"Alexandru Ioan Cuza" University of Iasi
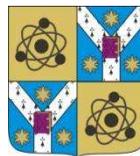
Faculty of Physics

ABSTRACT OF PhD THESIS

EVOLUTION OF MESOSCALE QUANTUM SISTEM

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Iaşi – 2012

ACKNOWLEDGMENTS

The results of our research became possible due to a qualified and professional guidance, and the necessary conditions appropriate to perform the scientific research of the approached subjects as well.

In this respect, I want to express my deep gratitude to my scientific adviser, prof.univ.dr. Marina-Aura DARIESCU, for her patience and understanding in leading my way in this beautiful and broad domain of research, for her competence and valuable suggestions offered during my investigations, as well as for her support while finalizing the PhD thesis.

I also express the deepest thanks to prof.univ.dr Ciprian DARIESCU, for both moral support and scientific advice during the preparation of the PhD thesis.

My thanks and gratitude to prof.univ.dr.Liliana MITOSERIU, prof. univ.dr. Violeta GEORGESCU, prof.univ.dr. Alexandru STANCU, and prof. univ.dr. Florin-Ovidiu CALTUN, who assured the quality of the educational process during my instruction and specialization under the "Advanced university training program" which I attended during my first year of doctorate school.

My thanks to prof.univ.dr. Felicia IACOMI, prof.univ.dr. Ioan MERCHES, prof.univ.dr. Viorel MELNIG, conf.univ.dr. Liviu LEONTIE, conf. univ.dr. Laurentiu STOLERIU, as well as my colleague postdoc. researcher Cristian STELEA for their help, advice and encouragement offered during all these years.

Lots of thanks to my sun Vlad-Ionel, my wife Luminita, my mother and -last but not least - my sister, for their moral support, understanding, spiritual warmth and devotion showed to me while finalizing the PhD thesis, who were at my elbow during these years and whom this thesis is dedicated to.

Finally, I want to thank The Lord for being with me in my endeavor of preparing this thesis, and for all my achievements so far.

CONTENTS

INTRODUCTION

The study of mesoscopic dynamics, within the frame of relativistic quantum theories and finite temperatures, is one of the most actual subjects, with deep implications in both understanding the microscopic processes and development of high technology at the nanometric scale.

The aims of our PhD thesis entitled Evolution of mesoscale quantum systems are:

a. Study of behavior of relativistic particles, bosons and fermions, by means of both functional and analytic-numeric analysis of the corresponding differential equations describing their evolution in external electric and magnetic fields, weak or intense, static or time-variable, from quantum and thermodynamic point of view;

b. Detailed analysis of solutions compatible with the experimental

data, from the point of view of the quantization relations accompanying the model.

c. Determination of certain general relations of quantization of energetic levels, of currents components, of Hall conductivity and rezistance, within the frame of experimental results.

The thesis contains 4 chapters. Each chapter can be followed independenly from each other. At the end, a chapter of conclusions and a list of references are inseted.

The relativistic quantum mechanics formalism, in $U(1)$ covariant

gauge formulation, the basics of the theory as well as sign conventions are presented in 3 Appendices.

The original search results have been published in four ISI-quoted periodicals, three B+ -quoted periodicals, one in Annals of the Timisoara University, and have been also presented at seven national conferences.

I. STUDY OF RELATIVISTIC BOSONS, PLACED IN STATIC FIELDS, AT FINITE TEMPERATURE

The Hall effect [1], which is essential in solid state physics, represents an important instrument in conductors and semiconductors diagnostics and description, especially after discovery of its quantum variants (QHE).

The experiments performed in 1980 by Klaus von Klitzing on twodimensional structures situated in high intensity magnetic fields, at very low temperature, led to the discovery of the integer quantum Hall effect (IQHE).

It was shown that the discrete values of the quantum Hall conductance are integer multiples of a fundamental constant [6].

In 1982, Horst Störmer, Daniel Tsui, and Robert Laughlin discovered the fractional quantum Hall effect (FQHE) [8] in a bi-dimensional electronic gas, limited by interfaces of a high quality semiconductor, placed in a very strong magnetic field (approxroximately 20 T). In 2005, Kostya Novoselov and collaborators have experimentally observed another type, unconventional, of quantum Hall effect (UQHE) in the graphen layer. The results show an anomaly of the usual quantum Hall effect, even if the Hall conductivity is also quantized [12].

Inspired by these results, in Chapter I we have studied the behavior of the relativistic scalar particles in electric and magnetic static orthogonal fields, in view of quantum theories. In the case of finite temperature the most important thermodinamic quantities as well as the equation of state have been calculated, in order to put into evidence contribution of the quantic and relativistic terms, which generalize the actual results of scientific literature.

SELECTIVE REFERENCES

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[29] M. A. Dariescu, O. Buhucianu , C. Cretu, The Lorentz-invariant *U(1)*-gauge theory of scalars in static external fields and thermal proper-ties, accepted for publication in Buletin of Polytechnical Institute of Iasi.

II. GENERATION OF SCALAR PARTICLES IN INTENSE ELECTRIC FIELDS

In this chapter we approach the process of particle generation in intense electric fields [3].

The first part of Chapter II is dedicated to the study of the relativistic bosons generation, in intense static electric fields, orthogonal to magnetic fields (the relation between the fields intensities is $E_0 \, / \, c > B_0$).

In the last section, the analysis has been extended over periodical fields. The resonance conditions and the instability intervals stand for original results and have been published in an ISI-quoted journal.

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[17] A. A. Grib, S. G.Mamayev, V. M. Mostepanenko, *Vacuum quantum effects in strong fields*, Friedmann Laboratory Publishing, St. Petersburg (1994).

[28] O. Buhucianu, M. A. Dariescu, C. Dariescu, *Relativistic bosons in time-harmonic electric fields*, International Journal of Theoretical Physics, **51**, (2), (2012), 526-535.

[30] N. W. McLachlan, *Theory and application of Mathieu function*, New York, Oxford University Press, (1951).

III. BEHAVIOR OF GRAPHENE-TYPE FERMIONS IN EXTERNAL STATIC FIELDS

As it is known, the graphene free quasiparticles show o linear dispersion relation $E = \hbar k v_F$, This relation characterize the relativistic massless particles. An important property is the existence of zero-energy state, meaning a null width of forbidden zone [12].

SELECTIVE REFERENCES

[12] A. K. Geim, K. S. Novoselov, *The rise of graphene,* Nature Materials, **6**, (2007), 183 – 191.

[40] M. A. Dariescu, O. Buhucianu, I. Aștefănoaei, *Chiral electrons in static fields at finite temperature*, Romanian Journal of Physics, **56**, (9-10), (2011), 1043-1052.

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[61] <u>O. Buhucianu</u>, *Massless fermions in external fields in terms of Heun's functions,* Acta Physica Polonica, B, **43**, (3), (2012), 397-404.

IV. STUDY OF EVOLUTION OF RELATIVISTIC BOSONS IN SPACE-PERIODICAL POTENTIALS

The first part of this chapter is dedicated to the investigation of behavior of scalar particles dynamics in periodical potentials. Our endeavor has been inspired by the importance of periodical potentials in solid state physics, as shown in paper [7]. Here the author uses a high-intensity laser, similar to that utilized in nuclear fusion. Next, we have performed a detailed analysis of relativistic bosons in high-intensity magnetic fields, similar to those existent in highly-magnetized neutron stars.

SELECTIVE REFERENCES

[7] W. Becker, R. Meckbach, H. Mitter, *Motion of relativistic particles in standing wave fields*, J. Phys. A: Math. Gen., **12**, (6), (1979), 798-809.

[12] M. A. Dariescu, C. Dariescu, <u>O. Buhucianu</u>, *Charged scalars in transient stellar electromagnetic fields*, Chinese Physics Letters, **28**, (1), 010303, (2011), 1-4.

[26] C. J. Wareing, R. Hollerbach, *Hall cascades versus instabilities in neutron star magnetic fields*, Astron. Astrophys., **508,** (2009), L39-L42.

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GENERAL CONCLUSIONS

Since each chapter contains a section of conclusions, where the main results are highlighted and comparisons with other authors' papers are performed, in this section we synthesize some general conclusions which we consider as being representative. These conclusions have been published in both ISI-quoted periodicals, and in periodicals acknowledged by CNCSIS.

The obtained results can be synthesized as follows:

1. For relativistic bosons placed in electric and magnetic static orthogonal fields have been obtained the wave functions and the energy spectrum, [M. A. Dariescu, O. Buhucianu , C. Creţu, *The Lorentz-invariant U(1)-gauge theory of scalars in static external fields and thermal properties,* Buletinul Institut Politehnic Iaşi, **2**, Tom LVII(LXII), (2012), 43-54.] in good agreement with the results found by other authors. Within the thermodynamic study, the partition function expressed by the generalized Euler and Riemann functions led us to the main thermodynamic quantities, magnetization and susceptibility. A Hall-type term, as well as supplementary contributions characterizing ultrarelativistic particles have been introduced in the equation of state. In some particular cases, according to a certain parameter range, the state equation leads to classical thermodynamic results (for high temperatures) and quantum effects (for low temperatures), in agreement with Nernst theorem.

2. In order to obtain information about the process of generation of relativistic particles in static intense electric field, orthogonal to a weak magnetic field, we developed a non-perturbative calculation of the generation probability. This procedure offers information on the control and suppression of particle generation by means of variation of the magnetic field induction [M. A. Dariescu, C. Dariescu, O. Buhucianu, *Quantum tunnelling of bosons in electro-magnetic static fields*, Bul. Institut Politehnic Iasi, Tom **LVI(LX)**, (2010), 105-112].

The same generation process has been approached in the frame of WKB formalism [M. A. Dariescu, C. Dariescu, O. Buhucianu, *Bosons generation in strong electric fields via WKB formalism*, acceptată spre publicare în Analele Universităţii Timişoara], generalizing the results existent in scientific literature.

This kind of generation processes take place in relativistic stellar objects, with electric field touching the critical value and intense magnetic

fields $(10^8 - 10^{11})$ T, of the type of those existent in magnetars [M. A. Dariescu, C. Dariescu, O. Buhucianu, *Charged Scalars in Transient Stellar Electromagnetic Fields*, Chinese Physics Letters, **28**, (1), (2011), 010303, 1-4].

3. In the case of time-variable electric fields, with considerable implications in technology, the wave functions of relativistic bosons are expressed by means of Mathieu functions. This way, the instability intervals appearing as a result of the paramagnetic resonance are highlighted [O. Buhucianu, M. A. Dariescu, C. Dariescu, *Relativistic Bosons in Time-Harmonic Electric Fields,* International Journal of Theoretical Physics, **51,** (2)**,** (2012), 526-535].

4. In the case of massless relativistic fermions of graphene-type, the solutions are described by the associated Hermite functions only in some particular cases [O. Buhucianu, M. A. Dariescu, C. Dariescu, *Graphene-like fermions in uniform magnetic fields,* Buletinul Institutului Politehnic din Iași, **LVII(LXI)**, (2011), Fascicula 3, 97-106], existant in literature. Our investigation is relevant by the fact that we have used a (3+1)-dimensional theory, which can also be applied on the graphene with defects. This way we have obtained closed forms of the orthogonal modes and of the current density components as well, the last ones depending on the sample dimensions.

Keeping the (3+1)-dimensional formulation to describe the minimally coupled fermions in external electric and magnetic fields, in addition to Novoselov's term in the energy spectrum of graphene, we obtained a term depending on the p_z - component of momentum and on the chemical potentialtype, which control the conduction properties of fermions in the sample [M. A. Dariescu, O. Buhucianu, I. Aștefănoaei, *Chiral Electrons in Static Fields at Finite Temperature*, Romanian Journal of Physics, **56**, (9-10), (2011), 1043-1052].

6. In the case of electric and magnetic fields of arbitrary intensities, the wave functions can be expressed in terms of HeunB functions. This procedure furnishes a generalization of the results existent in literature, as we have shown in paper [O. Buhucianu, *Massless fermions in external fields in terms of Heun's functions,* Acta Physica Polonica, B, **43** , (3), (2012), 397-404].

7. We extended our analysis on relativistic scalar particles, evolving in a stationary electromagnetic field, generated by two lasers which produce coherent, circularly polarized monochromatic radiation of

opposite helicity. The obtained energy spectrum depends on the intensity of laser beam, and brings to light quantum effects.

8. We have proved that, when high-intensity periodical fields are considered, when the relativistic particles momenta is situated in a certain interval, determined by the field structure and intensity, one can arrive at a resonance phenomenon. Such fields exits, for example, in a crust of a highlymagnetized neutron star, called magnetar. The instable behavior of the wave function can give rise to exotic phenomena, as we have shown in [M. A. Dariescu, C. Dariescu, O. Buhucianu, *Charged Scalars in Transient Stellar Electromagnetic Fields*, Chinese Physics Letters, **28**, (1), (2011), 010303, 1-4]. These phenomena could explain the giant flares explosions, displayed by these special astrophysical objects.

A.   LIST OF OWN PUBLICATIONS

A. 1. LIST OF ISI PUBLICATIONS

1. O. Buhucianu, M. A. Dariescu, C. Dariescu, *Relativistic Bosons in Time-Harmonic Electric Fields,* International Journal of Theoretical Physics, **51,** (2)**,** (2012), 526-535.

2. M. A. Dariescu, O. Buhucianu, I. Aştefănoaei, *Chiral Electrons in Static Fields at Finite Temperature*, Romanian Journal of Physics, **56**, (9-10), (2011), 1043-1052.

3. O. Buhucianu, *Massless fermions in external fields in terms of Heun's functions,* Acta Physica Polonica B, **43** , (3), (2012), 397- 404.

4. M. A. Dariescu, C. Dariescu, O. Buhucianu, *Charged Scalars in Transient Stellar Electromagnetic Fields*, Chinese Physics Letters, **28**, (1), (2011), 010303, 1-4.

A. 2. PUBLICATIONS IN UNIVERSITY PERIODICALS

1. M. A. Dariescu, C. Dariescu, O. Buhucianu , *Quantum tunnelling of bosons in electro-magnetic static fields*, Bul. Institut Politehnic Iasi, Tom **LVI(LX)**, (2010), 105-112.

2. O. Buhucianu, M. A. Dariescu, C. Dariescu, *Graphene-like fermions in uniform magnetic fields,* Buletinul Institutului Politehnic din Iaşi, **LVII(LXI)**, (2011), Fascicula 3, 97-106.

3. M. A. Dariescu, O. Buhucianu , C. Creţu, *The Lorentz-invariant U(1)-gauge theory of scalars in static external fields and thermal properties,* Buletinul Institut Politehnic Iaşi, **2**, LVII(LXII), (2012), 43-54.

4. M. A. Dariescu, C. Dariescu, Ovidiu Buhucianu, *Bosons Generation In Strong Electric Fields Via Wkb Formalism*, acceptată spre publicare în Analele Universităţii Timişoara.

B. PAPERS PRESENTED AT INTERNATIONAL CONFERENCES

1. M. A. Dariescu, O. Buhucianu , C. Dariescu, *Analytic Study of Fermions in Graphene; Heun Functions and Beyond*, The 9th (***oral presentation***) International Conference On Physics Of Advanced Materials (ICPAM-9), Alexandru Ioan Cuza University of Iasi, Romania, (2012).

C. PAPERS PRESENTED AT NATIONAL CONFERENCES

1. M. A. Dariescu, O. Buhucianu, C. Dariescu, *Quantum Hall Behavior of Relativistic Bosons*, National Conference on Theoretical Physics, fourth edition, Iasi, Romania, (2010).

2. M. A. Dariescu, C. Dariescu, O. Buhucianu, *Quantum tunnelling of bosons in electro-magnetic static fields*, The 4rd National Conference of Applied Physics, Iaşi, Romania, (2010).

3. M. A. Dariescu, C. Dariescu, <u>O. Buhucianu</u>, *Bosons Generation In Strong Electric Fields Via Wkb Formalism*, Physics Conference TIM – 10, Timişoara, Romania, (2010).

4. <u>O. Buhucianu</u>, *Relativistic bosons in static magnetic fields*, The 40-th Conference on Physics and Modern Education Technologies – FTEM, Iasi, Romania, (2011).

5. <u>O. Buhucianu</u>, G. Bîrzu, *Procese Cuantice De Generare In Câmpuri Externe*, PhD Students Workshop on Fundamental and Applied Research in Physics, Iaşi, Romania, (2011).

6. <u>O. Buhucianu</u>, M. A. Dariescu, *On the Quantum Evolution of Mesoscopic Systems*, Spring Meeting of Physicist PhD. Students Faculty of Physics, Alexandru Ioan Cuza University, Iaşi, Romania, (2012).

7. G. Bârzu, <u>O. Buhucianu,</u> M. A. Dariescu, *A semiclassical description of pair production in quantum mechanics,* The 41-th Conference on Physics and Modern Education Technologies, Faculty of Physics, Alexandru Ioan Cuza University, Iasi, Romania, (2012).