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Final Technical Report

Grant number: DE-FG02-86ER13596

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Office of Intellectual
Property Counsel

11/17/99
Date

DOE Field Office, Chicago

Submitted to: US Department of Energy
Chicago Operation Office
9800 South Cass Avenue
Argonne, Illinois 60439

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Date: October 1, 1999

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1. Introduction

This report summarizes the research accomplishments performed under the grant entitled "Atomic Physics of Strongly correlated Systems," grant number DE-FG02-86ER13596, for the period from August 1, 1986 through July 31, 1999. During this period, an annual report has been submitted each year to the program director Dr. J. V. Martinez, and the grant has been renewed for each three-year period. This report serves as the final report under the above grant number.

2. Summary of Accomplishments

The goal of this research is to develop new novel methods for studying correlated motion of atomic systems. This involves new formulations of the theoretical approaches, the performance of numerical calculations, and th detailed comparison with available experiments. Different theoretical methods have been developed for different classes of problems. They are briefly summarized below. The 68 journal articles published under this grant are listed in the Appendix. Each article is referred to by its number in the following:

2.1. Existence of weakly bound atomic and molecular systems

We have shown some molecules have binding energies of the order of milli-degree Kelvins (#1, 5, 21) and that a positron can be bound to a neutral atom (#6).

2.2. Calculations and visualization of triply excited states of atoms

We have shown how to visualize the triply excited states wavefunctions and analyzed the doubly and triply excited states of Li and He⁻—and shown that there are no triply excited states in H⁻ (#2, 3, 8, 9, 10).

2.3. Analysis of the electron correlations of intrashell states of atoms

We have formulated the visualization of intrashell triply excited states of atoms (#13, 20, 23, 30, 31, 39, 40, 65).

2.4. Calculations of doubly excited states and their regularities

Using the hyperspherical close coupling method and other approaches, we have analyzed the systematic behaviors of the energy levels and autoionization widths of doubly excited states of atoms and atomic ions. We also calculated the photoabsorption cross sections and elastic and inelastic scattering cross sections (#7, 11, 17, 34, 36, 41, 44-50, 53, 55-57, 59-61, 66-68).

2.5. General hyperspherical approach for three-body system

The hyperspherical approach for a Coulomb three-body system is formulated (#54, 58, 64).

2.6. Collisions of positrons with atomic hydrogen and other systems

We have developed hyperspherical close-coupling method for calculating the excitation and positronium formation cross sections for positron colliding with atomic hydrogen and other systems (#22, 16, 28, 32, 33, 38, 43).

2.7. Review articles

We have written a few review articles and some popular articles on the few-body problems (12, 18, 29, 35, 42, 62).

2.8. Other articles

We have carried out studies in some other areas, like laser-atom collisions and some ion-atom collisions and ion-molecule collisions (#4, 15, 19, 24-27, 51, 52, 63).

Appendix: List of Publications Under the Grant DE-FG02-86ER13596

Publications in 1999:

1. Yong Li and C.D. Lin, "Calculations of Some Weakly-Bound Diatomic Molecular Negative Ions," Phys. Rev. A60, 2009 (1999).
2. C.D. Lin and T. Morishita, "Visualization of Correlations in Intrashell Triply Excited States of Atoms," J. Phys. IV France 9, Pr6-25 (1999).

Publications 1998:

3. Toru Morishita, Yong Li and C.D. Lin, "Visualization of Correlations in Intrashell Triply Excited States of Atoms," Phys. Rev. A58, 4214 (1998).
4. Jianmin Yuan and C.D. Lin, "Effect of Core-Valence Electron Correlation in Low Energy Electron Scattering with Ca Atoms," Phys. Rev. A58, 2824 (1998).
5. Jianmin Yuan and C.D. Lin, "Weakly-Bound Triatomic He₂Li and He₂Na Molecules," J. Phys. B31, L637 (1998).
6. Jianmin Yuan, B.D. Esry, Toru Morishita, and C.D. Lin, "Stable Bound States of e⁺+ Li and e⁺+ Na," Phys. Rev. A58, R4 (1998).
7. K.T. Chung and C.D. Lin, "2l2l' and 3l3l' Doubly Excited States of Li⁺," Atomic and Nuclear Data Tables, 69, 101-124 (1998).
8. Toru Morishita and C.D. Lin, "Hyperspherical Analysis of Doubly and Triply Excited States of Li," Phys. Rev. A57, 4268 (1998).
9. Toru Morishita and C.D. Lin, "Analysis of 1s2l2l' and 2l2l'2l' Resonances of He⁻ Ions," J. Phys. B31, L209 (1998).
10. Toru Morishita, C. D. Lin and C. G. Bao, "On the Nonexistence of Resonances in H²⁻," Phys. Rev. Lett. 80, 464 (1998).

Publications 1997:

11. Ming-Keh Chen, C.D. Lin and J. Z. Tang, "Accurate Hyperspherical Close-Coupling Calculation of Electron-Hydrogen Scattering Cross Sections," Phys. Rev. A56, 2435 (1997).
12. C.D. Lin, "The Stability of Simple Quantum Systems," Chinese J. Physics 35, 462 (1997).

13. C.G. Bao X.Z. Yang and C.D. Lin, "Nodal Structures of Intrashell States of 3-Valence-Electron Atoms," Phys. Rev. A 55, 4168 (1997).
14. C.D. Lin, "Helium Atom as Viewed Under Synchrotron Radiation," Wu-Li Bimonthly, 18, 649 (1996). In Chinese.
15. T.F. Jiang and C.D. Lin, "Ionization of Oriented Elliptic Rydberg States by Half-Cycle Pulses," Phys. Rev. A 55, 2172 (1997).

Publications in 1996:

16. B.D. Esry, Chris H. Greene, Y. Zhou and C.D. Lin, "Role of the Scattering Length in Bose-Einstein Condensation," J. Phys. B 29, L51 (1996).
17. Y.D. Wang, W.C. Fon, B.R. Odgers and C.D. Lin, "A Benchmark Calculation for Resonant Electron-Hydrogen Elastic Scattering at Low Energies," J. Phys. B 29, L59 (1996).
18. C.D. Lin, "Hyperspherical Way for Coulomb Few-Body Systems," Comments AMO Phys. 32, 127 (1996).
19. Jiyun Kuang and C.D. Lin, "On the Convergence of Two-Center AO Close-Coupling Method in Ion-Atom Collisions," J. Phys. B 29, 1207 (1996).
20. Xiazhou Yang, C. G. Bao and C. D. Lin, "Analysis of Triply Excited States of Atoms in Hyperspherical Coordinates," Phys. Rev. Lett. 76, 3096 (1996).
21. B.D. Esry, C.D. Lin and Chris H. Greene, "An Adiabatic Hyperspherical Study of the Helium Trimer," Phys. Rev. A 54, 394 (1996).
22. Yan Zhou and C.D. Lin, "Hyperspherical Close-Coupling Calculation of D-Wave Positronium Formation and Excitation Cross Sections in Positron-Hydrogen Scattering," Can. J. Phys. 74, 353 (1996).
23. Xiazhou Yang, C.G. Bao and C.D. Lin, "Hyperspherical Approach to Three-Electron Atomic Systems," Phys. Rev. A 53, 3934 (1996).
24. S. Kato, J. de Gouw, C.D. Lin, V.M. Bierbaum and S.R. Leone, "Charge Transfer Rate Constants for N^{2+} ($v=0-4$) with Ar at Thermal Energies," Chem. Phys. Lett. 256, 305 (1996).
25. S. Kato, J. de Gouw, C.D. Lin, V.M. Bierbaum and S.R. Leone, "Vibrational Enhancement of the Charge Transfer Rate Constant of N^{2+} ($v=0-4$) with Kr at Thermal Energies," J. Chem. Phys. 103, 5455 (1996).

26. Wolfgang Fritsch and C.D. Lin, "A Study of One- and Two-Electron Transitions in Slow C^{5+} -He Collisions: Total and Angle-Differential Cross Sections and Coherence Parameters," Phys. Rev. A 54, 4931 (1996).
27. J.T. Lin, T.F. Jiang and C.D. Lin, "Coulomb Trajectory Effects on Electron-Impact Detachment of Negative Ions and on Mutual Neutralization Cross Sections," J. Phys. 29, 6175 (1996). Local link.

Publications 1995:

28. Yan Zhou and C.D. Lin, "Hyperspherical Close-Coupling Calculation of Positronium Formation and Excitation Cross Sections in Positron-Hydrogen Scattering at Energies below the $H(n=4)$ Threshold," J. Phys. B 28, 4907 (1995).
29. C.D. Lin, "Hyperspherical Coordinate Approach to Coulomb Three-Body Systems," edited by C. Cisneros and T. Morgan. World Scientific, p. 14 (1995).
30. C.G. Bao and C.D. Lin, "Effect of Quantum Mechanical Symmetry on Electron Correlations in Intrashell States of 3-Valence-Electron Atoms," Phys. Rev. A 52, 3586 (1995).
31. Xiazhou Yang, Jinhua Xi, C.G. Bao and C.D. Lin, "Analysis of Hyperspherical Channels of Three-Electron Atomic Systems," Phys. Rev. A 52, 2029 (1995).
32. Yan Zhou and C.D. Lin, "Comparative Studies of Excitations and Resonances in H^- , Ps^- and $e^+ + H$ Systems," Phys. Rev. Lett. 75, 2296 (1995).
33. Yan Zhou and C.D. Lin, "On the Nonexistence of Resonances Above the Ionization Threshold in Positron-Hydrogen Scattering," J. Phys. B 28, L519 (1995).
34. J.Z. Tang, C.D. Lin, B. Zhou and Isao Shimamura, "Resonances in Photodetachment of $H(2p^2, 3P^o)$," Phys. Rev. A 51, 4694 (1995).
35. C.D. Lin, "Hyperspherical Coordinate Approach to Atomic and Coulombic Three-Body Systems," Phys. Rept. 257, 1 (1995).
36. Bin Zhou and C.D. Lin, "Photoionization of Beryllium Atom," Phys. Rev. A 51, 1286 (1995).

Publications 1994

37. Z. Chen and C.D. Lin, "Close-Coupling Calculations of Alignment Parameters in $p+Mg(2p)$ Collisions," Phys. Lett. A 194, 201 (1994).

38. Yan Zhou and C.D. Lin, "Hyperspherical Close-Coupling Calculation of Positronium Formation Cross Sections in Positron-Hydrogen Scattering at Low Energies," J. Phys. B27, 5065 (1994).
39. Bao Cheng-Guang and C.D. Lin, "Hyperspherical Approach to Three-Electron Atomic Systems Few-Body Systems," 16, 47 (1994).
40. C.G. Bao, W.F. Xie and C. D. Lin, "Symmetry and Low-Lying Intrashell States of Three-Electron Atoms," J. Phys. B27, L193 (1994).
41. Bin Zhou and C.D. Lin, "Photoionization from Metastable (1s2s) $^1S^e$ and $^3S^e$ states of He Atom for Energies between the N=2 and 3 Thresholds of He^+ ," Phys. Rev. A49, 1057 (1994).

Publications: 1993

42. C.D. Lin, "Classifications and Properties of Doubly Excited States of Atoms a Chapter in the book "Review of Fundamental Processes and Applications of Atoms and Ions," edited by C.D. Lin, World Scientific Pub. (1993).
43. Yan Zhou, C.D. Lin and J. Shertzer, "Hyperspherical Approach to Coulombic Three-Body Systems with Different Masses," J. Phys. B26, 3937 (1993).
44. Zhou, C.D. Lin, J.Z. Tang, S. Watanabe, M. Matsuzawa, "Enhancement of Narrow Resonances in Photoabsorption from He Atom in Metastable States," J. Phys. B26, L337 (1993).
45. B. Zhou, C.D. Lin, "A Hyperspherical Close-Coupling Calculation of Photoionization from the He Atom, Li^+ and C^{4+} Ions .2. Between the N=2 and N=3 Thresholds," J. Phys. B26, 2575 (1993) .
46. B. Zhou, C.D. Lin, J.Z. Tang, S. Watanabe, M. Matsuzawa, "A Hyperspherical Close-Coupling Calculation of Photoionization from the He Atom, Li^+ and C^{4+} Ions .1. Below the N = 2 Threshold," J. Phys. B26, 2555-2573 (1993).
47. Z. Chen, C.D. Lin, "Fluorescence Yields of High-Lying Doubly Excited States of Ar^{16+} ," J. Phys. B26 (1993) 957-963.
48. C.D. Lin, "Classification of Highly Correlated Electronic States," Physica Scripta T46, 65-74 (1993).

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49. B. Zhou and C.D. Lin, "Shifts of Photodetachment Thresholds and Induced Shape Resonances in H^- in an Electric Field," Phys. Rev. Lett. 69, 3294 (1992).

50. J.Z. Tang, S. Watanabe, M. Matsuzawa and C.D. Lin, "Evidence of an Excited Angular Correlation Mode in High-Lying He**," Phys. Rev. Lett. 69, 1633 (1992).
51. J.Q. Sun and C.D. Lin, "Diabatic States in the Avoided-Cross Region," J. Phys. B25, 1363 (1992).
52. J.Q. Sun and C.D. Lin, "A single Channel Quantum Defect Theory for the Description of Doubly Excited States of Helium," Phys. Rev. A46, 5489 (1992).

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53. Z. Chen, C.-G. Bao and C.D. Lin, "Analysis of the Projection of the Total Orbital Angular Momentum along the Interelectronic Axis for Doubly Excited States of Atoms," J. Phys. B25, 61 (1991).
54. X.H. Liu, Z. Chen and C.D. Lin, "Demonstration of Molecule-like Normal Modes of Coulombic Three-Body Systems in Hyperspherical Coordinates," Phys. Rev. A44, 5468 (1991).
55. BingCong Gou, Z. Chen and C.D. Lin, "Radiative and Auger Rates of High-Lying Doubly Excited States of Multiply Charged Helium-Like Ions," Phys. Rev. A43, 3260 (1991).

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56. M. Dunn, Z. Chen and C. D. Lin, "Systematic Studies of the Molecular Properties of Intrashell and Intershell Doubly Excited States of C⁴⁺ and He," J. Phys. B23, 2435 (1990).
57. Z. Chen and C.D. Lin, "Reply to 'Comment on Calculations of Energies of Intrashell Doubly Excited States of Beryllium-Like Ions,'" J. Phys. B23, L87 (1990).
58. Z. Chen and C.D. Lin, "Classification of Coulombic Three-Body Systems in Hyperspherical Coordinates," Phys. Rev. A42, 18 (1990).

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59. Z. Chen and C.D. Lin, "Novel Systematics of Autoionization Widths of Doubly Excited States of Atoms," Phys. Rev. A40, 6712 (1989).
60. Z. Chen and C.D. Lin, "Calculations of Energies of Doubly Excited States of Berylliumlike Ions," J. Phys. B22, 2875 (1989).
61. C.D. Lin, "Systematics of Energies of Double Excited States of Heliumlike Ions," Phys. Rev. A39, 4355 (1989).

Publications:1988:

62. C.D. Lin, "Classification of Doubly Excited States of Two-Electron Atoms," in "Fundamental Processes of Atomic Dynamics," Plenum, 1988 edited by Briggs et al.
63. A. Jain, N.C. Deb, N.C. Sil and C.D. Lin, "Orientation and Alignment Parameters in e^- and e^+ Impact Excitation of Hydrogenlike Positive Ions," J. Phys. B21, 3793 (1988).
64. C.D. Lin and X.H. Liu, "Methods of Solving Coulombic Three-Body Problems in Hyperspherical Coordinates," Phys. Rev. A37, 2749-63 (1988).

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65. S. Watanabe and C.D. Lin, "A Classification Scheme of Triply Excited States from a Molecular Viewpoint," Phys. Rev. A36, 511 (1987).
66. C.D. Lin, "A Simple Formula for the Energies of Doubly Excited States," Nuc. Inst. Methods, B24/25, 284 (1987).
67. C.D. Lin, "Classification of Two-Electron Doubly Excited States," Comments on Atomic and Mol. Phys. 19, 89 (1987).
68. C.D. Lin and S. Watanabe, "Double Rydberg Formula and Applications to Doubly Excited States of Highly Charged Ions," Phys. Rev. A35, 4499 (1987).