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NUCLEAR STRUCTURE THEORY

Annual Technical Progress Report

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Abstract

This report summarizes progress during the last year in the following areas of nuclear structure and reaction theory:

Theory of the effective interaction, including behavior of the expansion in orders of the reaction matrix.

Meson interactions with nuclei, including inelastic scattering of pions, and three-body theories of scattering and absorption of pions by deuterons.

Statistical spectroscopy including level densities, low-lying spectra and ground-state energies for complex nuclei, sum rules and strength distributions for various excitation processes.

Nuclear symmetries including their effects on α-transfer cross-sections, and symmetry breaking as measured by partial widths connecting different representations.

There has been considerable interest in whether the calculation of the effective interaction for shell-model spectroscopy, order by order in a perturbation series involving the reaction matrix, is a convergent procedure. Although calculations to a given order (usually second) may give apparent agreement with spectra, there are indications of difficulties, possibly divergences, both from formal considerations and from numerical examples. Two years ago we developed new methods of diagrammatic perturbation theory to allow a fuller investigation of higher-order contributions to the effective interaction. The first applications, to third order, indicated that the rate of convergence might not be as slow as had been thought (these results were published in 1972). More recently, we have been able to extend our calculation to fourth order. The fourth-order contributions turn out to be larger than third order, which has led us to a long investigation to find the "origin" of the large affects calculated. There are indications that the behavior of the series expansion, to this order, may be associated with "dressing" of the interacting valence particles, through separate interaction with the residual nucleus. Publication of these results, and of the diagrammatic methods, is in preparation.

The investigation of inelastic scattering of pions by nuclei appears to introduce new possibilities for learning about nuclear structure and the meson-nuclear interaction itself. One example which we have studied is the excitation of electric-dipole states of nuclei. The distorted-wave impulse theory of inelastic scattering leads us to claim that dipole excitation is quite sensitive to the degree of velocity dependence (or non-locality) of the pion-nucleon interaction. Our theoretical understanding of this interaction implies that there should be considerable velocity dependence, which also leads to strong non-locality in the optical model for elastic pion-nucleus scattering (as for example in the Kisslinger potential). This has not yet been directly confirmed by experiment; the inelastic excitation of electric-dipole states of nuclei appears to be the best test. We have reported preliminary DWBA calculations for a number of targets, which exhibit this sensitivity to velocity-dependence, by an enhancement of the inelastic differential cross sections at small angles. Assuming that this enhancement is found experimentally, it may in turn prove to be useful in the study of the nuclear physics of electric-dipole states. A more extensive survey of the dependence of the reaction cross-section on target structure (particularly isospin) and beam energy is underway.

A second example is the excitation of spin-coupled quadrupole states in nuclei. That such states should show up in the low-energy spectrum of medium and heavy nuclei has been predicted by L. Lin, et al., using the schematic surface-delta interaction. In order to see that such collective states are not just an outcome of such a special interaction, we have repeated the calculation using a realistic force. Our preliminary results indicate that the conclusions of the previous authors do not change much and that the spin-coupled quadrupole states should be seen in an energy region of 4 to 7 MeV in medium and heavy nuclei. We propose that these states should be excited also by inelastic pion scattering around the 3-3 resonance. The strong p-wave spin-orbit term in the pion-nucleon interaction should excite the spin-coupled quadrupole state preferentially at $\theta = 90^{\circ}$ (π-N c.m. system).

Many nuclear reactions induced by pions are in fact dominated by the 3-3 resonance in the free pion-nucleon scattering. How that comes about dynamically, and how the resonance is modified in the nuclear medium, has been under investigation. As previously reported, we have constructed a soluble three-body model for π-d scattering, based on Faddeev's integral equations, with a resonance in the pion-nucleon system. We have enlarged the scope of this theory by including a model (based on Chew-Low theory) for the resonance itself. This leads to a coupled channel theory, in which pions may be absorbed and produced, as well as scattered, by the nuclear target. We are presently studying this problem for the more tractable case of a deuteron target; but the theory may provide a basis for an improved treatment of absorption and scattering of pions by nuclei in general.

Spectroscopic amplitudes for alpha-particle stripping and pickup among the stable sd-shell nuclei with $A \leq 28$ have been tabulated. The results are exact in the limit that the eigenstates of the target and residual nuclei correspond to members of pure $(\lambda\mu)K_J$ bands obtained by angular-momentum projection from a single SU_3 representation. Sum rules which provide a measure of the total strength expected in a particular channel have been derived. The results have been used to predict systematic effects in sd-shell α-particle transfer.

The effect of representation mixing has been demonstrated for $^{18}O + \alpha \rightleftarrows {}^{22}Ne$ and $^{20}Ne + \alpha \rightleftarrows {}^{24}Mg$. A detailed comparison between the simple predictions and the corresponding results obtained with wave functions generated by using "realistic" effective interactions of the Kuo-Brown type has been carried out for $^{21}Ne + \alpha \rightleftarrows {}^{25}Mg$. A study of the effect of the prolate to oblate shape transition for nuclei near the middle of the shell is underway with both experimental and theoretical results for $^{24}Mg(^{6}Li,d)^{28}Si$ currently available.

The $^{18}O(^{6}Li,d)^{22}Ne$ and $^{24,25}Mg(^{6}Li,d)^{28,29}Si$ experiments have been performed in collaboration with members of the Nuclear Structure Research Laboratory at Rochester. We anticipate carrying out the $^{25}Mg(d,^{6}Li)^{21}Ne$

experiment on the Princeton cyclotron to test the theoretical prediction of an unusually strong ℓ=4 transfer to the 2.96 MeV $J^{\pi} = 9/2^{+}$ state in ^{21}Ne. The feasibility of (^{6}Li,d) experiments on the Ne isotopes is being investigated.

The work, described last year, on the eigenvalue distributions for the EGOE (embedded Gaussian orthogonal ensemble) which, unlike the ordinary GOE, makes close contact with spectroscopy, has been completed and two papers are in preparation. We have continued to study some aspects of energy-level fluctuations, attempting, in particular (but so far without real success) to understand why the Dyson-Mehta GOE results apply in much more general circumstances, for example in the ground-state domain. The work on ensemble results has been done in collaboration with persons in Mexico and at Cornell.

Work on ground-state energies and level densities for interacting particles continues, and applications to intermediate nuclei are now being made. Our method of locally averaged expectation values has been used by J. N. Ginocchio to give a theory for the spin-cut-off factor. The computing programs for constructing distributions with fixed angular momentum (and isospin) are in full operation and the first results (for large sd-shell spectra) are being studied. These programs have many uses but we think of them primarily as making it feasible to do theoretical spectroscopy in "huge" spaces, enormously larger than could be feasible by matrix methods. As the programs are used now the spectra, transition strengths and so forth are generated by purely statistical methods. We hope soon to develop also a spectroscopy, more accurate in the ground-state domain, in which the fixed-J distributions are used to correct and extend conventional matrix results.

Group-theoretical techniques for evaluating partial widths of spectral distribution theory have been developed in collaboration with

K. T. Hecht of the University of Michigan. The results can be used to evaluate the total intensity with which all states of a particular symmetry admix into a typical state of another symmetry, hence providing a measure of the goodness of nuclear symmetries. Application has been made to the spin-isospin SU_4 symmetry in ^{25}Mg treated as $(sd)^9$. It was found that leading symmetries are strongly admixed, with the symmetry breaking dominated by the one-body part (ℓ^2 as well as $\ell \cdot s$) of the effective interaction.

The technique of local energy averaging has been used to extend the single-nucleon-transfer non-energy-weighted and linear-energy-weighted sum rules; assuming that the level-to-level fluctuations in the sums are small (and measures for this can be sometimes calculated) one is able to evaluate the sum-rule quantities directly in terms of the Hamiltonian parameters even for very complicated nuclei. These quantities are moments of the strength distribution. Going well beyond sum rules we have been able recently to derive the strength function itself (for single-nucleon or two-nucleon transfer and for electromagnetic and other "hole-particle" transitions) as a double series in the orthogonal polynomials which are defined by the density. Considerations based on the central-limit-theorem indicate that the convergence should be rapid. We are presently making comparisons with shell-model results, after which we shall proceed to serious applications. Papers on both sum-rules and strength are in preparation.

During the year, we have had a number of visitors, for periods of one to several weeks, supported in part by the contract. They were: D. Agassi, Weizmann Institute (Israel), R. K. Bansal, Panjab University (India), A. E. L. Dieperink, I. K. O., Amsterdam (Netherlands), P. Goode, Rutgers University, C. Mahaux, University of Liege (Belgium), P. A. Mello, National University of Mexico, and J. K. Mon (Cornell).

The work reported includes that of J. P. Draayer and O. Nalcioglu, Research Associates, and three graduate students: T. Mizutani, V. Potbhare, and M. Prasad.

Through our research in collaboration with S. S. M. Wong at the University of Toronto, and P. Goode at Rutgers University, we have been aided by large grants of computer time by these institutions.

The co-principle investigators, Prof. J. B. French and Prof. D. S. Koltun, have devoted approximately 66 2/3% of their effort to the research project, during the academic year.

Reports and Publications July 1, 1973-June 30, 1974

1. F. Myhrer and D. S. Koltun
Pion-Deuteron Scattering in the $\Delta(1236)$ Energy Region as a Three Body Problem
Physics Letters 46B, 322(1973) (COO-2171-30).

2. Daniel S. Koltun
Theory of Mean Removal Energies for Single Particles in Nuclei
Physical Review C9, 484 (1974) (COO-2171-31).

3. O. Bohigas, J. G. Flores, J. B. French, M. J. Giannoni, P. A. Mello, and S. S. M. Wong
Recent Results on Energy Level Fluctuations
Phys. Rev. C (in press) (COO-2171-37).

4. J. B. French, P. E. Mugambi, S. K. M. Wong and S. S. M. Wong
Spectroscopy in Huge Spaces
To be submitted to Nuclear Physics (COO-2171-38).

5. O. Nalcioglu, D. J. Rowe and C. Ngo-Trong
Excitation of the $T_>$ Components of the Giant Dipole States in N>Z Nuclei by Muon Capture
Nuc. Phys. A218, 495(1974) (COO-2171-32).

6. D. S. Koltun and O. Nalcioglu
Sensitivity of Inelastic Pion Scattering to Non-Local Interactions
Phys. Lett. (in press) (COO-2171-35).

7. Y. Baudinet-Robinet and C. Mahaux
Statistical Analysis of Intermediate Structure
Physical Review C9, 723 (1974) (COO-2171-36).

8. J. P. Draayer
Alpha-Particle Spectroscopic Amplitudes for sd Shell Nuclei
Nucl. Phys. (in press) (COO-2171-34).

9. Annual Technical Progress Report for Period October 1, 1972-September 30, 1973 (COO-2171-21).

Papers Contributed to Conferences and Meetings:

10. J. P. Draayer and N. Anantaraman
Spectroscopic Amplitudes for Alpha Particle Stripping and Pickup between ^{25}Mg and ^{21}Ne
Bull. Am. Phys. Soc. 19, 472 (1974).

11. N. Anantaraman, R. M. De Vries, J. P. Draayer, H. E. Gove and J. P. Trentelman
A Study of the $^{18}O(^{6}Li,d)^{22}Ne$ Reaction at 32 MeV
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12. N. Anantaraman, R. M. De Vries, J. P. Draayer, H. E. Gove and J. P. Trentelman
A Comparison Between $^{16}O(^{6}Li,d)^{20}Ne$ and $^{18}O(^{6}Li,d)^{22}Ne$
International Conference on Reactions between Complex Nuclei, Nashville, Tenn. June 10-14, 1974.

13. J. P. Draayer, H. E. Gove, J. P. Trentelman, N. Anantaraman and H. Collins
The $^{24}Mg(^{6}Li,d)^{28}Si$ Reaction: Theory and Experiment
International Conference on Nuclear Structure and Spectroscopy, Amsterdam, September 9-13, 1974.

14. D. S. Koltun and O. Nalcioglu
Nuclear Recoil Effects in Inelastic Pion Scattering
Bull. Am. Phys. Soc. 18, 1409 (1973).

15. D. S. Koltun and O. Nalcioglu
Sensitivity to Non-Local Interactions in Inelastic Pion Scattering
Bull. Am. Phys. Soc. 19, 576 (1974).