STUDIES IN THEORETICAL HIGH ENERGY PARTICLE PHYSICS

Technical Progress Report

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ABSTRACT

This is a technical progress report for grant no. DE-FG02-84ER40173 describing research carried out in 1989-1990.

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TECHNICAL PROGRESS REPORT (Grant No. DE-FG02-84ER40173)

In this report, we describe technical progress achieved in various areas of research in 1989-1990. A detailed account of our work can be found in the following articles, which have either been published or circulated in preprint form. The publications are labeled by the names of physicists in our group [A = Aratyn, B = Brekke, K = Keung, P = Panigrahi, S = Sukhatme].

- A1. Abelianized Virasoro Operators, Geometry and the String Vertex Operator
Aratyn, R. Ingermanson
Published in Int. J. Mod. Phys. **A4**, 3503-3575 (1989)
- A2. Covariant BRS Quantization of the 10D $N = 1$ Brink-Schwarz Superparticle
Aratyn and R. Ingermanson
Published in Phys. Rev. **D39**, 503-508 (1989)
- A3. On the Geometry of the Graded Constraint Algebras; Vielbeins, Metric Tensors and the String Vertex Superoperators
Aratyn
Published in Mod. Phys. Lett. **A4**, 1667-1679 (1989)
- A4. BRS Cohomology in Terms of the Abelian String Operators
Aratyn
Published in Classical and Quantum Gravity **6**, L125-L131 (1989)
- A5. BRS Cohomology in String Theory; Geometry of Abelianization and the Quartet Mechanism
Aratyn
Published in Journal of Mathematical Physics **31**, 1240-1252 (1990)
- A6. A Geometric Approach to the String BRS Cohomology
Aratyn
Talk at the XVIIth International Conference on Differential Geometric Methods in Theoretical Physics: "Physics and Geometry", Tahoe City, CA, July 2-8, 1989, in Differential Geometric Methods in Theoretical Physics, Plenum, N.Y. (1990) 423-435
- A7. Superspace Actions on Coadjoint Orbits of Graded Infinite-Dimensional Groups
Aratyn, E. Nissimov, S. Pacheva and S. Solomon
Published in Phys. Lett. **234B**, 307-314 (1990)
- A8. Symplectic Actions on Coadjoint Orbits
Aratyn, E. Nissimov, S. Pacheva and A. H. Zimmerman
Published in Phys. Lett. **240B**, 127-132 (1990)
- A9. Noether Theorem for Geometric Actions and the Area Preserving Diffeomorphisms on Torus
Aratyn, E. Nissimov, S. Pacheva and A.H. Zimmerman
Published in Phys. Lett. **242B**, 377-382 (1990)

- A10. On the Group Theoretical Meaning of the Conformal Field Theories in the Framework of Coadjoint Orbits
 Aratyn, E. Nissimov and S. Pacheva
 UICHEP-TH/90-6
 May 1990, 6pp, to be published in Phys. Lett. B
- A11. The Hidden Kac-Moody Symmetry of the Geometric Actions
 Aratyn, E. Nissimov and S. Pacheva
 UICHEP-TH/90-15
 July 1990, 10pp, to be published in Mod. Phys. Lett. A
- A12. Coset Construction of Superstrings via the Coadjoint Orbit Method
 Aratyn, E. Nissimov and S. Pacheva
 UICHEP-TH/90-16
 Aug. 1990, 9pp, to be published in Mod. Phys. Lett. A
- A13. Kac-Moody Construction of Toda Type Field Theories
 Aratyn, L.A. Ferreira, J.F. Gomes and A.H. Zimerman
 UICHEP-TH/90-17
 Sept. 1990, 11pp. to be published in Phys. Lett. B
- A14. Infinite-Dimensional Noether Symmetry Groups and Quantum Effective Actions from Geometry
 Aratyn, E. Nissimov and S. Pacheva
 UICHEP-TH/90-20
 Sept. 1990, 11pp submitted for publication
- B1. Statistics of 2D Solitons and 3D Vortices
 Brekke and T. Imbo
 Univ. of Illinois at Chicago preprint UICHEP-TH/90-21 (1990)
- B2. Anyonic Nielsen-Olesen Vortices
 Brekke, A.F. Falk, S.J. Hughes and T. Imbo
 Univ. of Illinois at Chicago preprint UICHEP-TH/90-22 (1990)
- K1. Higgs-Boson-Mediated Neutrinoless Double Beta-Decay and Neutrino Mass in a Majoron Model
 Keung and D. Chang
 Phys. Rev. D **39**, 1386-1390 (1989)
- K2. Constraints on Muonium-Antimuonium Conversion
 Keung and D. Chang
 Phys. Rev. Lett. **62**, 2583-2585 (1989)
- K3. Z Boson Bremsstrahlung in Heavy Quark Decay
 Keung, V. Barger and T. Rizzo
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- K4. Flavor-Changing Decays of Fourth Generation Quarkonium
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- K5. Z-Boson Decays to Heavy Quarkonium
Keung, V. Barger and K. Cheung
Phys. Rev. **D41**, 1541 (1990)
- K6. QCD Corrections to CP Violation from the Color Electric Dipole Moment of the b Quark
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Phys. Lett. **241B**, 589-592 (1990)
- K7. Gauge Hierarchy and Attractive Feeble Long-Range Force
Keung, D. Chang and P. Palash
Phys. Rev. **D42**, 630-635 (1990)
- K8. Neutrino Magnetic Moment and Nonabelian Discrete Symmetry
Keung, D. Chang and G. Senjanovic
Phys. Rev. **D42**, 1599-1603 (1990)
- K9. Photon Bremsstrahlung In Heavy-Top-Quark Decay
Keung, V. Barger and A. Strange
Phys. Rev. **D42**, 1835-1936 (1990)
- K10. Two Loop Bosonic Contribution to the Electron Electric Dipole Moment
Keung, D. Chang and T.C. Yuan
submitted to Phys. Rev. **D** (1990)
- K11. The Electric Dipole Moment of W Boson
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submitted to Nucl. Phys. **B** (1990)
- K12. Chromoelectric Dipole Moment of Light Quarks Through Two Loop Mechanism
Keung, D. Chang and T.C. Yuan
submitted to Phys. Lett. **B** (1990)

- P1. Radiative Symmetry Breaking in (2+1)-dimensional Space
Panigrahi, K. S. Babu and S. Ramaswamy
Phys. Rev. **D39**, 1190 (1989)
- P2. Canonical Structure of the O(3) Non-linear Sigma Model with a Topological Term
Panigrahi, T. L. Olczyk and S. Ramaswamy
Z. Phys. **C45**, 653-656 (1990)
- P3. Radiative Decay of Mesons and Anomaly in 2+1 Dimensions
Panigrahi, T. L. Olczyk and C. Roy
to appear in Z. Phys. **C** (1990)

- P4. Effective Lagrangian for a System of Non-relativistic Fermions in 2+1 Dimensions Coupled to an Electromagnetic Field: Application to Anyonic Superconductors
Panigrahi, R. Ray and B. Sakita
submitted to Phys. Rev. **B42**, 4036 (1990)

- P5. Covariant Operators, Higher Spin Conformal Algebras and the Boussinesq Sequence
Panigrahi, Q. Wang, U. Sukhatme and W.-Y. Keung
Nucl. Phys. **B344**, 196 (1990)

- S1. Phase Equivalent Potentials Obtained from Supersymmetry
Sukhatme and A. Khare
Jour. Phys. **A22**, 2847 (1989)

- S2. Families of Strictly Isospectral Potentials
Sukhatme, W.-Y. Keung, Q. M. Wang and T. Imbo
Jour. Phys. **A22**, L987 (1989)

- S3. Countable Infinity of Isospectral Potential Families
Sukhatme and A. Khare
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- S4. Solitons from Supersymmetry
Sukhatme, Q. M. Wang, W.-Y. Keung and T. Imbo
Mod. Phys. Lett. **A5**, 525 (1990)

- S5. Supersymmetry Inspired WKB Approximation in Quantum Mechanics
Sukhatme, R. Dutt and A. Khare
Univ. of Illinois at Chicago preprint UICPHY-TH/90-4 (1990)

- S6. Analog of the EMC Effect in Neutrino-Nucleus Interactions
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Int. Jour. Mod. Phys. A (1990)

- S7. Small- x Shadowing in Dimuon Production
(with K. Lassila)
Univ. of Illinois at Chicago preprint UICHEP-TH/90-8 (1990)

- S8. Dilepton Production by Protons on Nuclei and the Partonic Origin of Depletion at Small Momentum Fraction
(with K. Lassila, A. Harindranath and J. Vary)
Univ. of Illinois at Chicago preprint UICHEP-TH/90-11 (1990)

- S9. Gluon Structure Functions in Nuclei from the Quark Cluster Model
(with G. Wilk and K. Lassila)
Univ. of Illinois at Chicago preprint UICHEP-TH/90-10 (1990)

- S10. Backward Hadrons from Deep Inelastic Lepton Scattering on Nuclei
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- S11. Nuclear Effects in the Hadroproduction of Charm
Sukhatme, P. Hoyer, B. P. Mahapatra and K. Sridhar
Phenomenology of the Standard Model and Beyond
Proc. Workshop on High Energy Physics Phenomenology, TIFR, Bombay (1989),
edited by D. P. Roy and P. Roy, p. 173

- S12. Violation of Factorization in Charm Hadroproduction
(with P. Hoyer and M. Vanttinen)
Phys. Lett. **246B**, 217 (1990)

- S13. Finite Eigenfunctions in the WKB Approximation
(with A. Pagnamenta)
Univ. of Illinois at Chicago preprint UICHEP-TH/90-5 (1990)

- S14. Non-Divergent Semiclassical Wave Functions in Supersymmetric Quantum Mechanics
(with A. Pagnamenta)
Univ. of Illinois at Chicago preprint UICHEP-TH/90-9 (1990);
to appear in Phys. Lett. **A**

We give below a brief description of the main areas in which new physics results were obtained.

I. H. Aratyn

A. BRS Operator and Physical States of the String Model (A1,A3-A6)

We found the abelian representation of the string BRS cohomology in terms of basic operators forming naturally two dual Kugo-Ojima quartets. Furthermore, using our gauge-fixing scheme, we constructed a method providing the explicit realizations of both the physical and unphysical subspaces for the string theory.

The passage between abelian and nonabelian quantities was realized geometrically through the use of the moments of the vertex operator, which acted as vielbeins between infinite-dimensional algebras. We have clarified the connection between the Virasoro and the spectrum-generating algebra and uncovered the algebraic duality relation between them.

B. Covariant BRS Quantization of the Green-Schwarz Superstring (A2)

The superstring action can be written in two different ways. The corresponding actions are called, respectively, the Neveu-Schwarz-Ramond and the Green-Schwarz actions. The Neveu-Schwarz-Ramond formalism allows covariant quantization but the space-time supersymmetry is obscure in this model. On the other hand, the Green-Schwarz action possesses the attractive feature of being manifestly supersymmetric. For this reason there has recently been an extensive amount of work dedicated to the investigation of quantizing the Green-Schwarz superstring in the covariant manner and keeping the supersymmetry manifest. Although the light-cone quantization of this model was easily performed the covariant quantization has presented formidable difficulties, due to the presence of both first and second class constraints and the difficulty in separating them covariantly. This lack of covariant quantization of the superstring model is highly unsatisfactory and called therefore for invention of new quantization scheme for dealing with second class constraints. As a step in this direction we have performed the covariant BRS quantization of the $N = 1$ superparticle prototype of the Green-Schwarz superstring in ten dimensions. One of the key ideas was addition of the auxillary variables according to the Batalin-Fradkin formalism for the second class constraints.

C. Construction of the Invariant Actions by the Method of Coadjoint Orbits (A7-A8)

Recently we have extended the method of coadjoint orbits of infinite-dimensional Lie groups for derivation of geometric $D = 2$ field theory actions to the super-Kac-Moody and super-Virasoro groups in a manifestly supersymmetric form. In this way we

derive the explicit expressions for the actions of the supersymmetric chiral Wess–Zumino–Novikov–Witten (WZNW) model and of the induced supergravity (the super–gravitational Polyakov action).

We have also derived a new formula to produce general actions in this framework only in terms of the basic group theoretical objects. The method was illustrated in the number of examples including extended superconformal models.

D. Noether Theorem for Geometric Actions and the Area Preserving Diffeomorphisms on Torus (A9)

We found that within the formalism of coadjoint orbits of the infinite dimensional Lie group the Noether procedure leads, for a special class of transformations, to the constant of motion given by the fundamental group one-cocycle S . Use is made of the simplified formula giving the symplectic action in terms of S and the Maurer–Cartan one-form.

The area preserving diffeomorphisms on the torus $T^2 = S^1 \times S^1$ constitute an algebra with central extension, given by the Floratos–Illopoulos cocycle. We applied our general treatment based on the symplectic analysis of coadjoint orbits of Lie groups to write the symplectic action for this model and study its invariance. We found an interesting abelian symmetry structure of this non-linear problem.

E. On the Group Theoretical Meaning of the Conformal Field Theories in the Framework of Coadjoint Orbits (A10)

We presented an unifying approach to conformal field theories and other geometric models within the formalism of coadjoint orbits of infinite dimensional Lie groups with central extensions. Starting from the previously obtained general formula for the symplectic action in terms of two fundamental group one-cocycles, we derived the most general form of the Polyakov–Wiegmann composition laws for any geometric model. These composition laws are succinct expressions for all pertinent Noether symmetries. As a basic consequence we obtain Ward identities allowing for making further progress in determining the quantum properties of the geometric models.

F. Hidden Kac–Moody of the Geometric Models (A11)

A general formalism was proposed to study infinite-dimensional Noether symmetries in arbitrary field theories on group coadjoint orbits as well as in their gauged versions (coset geometric models). The basic tools are generalized group composition laws valid for any geometric action. As a main application, we presented a general scheme for constructing the "hidden" Kac–Moody currents.

G. Coset Construction of Superstrings via the Coadjoint Orbit Method (A12)

The previously proposed general construction of geometric actions on infinite-dimensional group coadjoint orbits in terms of fundamental group one-cocycles was applied to provide an alternative formulation of the Green-Schwarz superstring. It was shown that the latter model can be consistently constructed as geometric action on a certain infinite-dimensional coset space of the semidirect product of left- and right-handed Virasoro groups with a Kac-Moody group based on an appropriate modification of the super-Helisenberg-Weyl group.

H. Kac-Moody Construction of Toda Type Field Theories (A13)

Using the coadjoint orbit method we derived a geometric WZWN action based on the extended two-loop Kac-Moody algebra, which we had introduced for the purpose of study models exhibiting both conformal invariance and integrability. We have shown that under a Hamiltonian reduction procedure, which respects conformal invariance, one obtains a hierarchy to Toda type field theories, containing as submodels the Toda molecule and periodic Toda lattice theories. We also discussed the classical r -matrix and the integrability properties of resulting models.

I. Infinite-Dimensional Noether Symmetry Groups and Quantum Effective Actions from Geometry (A14)

We have considered quantum effective actions for arbitrary models possessing an infinite-dimensional group G of Noether symmetries. We observed that the relevant Ward identities yield functional differential equations for the effective action whose exact solution is found to be given by the geometric action on a coadjoint orbit of the (central extended) Noether group $\tilde{G}$. As a particular application we show that the effective action of the light-cone quantized toroidal membrane is explicitly given by the geometric co-orbit action of the group of area-preserving diffeomorphisms on torus.

Starting from the general symplectic manifold's formalism (generalizing the group coadjoint orbit formalism) we discussed arbitrary models (in $D \geq 2$ dimensions) possessing an infinite-dimensional group G of Noether symmetries and consider coupling of the Noether currents to external "sources". We wrote down the Ward identities for the corresponding quantum effective actions and employed the W-Z consistency relations to uncover the following remarkable property: no matter what is the specific action of the initial classical model, its quantum effective action is always given by the geometric action on a generic coadjoint orbit of the (central extension of the) Noether symmetry group $\tilde{G}$. Given therefore the model with Noether symmetry algebra which admits central extension, the geometric action approach developed by us can then be employed to find its unique quantum effective action.

II. L. Brekke

A. Various Aspects of Statistics of Solitons (B1-B2)

In the preprint B1, "Statistics of 2D solitons and 3D vortices", we give a general technique for defining and calculating the possible statistics of solitons in 1+1 dimensional sigma models (with space a circle) and of vortices in spontaneously broken gauge theories in 2+1 dimensions. These results also apply to cosmic strings in 3+1 dimensional gauge theories. Several specific examples were given - some of which give solitons with an exotic form of statistics known as ambistatistics. This form of statistics effectively violates the superselection rule between Bose and Fermi statistics. One model which admits ambistatistical vortices is the "Alice vortex" model previously studied by Coleman and collaborators. Models with fractional ambistatistics were also found.

In the preprint B2, "Anyonic Nielsen-Olesen Vortices", we explicitly display a topological term which gives fractional statistics to the Nielsen-Olesen vortex of the abelian Higgs model in 2+1 dimensions. The resulting anyons are different from anyons created by adding a Chern-Simons term to the action in that they are not charged. The statistics of composites of anyons are also different in the two cases.

III. W.-Y. Keung

A. Symmetries in Gauge Theories (K1,K2,K7,K8)

(i) We have studied a simple model in which the muonium-antimuonium conversion can occur at a level around the recent experimental bound but the process $\mu \rightarrow e\gamma$ is strictly forbidden. Measurements of the anomalous muon magnetic moment and the high energy Bhabha scattering $e^+e^- \rightarrow e^+e^-$ together provide an indirect and interesting constraint on the conversion. The model predicts anomalous events $ep \rightarrow \bar{e}\mu\mu X$ at high energy ep colliders. (ii) We have related the long range of an attractive feeble force to the gauge hierarchy in grand unification. (iii) We have studied a mechanism which gives a small mass but a large magnetic moment for the neutrino such that the solar neutrino deficit problem can be explained. The idea is a discrete version of Voloshin's SU(2) mechanism. An example using the quaternion group is illustrated.

B. Collider Physics (K3-K5,K9)

(i) The decay of a massive top quark accompanied by the emission of a "hard" photon or a Z boson has been studied. This process may be used to test the trilinear gauge boson coupling of the standard model. (ii) The decay of a fourth generation quarkonium into flavor-changing channels $c\bar{c}$ etc. has been shown to occur at a branching fraction of order 1% under favorable mass and mixing conditions. (iii) We also studied the inclusive quarkonium production in Z decays.

C. Electric Dipole Moments (K6,K10-K12)

Following the recent works of Weinberg, and Barr and Zee on the electric dipole moments of the neutron and the electron, we have set up the correct QCD evolution equation for the relevant operators, in particular, the chromoelectric dipole moments of quarks which play an important role in the neutron electric dipole moment. For the electron dipole moment, we have performed a general analysis in multi (>2)-Higgs models, with technical calculations of the two-loop contribution.

IV. P. Panigrahi

A. Radiative Symmetry Breaking in (2+1) Dimensional Space (P1)

A systematic study of the one-loop effective potential in $U(1)$ invariant theories involving scalars, fermions and gauge fields in (2+1) dimensional space-time was carried out. Radiative symmetry breaking was investigated. Both for ordinary and Chern-Simons QED, no radiative symmetry breaking occurs, if this theory is scale invariant at the tree level. However the symmetry always breaks down, when the scalars are coupled to charged fermions. At a sufficiently high temperature symmetry is again restored.

B. Canonical Structure of the $O(3)$ Non-linear Sigma Model with a Topological Term (P2)

In 1+1 space-time the $O(3)$ non-linear σ -model with a topological term was quantized following Dirac's method of quantization. The current algebra was investigated for a specific value of this coefficient of the topological term. We showed the equivalence of this algebra with $k \rightarrow \infty$ limit of the algebra of $SU(2) \times SU(2)$ invariant WZW model. The operator ordering ambiguities were resolved following the prescriptions of non-linear quantum mechanics and the quantum Hamiltonian was obtained.

C. Radiative Decay of Mesons and Anomaly in 2+1 Dimensions (P3)

Decay of mesons coupled to fermions by Yukawa couplings was studied in two dimensional space. In a four component theory, the electromagnetic current is free of parity odd radiative corrections; however an axial $U(1)$ current is shown to develop a finite vacuum expectation value. Unlike even dimensions this anomaly is temperature dependent and does not play any role in the radiative decay. We calculate the effective action for the mesons and show that a finite kinetic term for these fields is induced at the one-loop level and vanishes as the temperature goes to infinity.

D. Effective Lagrangian for a System of Non-relativistic Fermions in the Presence of Electromagnetic Field: Application to Anyonic Superconductors (P4)

The effective action for non-relativistic fermions was computed in the presence of background electromagnetic field. The one loop action yields a Chern-Simons like term. The results were then applied to the system of anyons. We showed that the cancellation of the induced C-S term against a C-S term included from the beginning to change the fermions to anyons is favoured energetically, together with the expulsion of $B(x)$ from the system of anyons. A massless collective mode, representing the density fluctuation is shown to exist.

E. Covariant Operators, Higher Spin Conformal Algebras and the Boussinesq Sequence (P5)

Operators transforming covariantly under the action of $\text{Diff } S^1$ are used as Lax operators to study the second Hamiltonian structure of the Lax equations. The classical spin-4 algebra is explicitly obtained. The associated non-linear equations are also studied. The Boussinesq sequence arises naturally for the spin-3 case.

V. U. Sukhatme

A. Multi-Soliton Solutions and Supersymmetric Quantum Mechanics (S1-S5)

There have been a large number of publications in the past few years dealing with the application of supersymmetry to quantum mechanics. This has yielded a deeper understanding of analytically solvable potentials as well as improvements of approximation techniques like large N expansions and the WKB method. In particular, supersymmetric quantum mechanics provides a powerful new way of constructing families of isospectral potentials. Given any potential, we have solved the problem of finding the most general family of potentials which has the same bound state energies and scattering amplitudes. It turns out that this family has n parameters, where n is the number of bound states in the potential. Such families are known to solve nonlinear differential equations of physical interest e.g. Korteweg-de Vries equation. By suitably identifying the n parameters in our isospectral families, we have obtained explicit, simple expressions for pure multi-soliton solutions [corresponding to reflectionless potentials].

B. Effects of Quark Clusters in Nuclei (S6-S10)

One of the successful phenomenological explanations of the EMC effect (for deep inelastic lepton scattering on nuclei) is based on the formation of "quark clusters" in nuclei. It is natural to look at other processes involving nuclei for related phenomena. We have investigated the consequences of clusters in neutrino and antineutrino charged current events. Although, in principle, discriminating neutrino experiments which empha-

size parton structure functions in different momentum fraction regions are possible, unfortunately accurate data will be hard to obtain. The situation is quite different for the Drell-Yan process. The shadowing behavior at small- x predicted by the quark cluster model has recently been confirmed by dimuon production measurements for protons incident on nuclei [experiment E772 at Fermilab]. The model also predicts that gluon and ocean quark structure functions in nuclei are shadowed but the valence quarks are not. We have also calculated the spectrum of hadrons produced in the backward hemisphere from deep inelastic lepton scattering on nuclear targets.

C. Nuclear Effects in the Hadroproduction of Charm (S11-S12)

Several experiments on open charm and J/ψ hadroproduction suggest that the steepness of the Feynman x_F -distribution of charm increases markedly with the size of the nuclear target. Furthermore, this A -dependence of the x_F -distribution is observed to be essentially independent of energy. We have shown that the existing data are incompatible with the standard lowest order QCD factorization formula, which predicts the x_F -distribution to be essentially determined by the gluon structure function of the beam. This implies that charm hadroproduction contains substantial contributions from "higher twist" effects.

D. Non-Divergent Semiclassical Wavefunctions (S13-S14)

A long-standing problem and major shortcoming of semiclassical (WKB) bound state wave functions is their divergence at the classical turning points. Presently available regularization schemes are accurate but rather complicated. We show how finite wave functions can be simply obtained by reorganizing the WKB perturbation expansion in powers of $\hbar$ and retaining appropriate higher order terms. This technique has been applied both to the ordinary WKB as well as the supersymmetric WKB approximation. The resulting finite wave functions compare well with numerical results, and provide a useful starting point for the calculation of physically interesting matrix elements.

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