Tutorial on shell model calculations and the production of nuclear Hamiltonians

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Tutorial of the *Espace de Structure Nucléaire Théorique*

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CEA/SPhN, Orme des Merisiers, build. 703, room 135, F-91191 Gif-sur-Yvette Cedex

I. OUTLINE

1. Lecture 0 : Introduction
   - (a) Schedule
   - (b) Expectations
   - (c) Topics covered in lectures and tutorials
   - (d) Practical information
2. Lecture 1 : Motivation for shell model
   - (a) Nuclear Schrödinger equation (mesoscopic system, undefined force)
   - (b) Bare nuclear forces
   - (c) Experimental magic numbers leading to shell structure
   - (d) Reproduction with HO + SO potential
   - (e) Fundamental assumptions for shell model
   - (f) Independent particle model
   - (g) Failure for ^{18}O
   - (h) Connection to HF
   - (i) Inclusion of correlations
   - (j) Effective interaction
   - (k) Model space
   - (l) Examples in *sd* shell- proof of principle
   - (m) Failure for exotic isotopes (island of inversion region)
3. Lecture 2 : Shell model formalism
   - (a) Brief review

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   (b) CI theory (idea behind)
   (c) Single particle wavefunctions/basis
   (d) Many-body conserved quantities
   (e) Many-body problem
   (f) Comparison of MBPT and CI
   (g) Matrix formulation
   (h) Center of mass motion/spurious states
   (i) Angular momentum coupling
   (j) m-scheme vs. J-scheme
   (k) Partitions
   (l) Examples : ^{18}O and ^{48}Cr
   (m) Matrix dimensions and computational time for typical model spaces
4. Lecture 3 : Introduction to NUSHELLX
   (a) Review
   (b) Bill Rae's NuShellX code
   (c) Alex Brown's wrapper code NUSHELLX@MSU
   (d) Treatment of center of mass motion
   (e) Lanczos procedure
   (f) Input : selection/creation of model space and interaction, selection of nuclei and properties to calculate
   (g) Performing calculations : setup and inputs
   (h) Calculation of level schemes
   (i) Level schemes in sd shell
   (j) Calculation of transition properties
5. Lecture 4 : Results with NUSHELLX
   (a) One-body transition densities
   (b) Gamow-Teller transitions
   (c) Electromagnetic transitions
   (d) Spectroscopic factors
   (e) Two-nucleon transfer
   (f) Input for reaction calculations
6. Tutorial 1 : Implementation and running of NUSHELLX
   (a) $A = 24$ nuclei (level schemes and isospin)
   (b) Mass of ^{30}Al
   (c) Spectroscopic factors
   (d) B(E2) transitions in neon isotopes
7. Tutorial 2 : Selection of model space and interaction
   (a) Selection of model space and interaction (^{48}Ti)
   (b) Selection of model space and interaction (^{11}Be)
   (c) Conceptual question : reliability of shell model calculations for exotic isotopes
8. Lecture 5 : The NN interaction
   (a) From Yukawa to one-boson exchange models : The anatomy of an interaction
   (b) Ideas of effective field theory
   (c) Nuclear interactions from symmetries of QCD : Chiral Effective Field Theory (EFT)
   (d) Ideas of Renormalization Group (RG)
9. Lecture 6 : Renormalization of NN interactions and construction of valence space interactions
   (a) Generating low-momentum interaction

   (b) Benefits of lower cutoffs
   (c) Another way : G-matrix renormalization
   (d) Solving the many-body problem in medium/heavy mass nuclei
   (e) Calculating effective valence shell interactions
   (f) Monopole part of the interaction
10. Tutorial 3 : Implementation of model space and interaction
    (a) Gamow-Teller/β decay
    (b) Approximations : modifying interactions (^{31}Mg)
    (c) Decay channels for oxygen isotopes
11. Tutorial 4 : More microscopic effective interactions
    (a) Effective interactions in the sd shell
    (b) Effective interaction in an appropriate model space for exotic nuclei (^{30}Ne and ^{31}Mg)
12. Lecture 7 : Effective interactions
    (a) Components of nuclear forces
    (b) Motivation behind empirical interactions
    (c) Procedure to produce empirical interactions
    (d) Accuracy with empirical interactions
    (e) Effective interactions derived from a realistic basis
    (f) Problems with multiple oscillator shells
    (g) Procedure to produce realistic interactions (ham)
    (h) Accuracy with realistic interactions
13. Lecture 8 : Three nucleon forces for medium-mass nuclei
    (a) Deficiencies in valence space interactions based on NN forces only
    (b) Three nucleon forces : Basics and construction in chiral EFT
    (c) Implementation in valence-space calculations
    (d) Relation to monopoles
    (e) Results
    (f) Approximation with density-dependent NN interactions
14. Tutorial 5 : Production of interactions (inclusion of three-body forces)
15. Group Projects :
    (a) See handouts (provided on Thursday)
16. Presentations

II. GOALS OF THE PROGRAM

In summary, the goals of the program are

1. To outline the underlying formalism and theoretical background to nuclear shell model codes
2. To provide shell model codes and instruction on their utilization
3. To perform standard shell model calculations
4. To produce effective interactions in the nuclear medium from underlying microscopic interactions
5. To culminate in a practical application to a realistic case of interest for nuclear structure