Taylor and D.B. Newwell, Rev. Mod. Phys. **84** (2012) 1527.

[3] E. Borie, Ann. Phys. **327** (2012) 733.

[4] R.N. Faustov, A.P. Martynenko, G.A. Martynenko, V.V. Sorokin, Phys. Lett. B **733** (2014) 354; Phys. Rev. A **90** (2014) 012520.

Interplay of torsion, equivalence principle and Lorentz symmetry violation in spin dragging

Oleg Teryaev

BLTP, Joint Institute for Nuclear Research, Dubna

The physical effects relevant for spin dragging are discussed, with the particular emphasis on modern comagnetometer experiments. The possibility that different effects mimic each other and the options of their disentangling are addressed. The respective bounds are compared and discussed.

Сверхтонкая структура ионов мюонного лития

А.П. Мартыненко[a,b], А.А. Улыбин[a]

[a] *Самарский государственный университет*

[b] *Самарский государственный аэрокосмический университет*

Ионы мюонного лития $(\mu\ e\ {}^6_3Li)^+$, $(\mu\ e\ {}^7_3Li)^+$ представляют собой простейшие трёхчастичные системы, состоящие из электрона, отрицательно заряженного мюона и положительно заряженного ядра лития. Эти атомы имеют сложную сверхтонкую структуру, обусловленную взаимодействием магнитных моментов всех трёх частиц. Расчёты сверхтонкого расщепления основного состояния ионов мюонного лития были выполнены в рамках вариационного метода в [1]. Сверхтонкая структура основного состояния $(\mu\ e\ {}^{6,7}_3Li)^+$ определяется следующим гамильтонианом:

$$\Delta H_0^{hfs} = \frac{2\pi\alpha}{3}\frac{g_\mu g_N}{m_\mu m_p}(\mathbf{S}_\mu\cdot\mathbf{I})\delta(\mathbf{x}_\mu) - \frac{2\pi\alpha}{3}\frac{g_e g_\mu}{m_e m_\mu}(\mathbf{S}_e\cdot\mathbf{S}_\mu)\delta(\mathbf{x}_\mu - \mathbf{x}_e) + \frac{2\pi\alpha}{3}\frac{g_e g_N}{m_e m_p}(\mathbf{S}_e\cdot\mathbf{I})\delta(\mathbf{x}_e), \tag{4}$$

где g_e, g_μ и g_N - гиромагнитные факторы электрона, мюона и ядра. Полный момент трех частиц равен 2, 1 и 0 для $(\mu\ e\ {}^6_3Li)^+$ и 5/2, 3/2 и 1/2 для $(\mu\ e\ {}^7_3Li)^+$. Сверхтонкое расщепление уровней энергии в ионах мюонного лития определяется следующими матричными элементами:

$$\nu = <\Delta H_0^{hfs}> = a\ <\mathbf{I}\cdot\mathbf{S}_\mu> - b\ <\mathbf{S}_\mu\cdot\mathbf{S}_e> + c\ <\mathbf{S}_e\cdot\mathbf{I}>. \tag{5}$$

Цель настоящей работы состоит в прецизионном расчёте коэффициентов b, c, которые определяют малые интервалы сверхтонкой структуры, в рамках теории возмущений, сформулированной в [2, 3]. Были исследованы следующие поправки:

- Поправки на отдачу порядка $\frac{m_e}{m_\mu}\alpha^4$, $\frac{m_e^2}{m_\mu^2}\ln\frac{m_e^2}{m_\mu^2}\alpha^4$, $\frac{m_e^2}{m_\mu^2}\alpha^4$,
- Поправки электронной поляризации вакуума порядка α^6,
- Поправки на структуру и отдачу ядра,
- Электронные вершинные поправки порядка α^5.

Численные значения интервалов малой сверхтонкой структуры равны $\Delta\nu_1 = 14152.55$ МГц и $\Delta\nu_2 = 21573.23$ МГц $(\mu\ e\ {}^6_3Li)^+$; $\Delta\nu_1 = 13996.28$ МГц и $\Delta\nu_2 = 21732.18$ МГц $(\mu\ e\ {}^7_3Li)^+$. Полученные результаты могут служить надёжной оценкой при сравнении с будущими экспериментальными данными и проверки предсказаний квантовой электродинамики.

————————————

[1] A.M. Frolov, Phys. Lett. A **357** (2006) 334; Phys. Rev. A **61** (2000) 022509.

[2] S.D. Lakdawala and P.J. Mohr, PRA **22** (1980) 1572; **24** (1981) 2224; **29** (1984) 1047.

[3] A.A. Krutov and A.P. Martynenko, PRA **78** (2008) 032513; EPJ D **62** (2011) 163.

Shadow size measurements as a tool to evaluate Λ-term

Alexander F. Zakharov[a,b]

[a] *Institute of Theoretical and Experimental Physics, Moscow, 117218, Russia*
[b] *Bogoliubov Laboratory of Theoretical Physics, JINR, Dubna, 141980 Russia*

The black hole at the Galactic Center is the closest supermassive black hole. So, there is an opportunity to check predictions of general relativity for the object and to evaluate black hole parameters. Using Schwarzschild – de-Sitter (Kottler) metric we derive a simple analytical relation between a shadow size and Λ-term. Current observations of the smallest spot to evaluate shadow size at the Galactic Center do not reach an accuracy comparable with cosmological Λ-term $\sim 10^{-52}\mathrm{m}^{-2}$, however, if in reality we have dark energy instead of a constant Λ-term then dark energy may be a function depending on time and space and it could be approximated with a local constant Λ-term near the Galactic Center and it is important to introduce a procedure to evaluate the Λ-term. We suggest such a procedure based on a black hole shadow evaluation. Surprisingly, current observational estimates of shadows are in agreement with anti-de-Sitter spacetimes corresponding to a negative Λ-term which is about $-0.4 \times 10^{-20}\mathrm{m}^{-2}$. A negative Λ-term has been predicted in the framework of a some class of multidimensional string models.

[1] A. F. Zakharov, *Physical Reviews D* **90** (2014) 062007.

[2] A. F. Zakharov, F. de Paolis, G. Ingrosso, A.A. Nucita, *New Astronomy Reviews*, **56** (2012) 64.

Spin-Statistic Selection Rules for Multi-Equal-Photon Transitions in Atoms: Extension of the Landau-Yang Theorem to Multiphoton Systems

T. Zalialiutdinov[1], D. Solovyev[1], L. Labzowsky[1,2] and G. Plunien[3]

[1]*Department of Physics, St.Petersburg State University, Ulianovskaya 1, Petrodvorets, St.Petersburg 198504, Russia*

[2]*Petersburg Nuclear Physics Institute, 188300, Gatchina, St. Petersburg, Russia*

[3]*Institute für Theoretische Physik, Technische Universität Dresden, Mommsenstrasse 13, D-10162, Dresden, Germany*

We establish the existence of spin-statistic selection rules (SSSR) for multi-equal-photon transitions in atomic systems. These rules are similar to the rules for systems of many equivalent electrons in atomic theory, which appears as the direct consequence of Pauli exclusion principle. In this sense the SSSR plays the role of an exclusion principle for photons: they forbid some particular states for the photon systems. We established the SSSR for few-photon systems for three cases: 1) SSSR-1: two-equivalent photons involved in any atomic transition can have only even values of the total angular momentum J . This SSSR is an extension of the Landau-Yang theorem [1], [2] to the photons involved in atomic transitions. 2) SSSR-2: three equivalent dipole photons involved in any atomic transition can have odd values of the total angular $J = 1, 3$. 3) SSSR-3: four equivalent photons involved in any atomic transition can have only even values of the total angular momentum J=0, 2, 4. We also suggest a method for a possible experimental test of SSSR with employment of lasers. As numerical examples we considered the two-photon decay of 2^3S_1, 2^1S_0 and 2^3D_3 states and three photon transitions $2^3P_2 \to 1^1S_0 + 3\gamma(E1)$, $2^3P_1 \to 1^1S_0 + 3\gamma(E1)$ in the helium-like uranium ion. These calculations were performed fully relativistic but with full neglect of the interelectron interaction since it scales like $1/Z$. Accordingly, for He-like HCI together with the neglect of the interelectron interaction the calculations become as simple as for one-electron ions. On the other hand the He-like ions have essentially more reach spectrum which allows to find many possibilities for the application of the SSSR. The latter, however are based on the symmetry properties will remain the same even after the inclusion of the interelectron interaction. Of course, the predicted values for the transition rates obtained in such an approximation will be far from being accurate for the neutral helium, but will become increasingly more accurate for the HCI with high Z values, in particular for uranium, where $Z = 92$. The SSSR should hold not only for two-electron atoms and ions but also for the multiphoton processes in any many-electron atoms or ions. Here we focus on two-electron HCI because in these systems the action of the SSSR becomes more transparent.

---

[1] L. D. Landau, Dokl. Akad. Nauk SSSR **60** (1948) 207.

[2] C. N. Yang, Phys. Rev. **77** (1950) 242.