PONTIFICIA ACADEMIA SCIENTIARVM

THE AWARD
OF THE
PIUS XI GOLD MEDAL

2006

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The aim of the Pontifical Academy of Sciences, which was founded on 28 October 1936 by the Holy Father Pius XI, is to honour pure science, wherever this may be found, to ensure its freedom, and to support the research essential for the progress of applied science.

On 28 October 1961, on the occasion of the XXVth anniversary of the foundation of the Pontifical Academy of Sciences, the Holy Father John XXIII established the Pius XI Gold Medal in honour of the founder of the Academy. The medal should be awarded to a young scientist who has already gained an international reputation.

The Council of the Academy unanimously decided to award the "Pius XI Gold Medal" for the year 2006 to

Prof. ASHOKE SEN

in recognition of his great merits as a scholar and the important contribution of his research to scientific progress.


PIVS·XI·PONTIFEX·MAXIMVS·FVNDATOR


PONTIFICIA·ACADEMIA·SCIENTIARVM
ASHOKE SEN
A.D.
MMVI

ASHOKE SEN

BIOGRAPHICAL DATA

Full Name: Ashoke Sen

Field of Specialisation: High Energy Physics

Designation: Professor

Professional Address:

Harish-Chandra Research Institute
Chhatnag Road, Jhusi
Allahabad 211019, India
Email: sen@mri.ernet.in
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Date of Birth: 15 July 1956

Place of Birth: Calcutta, West Bengal, India

Marital Status: Married to Sumathi Rao

Academic Records:

B.Sc. (Physics)
Calcutta University (1975)

M.Sc. (Physics)
IIT Kanpur (1978)

Ph.D. (Physics)
SUNY at Stony Brook (1982)

Post-Doctoral Fellowships:

October 1982-July 1985
Fermilab, USA

August 1985-February 1988
SLAC (USA)

Other Positions Held:

March 1988-September 1997
Tata Institute of Fundamental Research

Fellowships of Academies (National):

Fellow, Indian Academy of Sciences
(elected 1991)

Fellow, Indian National Science Academy
(elected 1995)

Fellow, National Academy of Sciences, India
(elected 1997)

Fellowships of Academies (International):

Fellow, Royal Society, London
(elected 1998)

Fellow, Third World Academy of Sciences
(elected 2004)

Awards (National):

(1994) S.S. Bhatnagar award

(1995) B.M. Birla Science Prize

(1996) G.D. Birla award

(1998) R.D. Birla award

(2001) Awarded Padmasree

(2001) Kamal Kumari National award

(2004) INSA S.N. Bose Award lecture

(2005) H.K. Firodia award

Awards (International):

(1989) ICTP prize in honour of H. Yukawa

(1997) Third World Academy of Sciences Prize

Honoroury Degrees:

D.Sc., University of Calcutta

Named Lectures and Visits (International):

Rothschild Visiting Professor,
Feb.-March, 1997 and June 21-July 20, 2002,
Isaac Newton Institute, Cambridge, UK

Morris Loeb Lecturer, April 17-27, 2000,
Harvard University, Cambridge, USA

Walter a. Eva Andrejewski foundation Lecturer,
Humboldt University, Berlin, Germany, Mar 4-10, 2002

James H. Simons lecturer, April 29 - May 10, 2002,
SUNY at Stony Brook, New York, USA

Dirac lecture, June 20, 2005,
DAMTP, Cambridge University, UK

Morningstar visiting Professor, 2004, 2005,
MIT, Cambridge, USA

Einstein Colloquium, December 2005,
Weizmann Institute, Israel.

Named Lectures and Visits (National):

Saha memorial lecture, November 23, 1998,
Saha Institute of Nuclear Physics, Kolkata, India

Subhashis Nag memorial lecture, December 29, 2003,
Institute of Mathematical Sciences, Chennai, India

Acharya J. C. bose memorial lecture, November 30, 2004,
Bose Institute, Kolkata

Invited Talks at Conferences and Schools:

1. Monopole '83, 6-9 Oct 1983, Ann Arbor, Michigan, USA
2. Workshop on Unified String Theories, 29 Jul-16 Aug 1985, Santa Barbara, USA
3. Summer Workshop on High-Energy Physics and Cosmology, 30 Jun-15 Aug 1986, Trieste, Italy
4. International Workshop on Superstrings, Composite Structures and Cosmology, 11-18 Mar 1987, College Park, Maryland, USA

5. CCAST Symposium/Workshop on Fields, Strings and Quantum Gravity, 29 May-10 Jun 1989, Beijing, China
6. Workshop on Superstrings, 12-14 Jul 1989, Trieste, Italy
7. 5th SERC School on High Energy Physics, November-December 1989, Indian Institute of Technology, Kanpur, India
8. International Colloquium on Modern Quantum Field Theory, 8-14 Jan 1990, Bombay, India
9. 25th International Conference on High-Energy Physics (ICHEP 90), 2-8 Aug 1990, Singapore, Singapore
10. Summer School in High-Energy Physics and Cosmology, 18 Jun-28 Jul 1990, Trieste, Italy
11. Strings and Symmetries 1991, 20-25 May 1991, Stony Brook, New York, USA
12. Trieste Summer School in High-Energy Physics and Cosmology, 17 Jun-9 Aug 1991, Trieste, Italy
13. International Conference on Gravitation and Cosmology (ICGC 91), 12-18 Dec 1991, Ahmedabad, India
14. 7th SERC School on High Energy Physics, December 1991, Physical Research Laboratory, Ahmedabad, India
15. Workshop on string theory, 8-19 Apr 1992, Trieste, Italy
16. 16th Johns Hopkins Workshop on Current Problems in Particle Theory, 8-10 Jun 1992, Goteborg, Sweden
17. Trieste Summer School on High-Energy Physics and Cosmology, 15 Jun-14 Aug 1992, Trieste, Italy
18. Meeting on Bose and 20th Century Physics, 30 Dec 1993 - 5 Jan 1994, Calcutta, India
19. Silver Jubilee Conference of the Indian Association For General Relativity and Gravitation, 14-18 Feb 1994, Pune, India
20. ICTP Summer School in High-Energy Physics and Cosmology, 13 Jun-29 Jul 1994, Trieste, Italy
21. 11th DAE Symposium on High-Energy Physics, 28 Dec 1994-2 Jan 1995, Shantiniketan, India
22. STRINGS 95: Future Perspectives in String Theory, 13-18 Mar 1995, Los Angeles, California, USA
23. ICTP Spring School on String Theory, Gauge Theory and Quantum Gravity, 27 Mar-4 Apr 1995, Trieste, Italy
24. International Workshop on Supersymmetry and Unification of Fundamental Interactions (SUSY 95), 15-19 May 1995, Palaiseau, France

25. ICTP Trieste Conference on S-Duality and Mirror Symmetry, 12-23 Jun 1995, Trieste, Italy
26. Frontiers in Quantum Field Theory in Honor of the 60th Birthday of Prof. K. Kikkawa, 14-17 Dec 1995, Toyonaka, Japan
27. 4th International Conference on Supersymmetries in Physics (SUSY 96), 29 May-1 Jun 1996, College Park, Maryland, USA
28. ICTP Summer School in High-Energy Physics and Cosmology, 10 Jun-26 Jul 1996, Trieste, Italy
29. European Research Conference on Advanced Quantum Field Theory in Memory of Claude Itzykson, 31 Aug - 5 Sep 1996, La Londe Les Maures, France
30. Workshop on Frontiers in Field Theory, Quantum Gravity and String Theory, 12-21 Dec 1996, Puri, India
31. 4th Jerusalem Winter School in Theoretical Physics on Dualities and Symmetries, 30 Dec 1996-8 Jan 1997, Jerusalem, Israel
32. Duality Symmetries in String Theory II, April 97, ICTP, Trieste, Italy
33. Strings 97 Meeting, 16-21 Jun 1997, Amsterdam, The Netherlands
34. 8th Marcel Grossmann Meeting on Recent Developments in Theoretical and Experimental General Relativity, Gravitation and Relativistic Field Theories (MG 8), 22-27 Jun 1997, Jerusalem, Israel
35. 13th SERC School on High Energy Physics, Feb 10 - Mar 3 98, Santiniketan, India
36. Strings 98, 22-27 Jun 1998, Santa Barbara, California, USA
37. 29th International Conference on High-Energy Physics (ICHEP 98), 23-29 Jul 1998, Vancouver, British Columbia, Canada
38. 22nd Johns Hopkins Workshop on Novelties of String Theory, 20-22 Aug 1998, Goteborg, Sweden
39. Strings 99, 19-25 Jul 1999, Potsdam, Germany
40. NATO Advanced Study Institute: TMR Summer School on Progress in String Theory and M-Theory (Cargese 99), 24 May-5 Jun 1999, Cargese, Corsica, France
41. Advanced School on Supersymmetry in the Theories of Fields, Strings and Branes, 26-31 Jul 1999, Santiago de Compostela, Spain
42. String Theory at the Millenium, Jan.12-15, 2000, Caltech, USA
43. Lennyfest, May 20-21, 2000, Stanford, USA.

44. 18th International Symposium on Lattice Field Theory (Lattice 2000), 17-22 Aug 2000, Bangalore, India
45. 14th DAE Symposium on High-Energy Physics, 18-22 Dec 2000, Hyderabad, India
46. Strings 2001: International Conference, 5-10 Jan 2001, Mumbai, India
47. 16th SERC School on Theoretical High-Energy Physics, 25 Feb - 16 Mar 2001, Allahabad, India
48. 8th International Symposium on Particle Strings and Cosmology (PASCOS 2001), 10-15 Apr 2001, Chapel Hill, North Carolina, USA
49. Avatars of M-Theory, June 5-8, 2001, ITP Santa Barbara, USA
50. The Duality Workshop: A Math/Physics Collaboration, June 18 - July 13, 2001, ITP, Santa Barbara, USA
51. Les Houches Summer School: Session 76: Euro Summer School on Unity of Fundamental Physics: Gravity, Gauge Theory and Strings, 30 Jul-31 Aug 2001, Les Houches, France
52. JHS/60, Nov.3-4, 2001, Caltech, USA
53. Supergravity At 25, 1-2 Dec 2001, Stony Brook, New York, USA
54. 14th Chris Engelbrecht Summer School in Theoretical Physics: Quantum Gravity, String Theory and Cosmology, 23 Jan-1 Feb 2002, Stellenbosch, South Africa
55. DPF 2002: The Meeting of the Division of Particles and Fields of the American Physical Society, 24-28 May 2002, Williamsburg, Virginia, USA
56. Strings 2002, 15-20 Jul 2002, Cambridge, England
57. International Conference on Theoretical Physics (TH 2002), 22-26 Jul 2002, Paris, France
58. 17th Nishinomiya-Yukawa Memorial Symposium: String Theory, 12-13 Nov 2002, Nishinomiya, Japan
59. 9th International Symposium on Particles, Strings and Cosmology (PASCOS 03), 3-8 Jan 2003, Mumbai (Bombay) India
60. ICTP Spring School on Superstring Theory and Related Topics, 31 Mar-8 Apr 2003, Trieste, Italy
61. Theoretical Advanced Study Institute in Elementary Particle Physics (TASI 2003): Recent Trends in String Theory, 1-27 Jun 2003, Boulder, Colorado, USA
62. Strings 2003, 6-11 Jul 2003, Kyoto, Japan

63. Summer School on Strings, Gravity and Cosmology: 14-25 Jul 2003, Vancouver, BC, Canada
64. Nobel Symposium 2003: Cosmology and String Theory, 14-19 Aug 2003, Sigtunastiftelsen, Sweden
65. IPM String School and Workshop 2003, 29 Sep-9 Oct 2003, Caspian Sea, Iran
66. 3rd ICTP Latin American String School (LASS 2003), 1-19 Dec 2003, Sao Paulo, Brazil
67. Spring School on Superstring Theory and Related Topics, 15-23 Mar 2004, Trieste, Italy
68. 18th Nordic String Meeting, May 13 to May 15, 2004, Groningen, The Netherlands
69. Onassis Lectures in Physics: Fields and Strings, 5-9 Jun 2004, Heraklion, Greece
70. Annual International Conference on Strings, Theory and Applications (Strings 2004), 28 Jun-Jul 2, 2004, Paris, France
71. Fourth Regional Conference of the Physics Academy of the North East(PANE), November 2004, Shilchar, India
72. International Workshop on String Theory (ISM04), 15-23 Dec 2004, Khajuraho, India
73. IPM String School and Workshop (ISS2005), 5-14 Jan 2005, Qeshm Island, Iran
74. ICTP Spring School on Superstring Theory and Related Topics, 14-22 Mar 2005, Trieste, Italy
75. Summer School on Strings, Gravity and Cosmology, Perimeter Institute, June 20-July 8, 2005, Waterloo, Ontario, Canada
76. Strings 05 Conference, Fields Institute, July 11-16, 2005, Toronto, Canada
77. Workshop on Einstein's Legacy in the New Millennium, 15-22 Dec 2005, Tohsali Sands, Puri, India
78. 23rd Winter School in Theoretical Physics: String Theory: Symmetries and Dynamics, 28 Dec 2005-6 Jan 2006, Jerusalem, Israel
79. 12th Regional Conference on Mathematical Physics, 27 Mar-1 Apr 2006, Islamabad, Pakistan
80. IPM String School and Workshop (ISS2006), 10-19 Apr 2006, Tehran, Iran
81. Strings 2006, 18-24 June, Beijing, China

RESEARCH SUMMARY

I have been working exclusively in the subject of string theory since 1985. My first major project in this field involved studying the relationship between the two dimensional σ-models describing string propagation in a given background field, and the space-time properties of these background fields. My main contribution during this project was to establish the relation between classical equations of motion of massless fields in string theory and conformal invariance of the two dimensional sigma model describing string propagation in background of these massless fields [19,20]. Working along this line I also showed that in order to get a string compactification that preserves $N=1$ spacetime supersymmetry, the corresponding two dimensional σ-model has (2,0) world-sheet supersymmetry [24,27]. This provided a way of looking for space-time supersymmetric vacua of string theory.

My second major project in string theory involved developing a method for generating new classical solutions of string theory from a known classical solution, when the original solution is independent of some of the space-time coordinates [60,62,R3]. Later, I used this method to generate the most general electrically charged rotating black hole solution in four dimensional heterotic string theory [81].

My third major project has been in the subject of string dualities. Most of the initial development in the subject of string theory was based on perturbation theory, and there was no method known for studying non-perturbative effects in string theory. In 1992 I presented evidence that a specific string theory, obtained by compactifying heterotic string theory on a six dimensional torus, has a symmetry that relates the strong coupling behaviour of this theory to its weak coupling behaviour [68,R4]. This conjectured symmetry can be used to understand non-perturbative behaviour of string theory. Although initially the evidence for this conjecture was not very strong, in 1994 I showed [78] that this conjecture leads to some precise prediction about the properties of some abstract manifolds (moduli spaces of multi-monopole solutions), and explicitly verified some of these predictions.

Soon after this paper Hull and Townsend – and later Witten – conjectured the existence of many other new duality symmetries, which may sometime relate even different string theories. One of these conjectures stated that the type IIA string theory, compactified on a complicated four dimensional manifold, known as K3, is related to the heterotic string theory compactified on a four dimensional torus. I found non-trivial evidence for this conjecture by showing that the fundamental heterotic string arises as a soliton solution of the type IIA string theory on K3, and that the fundamental type IIA string arises as a soliton solution of the heterotic string theory compactified on T^4 [83].

My fourth major project involves an attempt to understand the Bekenstein-Hawking entropy of black holes from counting the microscopic states in string theory. String theory contains black hole solutions (as found in ref. [81]) which carry the same quantum numbers as elementary string states. Thus it is natural to ask if the degeneracy of black hole states, as counted by the Bekenstein-Hawking entropy, agrees with the degeneracy of elementary string states. If true, this will indicate that there is no distinction between the black holes and elementary string states, and at the same time, this would provide a statistical interpretation of Bekenstein-Hawking entropy from the counting of microscopic states. The main obstacle to this calculation had been that the degeneracy of elementary string states is calculable only in the weak coupling limit, whereas these states become black holes only for sufficiently large coupling when the gravitational effects are appreciable. I circumvented this problem by looking at the states which preserve part of the spacetime supersymmetry (also known as BPS states), since it is known that for such states the degeneracy remains unchanged as we go from the strong to the weak coupling. Comparison of the black hole entropy according to (a stringy modification of) the Bekenstein-Hawking prescription, and the logarithm of the degeneracy of the elementary string states, showed an exact agreement between the two sides as functions of three independent parameters, – the mass and charge of the black hole, and the string coupling constant – upto an overall multiplicative numerical coefficient which could not be calculated explicitly [84]. (This factor has been calculated recently by Dabholkar). Later similar agreement was found by other authors in many other examples, including the numerical factor where it could be calculated.

My fifth major project involves study of non-supersymmetric solitons in string theory. Most of the earlier studies on solitons in string theory have been on supersymmetric (also known as BPS) configurations. In a series of papers in 1998 I showed how stable non-BPS states can also be used to test various duality conjectures [107,110,111]. During this study, I also found a novel construction of non-BPS states in terms of kink solution involving the tachyon field on a brane anti-brane pair. This study led to a series of conjectures about tachyon potential on the brane-antibrane system and non-BPS D-branes in superstring theory, as well as on D-branes of bosonic string theory [108-110,112,113,117]. Later, in various collaborations with Zwiebach, Berkovits, and Moeller I found evidence for these conjectures in string field theory[118-120,123].

Although initial studies of the non-BPS branes focussed on their static properties, in 2002 I found a set of time dependent solutions describing the 'decay' of these branes [140,141]. These are among the few time dependent solutions in string theory whose properties have been studied in detail and have been used extensively to build cosmological models out of string theory. Study of these solutions has also led to a new kind of duality conjecture between open and closed string theories [147,148,R10] and is currently under intense investigation.

My sixth major project has been on the study of entropy of extremal black holes in the presence of higher derivative terms. In 2005 I showed that in theories of gravity coupled to other matter fields with generally covariant higher derivative corrections, the near horizon field configuration of an extremal black hole is obtained by extremizing an 'entropy function' [159,160]. The entropy function is a function of the parameters characterizing the near horizon geometry of the black hole and there is a well defined algorithm for constructing this function from the lagrangian density of the theory. Furthermore the entropy itself is given by the value of the entropy function at its extremum. This led to a proof of the 'attractor mechanism' in a general higher derivative theory of gravity without invoking supersymmetry. In particular the results show that in a generic situation where the entropy function has no flat directions the near horizon field configuration is determined completely by extremizing the entropy function and hence cannot depend on the asymptotic values of the scalar fields of the theory. On the other hand if the entropy function has flat directions then the near horizon field configuration is not completely determined by extremizing the entropy function and could have some dependence on the asymptotic values of the scalar fields. But the entropy is still independent of the asymptotic data. Although initial studies focussed on spherically symmetric black holes, this analysis has now been generalized to black holes carrying angular momentum [162,166].

Besides these six major areas, I have also contributed to some of the more technical aspects of this subject that are listed below.

– In conventional SU(5) grand unified theories, the Higgs field belongs to a fundamental representation of SU(5) and it requires a high degree of fine tuning (1 in 10^{15}) to keep its colour triplet component heavy (which is required to avoid rapid proton decay) and at the same time the weak doublet Higgs light (so that it can induce symmetry breaking responsible for the mass of the $W^{\pm}$ and Z bosons). I showed how in string theory one might be able to get this mass hierarchy naturally, without the need of any fine tuning [16].

– In 1986, several authors found a new four loop contribution to the β-function in the σ-model describing string propagation on a Calabi-Yau manifold. This led to the possibility that Calabi-Yau manifolds are not valid backgrounds for string compactification as these would not be solutions of the equations of motion. In collaboration with D. Nemeschansky I showed that it is possible to modify the metric on the Calabi-Yau manifold order by order in string perturbation theory so that it continues to remain solutions of the equations of motion, and hence provides a conformally invariant σ-model [25].

– In 1987, Dine, Seiberg and Witten used low energy effective field theory to argue that in some four dimensional string theories with U(1) gauge symmetry one loop effects can generate a Fayet-Illiopoulos D-term that can break supersymmetry. In collaboration with J. Atick and L. Dixon I showed how the presence of such a D-term can be verified in an explicit one loop string computation for any string compactification [31]. We also found that for most of the known string theories, the generation of the D-term does not break supersymmetry, since one can find a new supersymmetric vacuum in the space of field configurations.

– In 1996 C. Vafa proposed a new way of compactifying type IIB theory known as F-theory. These compactifications are not accessible to the standard perturbative analysis, since the coupling constant of the theory becomes large in some regions in the internal space. Nevertheless based on various symmetry arguments Vafa argued that some of these compactifications are dual to more conventional string compactifications. I showed [94] that at least for some of these compactifications, one can take appropriate limits where they reduce to ordinary string compactifications amenable to perturbative techniques, and the dualities proposed by Vafa can be understood in terms of more conventional dualities proposed earlier. This method has been used later to find various other dualities involving F-theory, and has also led to the discovery of new string compactifications in the search for duals of F-theory compactification. Using the method of this paper I later showed[98] how one can take appropriate limit of a general F-theory compactification to map it into an orientifold.

– In 1996, T. Banks, W. Fischler, S. Shenker and L. Susskind proposed a nonperturbative definition of eleven dimensional supergravity theory in terms of quantum mechanics of infinite dimensional matrices. I gave a systematic description of this theory when we compactify some of the eleven dimensions [104]. This unified many of the ad hoc descriptions of this theory given earlier.

– $\mathcal{N}=4$ supersymmetric string theories typically contain a spectrum of dyon states which preserve 1/4 of the supersymmetries of the original theory. In collaboration with Justin David and Dileep Jatkar I computed the exact spectrum of dyons in a class of such string theories and verified the duality invariance of the spectrum [161,163,165].

LIST OF MAIN PUBLICATIONS

List of Publications in Journals in Chronological Order

1. Ashoke Sen, Asymptotic Behavior of the Sudakov Form-Factor in QCD, *Phys. Rev.*, D24:3281 (1981).
2. Ashoke Sen, Asymptotic Behavior of the Wide Angle On-Shell Quark Scattering Amplitudes in Nonabelian Gauge Theories, *Phys. Rev.*, D28:860 (1983).
3. Ashoke Sen, Asymptotic Behavior of the Fermion and Gluon Exchange Amplitudes in Massive Quantum Electrodynamics in the Regge Limit, *Phys. Rev.*, D27:2997 (1983).
4. Ashoke Sen, Conservation Laws in the Monopole Induced Baryon Number Violating Processes, *Phys. Rev.*, D28:876 (1983).
5. Ashoke Sen, George Sterman, Cancellation of Sudakov Effects in the Drell-Yan Process, *Nucl. Phys.*, B229:231 (1983).
6. Yoichi Kazama, Ashoke Sen, on the Conservation of Electric Charge Around A Monopole of Finite Size, *Nucl. Phys.*, B247:190 (1984).
7. Ashoke Sen, A Locally Supersymmetric Su(6) Grand Unified Theory Without Fine Tuning and Strong Cp Problems, *Phys. Rev.*, D31:900 (1985).
8. Ashoke Sen, Role of Conservation Laws in the Callan-Rubakov Process With Arbitrary Number of Generation of Fermions, *Phys. Rev. Lett.*, 52:1755 (1984).
9. Ashoke Sen, Monopole Induced Baryon Number Violation Due To Weak Anomaly, *Nucl. Phys.*, B250:1 (1985).
10. Ashoke Sen, Sliding Singlet Mechanism in N=1 Supergravity Gut, *Phys. Lett.*, 148B:65 (1984).
11. Ashoke Sen, Radiative Corrections in Grand Unified Theories Based on N=1 Supergravity. 1. Nongauge Theories, *Phys. Rev.*, D30:2608 (1984).
12. Ashoke Sen, Comparison of the Canonical Hamiltonian and the Hamiltonian of Callan and Rubakov For the Monopole Fermion System, *Phys. Rev.*, D31:433 (1985).
13. Ashoke Sen, Radiative Corrections in Supersymmetric Gauge Theories, *Phys. Rev.*, D31:2100 (1985).

14. Ashoke Sen, Baryon Number Violation Induced By the Monopoles of the Pati-Salam Model, *Phys. Lett.*, 153B:55 (1985).
15. Ashoke Sen, Hidenaga Yamagishi, Localization of the Dyon Charge, *Phys. Rev.*, D31:3285 (1985).
16. Ashoke Sen, Naturally Light Higgs Doublet in Supersymmetric E6 Grand Unified Theory, *Phys. Rev. Lett.*, 55:33 (1985).
17. Ashoke Sen, Radiative Corrections in Grand Unified Theories Based on N=1 Supergravity. 2. Gauge Theories, *Phys. Rev.*, D32:411 (1985).
20. Ashoke Sen, Equations of Motion For the Heterotic String Theory From the Conformal Invariance of the Sigma Model, *Phys. Rev. Lett.*, 55:1846 (1985).
21. Ashoke Sen, Local Gauge and Lorentz Invariance of the Heterotic String Theory, *Phys. Lett.*, 166B:300 (1986).
22. T. Banks, Dennis Nemeschansky, Ashoke Sen, Dilaton Coupling and Brst Quantization of Bosonic Strings, *Nucl. Phys.*, B277:67 (1986).
23. Ashoke Sen, Superspace Analysis of Local Lorentz and Gauge Anomalies in the Heterotic String Theory, *Phys. Lett.*, 174B:277 (1986).
24. Ashoke Sen, (2, 0) Supersymmetry and Space-Time Supersymmetry in the Heterotic String Theory, *Nucl. Phys.*, B278:289 (1986).
25. Dennis Nemeschansky, Ashoke Sen, Conformal Invariance of Supersymmetric Sigma Models on Calabi-Yau Manifolds, *Phys. Lett.*, 178B:365 (1986).
26. Ashoke Sen, Central Charge of the Virasoro Algebra For Supersymmetric Sigma Models on Calabi-Yau Manifolds, *Phys. Lett.*, 178B:370 (1986).
27. Ashoke Sen, Heterotic String Theory on Calabi-Yau Manifolds in the Green-Schwarz Formalism, *Nucl. Phys.*, B284:423 (1987).
28. Joseph J. Atick, Ashoke Sen, Correlation Functions of Spin Operators on A Torus, *Nucl. Phys.*, B286:189 (1987).
29. Joseph J. Atick, Ashoke Sen, Spin Field Correlators on an Arbitrary Genus Riemann Surface and Nonrenormalization Theorems in String Theories, *Phys. Lett.*, 186B:339 (1987).
30. Joseph J. Atick, Ashoke Sen, Covariant One Loop Fermion Emission Amplitudes in Closed String Theories, *Nucl. Phys.*, B293:317 (1987).

31. Joseph J. Atick, Lance J. Dixon, Ashoke Sen, String Calculation of Fayetiliopoulos D Terms in Arbitrary Supersymmetric Compactifications, *Nucl. Phys.*, B292:109 (1987).
32. Joseph J. Atick, Ashoke Sen, Two Loop Dilaton Tadpole Induced By Fayet-Iliopoulos D Terms in Compactified Heterotic String Theories, *Nucl. Phys.*, B296:157 (1988).
33. Ashoke Sen, Mass Renormalization and Brst Anomaly in String Theories. Nucl. Phys.B304:403 (1988).
34. Joseph J. Atick, Jeffrey M. Rabin, Ashoke Sen, An Ambiguity in Fermionic String Perturbation Theory, *Nucl. Phys.*, B299:279 (1988).
35. Joseph J. Atick, Gregory Moore, Ashoke Sen, Some Global Issues in String Perturbation Theory, *Nucl. Phys.*, B308:1 (1988).
36. Joseph J. Atick, Gregory Moore, Ashoke Sen, Catoptric Tadpoles, *Nucl. Phys.*, B307:221 (1988).
37. Samir D. Mathur, Sunil Mukhi, Ashoke Sen, Correlators of Primary Fields in the Su(2) W Z W Theory on Riemann Surfaces, *Nucl. Phys.*, B305:219 (1988).
38. Samir D. Mathur, Sunil Mukhi, Ashoke Sen, Differential Equations For Correlators and Characters in Arbitrary Rational Conformal Field Theories, *Nucl. Phys.*, B312:15 (1989).
39. Samir D. Mathur, Sunil Mukhi, Ashoke Sen, on the Classification of Rational Conformal Field Theories, *Phys. Lett.*, B213:303 (1988).
40. Samir D. Mathur, Sunil Mukhi, Ashoke Sen, Reconstruction of Conformal Field Theories From Modular Geometry on the Torus, *Nucl. Phys.*, B318:483 (1989).
41. Samir D. Mathur, Ashoke Sen, Differential Equation For Genus Two Characters in Arbitrary Rational Conformal Field Theories, *Phys. Lett.*, B218:176 (1989).
42. Ashoke Sen, Exactly Solvable String Compactification on Calabiyau Manifolds in the Green-Schwarz Formalism, *Phys. Lett.*, B224:278 (1989).
43. Sunil Mukhi, Sudhakar Panda, Ashoke Sen, Contour Integral Representations For the Characters of Rational Conformal Field Theories, *Nucl. Phys.*, B326:351 (1989).
44. Samir D. Mathur, Ashoke Sen, Group Theoretic Classification of Rational Conformal Field Theories With Algebraic Characters, *Nucl. Phys.*, B327:725 (1989).

45. P. Durganandini, Sudhakar Panda, Ashoke Sen, Some Properties of Supercharacters in Superconformal Field Theories, *Nucl. Phys.*, B332:433 (1990).
46. Ashoke Sen, Open String Field Theory in Nontrivial Background Field: Gauge Invariant Action, *Nucl. Phys.*, B334:350 (1990).
47. Ashoke Sen, Open String Field Theory in Arbitrary Background Field. 2. Feynman Rules and Four Point Amplitudes, *Nucl. Phys.*, B334:395 (1990).
48. Ashoke Sen, Open String Field Theory in Nontrivial Background Field. 3. N Point Amplitude, *Nucl. Phys.*, B335:435 (1990).
49. A.S. Schwarz, Ashoke Sen, Gluing Theorem, Star Product and Integration in Open String Field Theory in Arbitrary Background Fields, *Int. J. Mod. Phys.*, A6:5387-5408 (1991).
50. Ashoke Sen, Equations of Motion in Nonpolynomial Closed String Field Theory and Conformal Invariance of Two- Dimensional Field Theories, *Phys. Lett.*, B241:350-356 (1990).
51. Ashoke Sen, on the Background Independence of String Field Theory, *Nucl. Phys.*, B345:551-583 (1990).
52. Ashoke Sen, Nontrivial Renormalization Group Fixed Points and Solutions of String Field Theory Equations of Motion, *Phys. Lett.*, B252:566-572 (1990).
53. Ashoke Sen, On the Background Independence of String Field Theory. 2. Analysis of On-Shell S Matrix Elements, *Nucl. Phys.*, B347:270-318 (1990).
54. Ashoke Sen, Matrix Models and Gauge Invariant Field Theory of Subcritical Strings, *Int. J. Mod. Phys.*, A7:2559-2588,1992.
55. Ashoke Sen, Virasoro Constraints on the Matrix Model Partition Function and String Field Theory, *Int. J. Mod. Phys.*, A7:1553-1581 (1992).
56. Sudipta Mukherji, Ashoke Sen, Some All Order Classical Solutions in Nonpolynomial Closed String Field Theory, *Nucl. Phys.*, B363:639-664 (1991).
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