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NUCLEAR EXCITATIONS AND REACTION MECHANISMS

Report of Progress November 1, 1977 to 31 October 1978

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ABSTRACT

- A. (Fallieros). The nuclear Compton amplitude, dispersion relations, parity degeneracies, nuclear form factors in electromagnetic transitions, nucleon and nuclear polarizabilities.
- B. (Levin). Validity of bound state approximations in rearrangement collisions, Pauli principle effects in the CCA theory, comparison of different approximate nuclear reaction methods, non-hermitian matrix Hamiltonians, atomic and molecular bound state calculations.
- C. (Geben). Dispersion relation approach to three-body systems.

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SCOPE

The nuclear physics group at Brown University has continued to comprise five physicists, two faculty members in experimental physics and the two faculty members and one Research Associate engaged in theoretical research. As in the past, the collaboration between experimentalists and theorists continues.

This progress report contains in the three parts, A, B, and C, the descriptions of the work of Professors Fallieros and Levin and of Dr. Greben. Research is carried out in the Barus and Holley Physics-Engineering Building while numerical analyses have been done at Brown on the IBM System 360/67.

CURRENT RESEARCH

2A. (Fallieros)

The nuclear Compton amplitude and dispersion relations.

As was discussed in previous work, the Kramers-Kronig dispersion relations are not exactly valid for a system consisting of non-relativistic particles in interaction with electromagnetic radiation.

The reason is essentially the mixed kinematics (relativistic for the photons and non-relativistic for the particles) which creates anomalous singularities in the Compton amplitude. Dispersion relations however are quite useful in general and are becoming even more desirable now because of the increasing availability of photon scattering experiments above the particle-emission threshold. Our most recent work in connection with this problem was an attempt to bypass the difficulty mentioned above and derive dispersion relations under limited conditions where analyticity creates no problem. A well-known situation where this can be done is the case of pure, unretarded electric dipole radiation. The Kramers-Kronig relations can be derived in this case by purely algebraic manipulations with no reference to causality, etc. We have extended this method and considered processes where both electric quadrupole and retarded electric dipole transitions can take place. The dispersion relations were seen to be valid in this case and with exactly their usual form. The low-energy theorem is predictably unaffected by this generalization but the value of the forward scattering amplitude at high energies is

now different. It was easy to verify that the (incorrect) assumption that the high-energy amplitude is still given by a term describing Thomson scattering from individual nucleons leads to the conclusion that the electric quadrupole absorption is completely cancelled by the retarded part of the electric-dipole absorption. In reality, these two processes do not cancel and their effect appears as a correction to the high-energy amplitude. This makes it clear that this amplitude contains also contributions from mesonic effects since for retarded processes Siegert's theorem is not valid and the current operator cannot be replaced by the corresponding density.

Another aspect of the problem is related to the fact that in practice, the real part of the forward scattering amplitude is obtained by integration of the standard expression containing the absorption cross section to a finite upper limit, after the meson threshold. Strictly speaking this relation is not correct. What we have studied so far is the possibility of correcting for omitted integral by including some of the simplest terms that may compensate adequately for this omission. The polarizability of the nucleon is one example of such compensating term. Estimates have been made of the effect on the low-energy scattering amplitude of including such a term. Similar estimates for the corresponding magnetic susceptibilities have also been obtained.

Parity degeneracies and static dipole moments.

This problem was outlined in last year's proposal. We have since then considered some systems which exhibit degeneracies between states of

opposite parity. A number of quantum-mechanical models were constructed to illustrate the problem, but we shall not describe them here in any detail. In nuclear physics an interesting example can be found in cases where the electric-dipole giant resonance happens to overlap with the isoscalar monopole mode. This is not an exact coincidence reflecting any fundamental symmetry but rather, results from the relative proximity of the peak energies of the two excitations and the fact that their widths are rather large and tend to overlap. What we are considering is a coincidence experiment of the type $e, e'p$. At a given energy and momentum transfer both states might be excited. What results will then be a mixture of the two modes, i.e., a state with a static (diagonal) electric-dipole moment. The charge distribution of this state is then off center and this will be reflected in the angular distribution of the protons emitted in the last stage of the reaction. This might provide a rather simple interpretation of experimental results when coincidence experiments become possible and may also help in the identification of the monopole mode which is often hidden under the more dominant electric dipole resonance.

Exact calculation of the photon-scattering amplitude for a simple system.

An attempt has been made to evaluate exactly the dispersive part of the scattering amplitude describing the forward scattering of photons from a non-relativistic system. This amplitude is written as an infinite sum of terms with each term consisting of a matrix element squared and an energy factor. An exact calculation should (a) avoid any approximation

for the transition operator, i.e., include all multipolarities, (b) find the eigenstates of the system and evaluate all the transition matrix elements and (c) perform the summation over the individual terms. Obviously this is an impossible task unless the system happens to be exceptionally simple. We have chosen for our purpose the familiar three-dimensional isotropic harmonic oscillator. The simplicity of this system is not only related to the fact that all its eigenvalues and eigenfunctions are known, but also to the separability of its wave functions in Cartesian coordinates. This helps, because the transition operator, i.e., the electromagnetic current, acts in only two Cartesian directions, one along the polarization and one along the wave vector of the incident photon. The result is the separation of the exact matrix element into an unretarded term times a form factor which contains the wave length of the photon. We have accomplished parts (a) and (b) of the description given above but not yet part (c): the exact expression is still in the form of a series. It has been possible, however, to evaluate the sum for some specific cases, e.g., find the amplitude and some of its derivatives both at zero and at a very high energy. In addition, we have calculated the absorption cross section of all energies as well as a number of energy-weighted integrals over the absorption cross section. We have verified the expected lack of validity of the Kramers-Kronig relations, but as of now we have not identified the specific singularities in the Compton amplitude which cause this violation of the dispersion relations. A description of this work will appear in the Ph.D. thesis of Mr. C. Ercil which will be written up during the next few months.

The role of the nucleon form factor in nuclear electromagnetic transitions.

This is part of Mr. C. Ercil's work toward his Ph.D. degree. It involves detailed calculations within a specific model of various integrated photon-absorption cross sections. The model consists of a number of point-like particles forming a bound state whose center of mass is in turn bound to a fixed center. It can be interpreted equivalently either as a composite system bound in a potential or as a system of particles interacting both with each other and with an external potential. The second picture together with the assumption that the particles have no intrinsic structure makes it possible to write down unambiguously the charge-density and current-density operators for the entire system. No intrinsic form factors appear at any stage. In the first picture, however, we have a composite system with an intrinsic form factor and an infinite set of states describing intrinsic excitations. The composite system can be thought of as a nucleon moving in a shell-model potential. The electromagnetic density operators resemble in this case what one finds in ordinary nuclear physics where one multiplies the orbital charge and current densities by the nucleon form factor. The nucleonic excitations, however, have to be introduced as additional degrees of freedom in ordinary nuclear physics whereas in our simplified model they appear from the very beginning.

The integrated absorption cross sections included several multiplicities: unretarded electric dipole, magnetic dipole, electric quadrupole as well as a term representing interference between retarded and unretarded electric dipole. The calculations were performed in both

representations mentioned above. Comparison of the results was useful for their interpretation. We mention here only one example. We assume that the excitation energy Δ of the first excited state of the compound system is considerably higher than the excitation energies of the states describing the center of mass motion. If we then calculate the absorption cross section integrated up to an energy lower than Δ , we find as a result a sum of terms each of which contains the intrinsic form factor of the composite system. This is simply the probability for this system to remain unchanged during the transition. If we now want to extend the limit of integration to infinity we use the alternative picture of point-like particles. No form factor appears in the result since it never appears in this formulation. Returning now to our previous picture, we conclude that the integral from the upper limit considered there to infinity should be such as to cancel completely the form factors obtained before. A detailed calculation confirms this. The cancellation is coming from terms that describe the excitation of the composite system. Among other things, this result emphasizes the inconsistency resulting from an incomplete treatment where, e.g., the form factor of a particle is included but its excited-state spectrum is not.

2B. (Levin)

Test of the bound state approximation in two-body rearrangement collisions.

Research on this topic was proposed last year: the calculations were carried out with J. M. Greben and completed prior to his departure for TRIUMF. A short Letter on this topic has been recently accepted for publication.

The bound state approximation (BSA) is the most widely used approximation in the analysis of low energy atomic, molecular and nuclear collision data. It involves two main ingredients: the retention in the analysis of only those reaction channels containing two fragments (i.e., complete neglect of any breakup channels) and the use of only bound states of each of the clusters forming the various two-fragment channels (i.e., neglect of continuum states of the clusters). The treatment of the relative motion of the clusters in each two-fragment channel then defines the approximation, e.g., plane wave, distorted wave impulse coupled channels, etc. The successful fitting of data by such schemes supports the belief that the BSA supplemented where necessary by the use of empirical optical potentials, provides both a physically and a numerically correct procedure. Despite such empirical successes, no test of the BSA, for a system in which breakup can occur, seems to have been made prior to the present one. A very simple three-body model has been used in our calculation: two "nucleons" interacting with each other and with an infinitely heavy core via S-wave separable potentials. Exact results for "deuteron" stripping and elastic scattering had been previously obtained by Bouldin and Levin for incident energies of 1.78,

6.7, 11.2 and 15.12 MeV. The former energy is below the breakup threshold of 2.225 MeV, and it is for this energy that the BSA is expected to be most accurate. BSA calculations were made within the framework of the Faddeev-Lovelace form of the channel coupling array equations for this particular three-body problem, the detailed form of which were worked out by Bencze and Levin (see below). The results of the calculation are in agreement with our expectations: below breakup, the BSA reproduces the overall trend of the stripping and elastic angular distributions, and gives excellent fits to the exact cross section in the forward direction. The BSA is also considerably more accurate than the distorted wave Born approximation (DWBA) below the breakup threshold. Above this threshold these conclusions are reversed, and the BSA becomes progressively worse with increasing energy, an obvious consequence of the increase in the phase space available for breakup. The remarkable aspect of this calculation is that with only one bound state in each channel, the BSA has been successful below the breakup threshold. This success is very encouraging and clearly suggests several other calculations, which are discussed in the accompanying renewal proposal.

Pauli principle effects in the CCA theory.

Effects of particle identity in the channel coupling array (CCA) theory of many-body scattering have been of renewed interest since the discovery by Kruger and Levin (discussed in last year's Progress Report) that for the choice of a channel permuting array, the set of 3×3

coupled CCA equations describing the three-body problem do not reduce to one, uncoupled equation. This is in contrast to the behavior of, for example, the Alt, Grassberger, Sandhas equations or the CCA equations obtained with the use of the 3×3 Faddeev-Lovelace channel coupling array. The reason for this behavior is that the CCA equations based on a channel permuting array are not, in the terminology of Bencze and Redish, "label transforming". This results from labelling the distinguishable particle channels by an arbitrary index set rather than by partitions (groupings of labelled particles into n disjoint sets, $n \geq 2$). An investigation of this situation, undertaken with Dr. Gy. Bencze of the Central Research Institute for Physics of the Hungarian Academy of Sciences, was begun during his visit to Brown in May and continued during my visit to Budapest in September. The following results have been obtained so far. First, we have derived a connected pair of equations for the three-particle problem wherein two of the particles are identical. These are based on the Faddeev-Lovelace (FL) choice of the channel coupling array W , and were used in the calculations of Levin and Greben described above. Second, another pair of connected equations were derived for this same three-body system, these based on the use of the two channel permuting arrays (CPS's). These latter equations have been employed in the HeH^+ calculations discussed below. When all three particles are identical, the FL choice of W leads to a single, connected equation, but use of CPA's leads only to disconnected equations. Several attempts were made to derive a single connected equation for the cases of three and of n identical

particles, but only disconnected equations have resulted. We suspect that the freedom inherent in the channel coupling array scheme plus the use of an index set rather than a partition scheme for labelling channels are the causes of this seeming incompatibility with the Pauli principle, but have not yet found a rigorous proof. Work on this problem continues.

Some aspects of nuclear rearrangement reactions.

Work done in collaboration with J. M. Greben comparing the CCA and the coupled reaction channel (CRC) approaches to nuclear arrangement collisions for a simple three-body model was reported in last year's progress report. In the course of writing up that work for publication another set of calculations was performed and a few additional conclusions were reached. These are noted briefly below.

The new model calculations were carried out for the $^{16}\text{O}(\alpha, \alpha)^{16}\text{O}$ and $^{16}\text{O}(\alpha, ^3\text{He})^{17}\text{O}(\frac{1}{2}^+)$ reactions induced by 75 MeV α particles. Theoretical curves were compared with experimental data taken at the KVI at Groningen and supplied to us by J. van Popta. Of all the calculational schemes used (optical model, CRC in its various forms, folded- and non-folded-potential CCA), the non-folded form of the CCA equations yielded the best fit to the elastic data. However, none of the procedures yielded a fit to the transfer data, and it remains an interesting problem for future investigation.

We have also found that within the bound state approximation (BSA) used in this work, different optical potentials can lead to large differences in amplitudes and cross sections, exactly as for first-order

calculations, in agreement with the results, e.g., of Johnson et al. and Rawitscher et al. On the other hand, the exact results are independent of the choice of optical potential. The implication is that in the exact case the higher-order coupling terms must be large for most choices of the optical potential. In the BSA, the coupling to other channels is too small to achieve this compensation (for both CCA and CRC schemes). Hence one can conclude that rearrangement coupling effects are known to be small only within the BSA: multistep effects need not be unimportant. The importance of carrying out exact calculations for "realistic" local interaction is thus underscored again. These would almost certainly allow one to place limits on the parameters of empirical optical potentials and would also give a great deal of insight into the validity of empirical data-fitting schemes such as the DWBA. Although we are not proposing to undertake such calculations in the accompanying renewal proposal (i.e., not immediately), this is an area of research that will be of interest for some time.

Quantum theory for non-hermitian Hamiltonians.

Arrangement channel quantum mechanics (ACQM) is the name originally given to the time-dependent n-particle scattering theory based on the channel coupling array (CCA) method of obtaining connected kernel integral equations. It now includes the non-hermitian formalism used for our atomic and molecular bound state calculations. In last year's progress report, it was noted that rules for forming scalar products and matrix elements for the non-hermitian procedure had been developed. During this past year, considerable progress has been made in setting

up a general quantum theory for ACQM. Probability and single-particle (charge) densities have been formulated that are in the same relation to the expectation value of the non-hermitian Hamiltonian-like operator as the familiar quantal quantities are to expectation values of the usual Schrodinger Hamiltonian. An equation of continuity, perturbation theory, a virial-type formula for diatomic molecules and also an electrostatic formula for diatomics have also been derived. The formula for charge density has been applied to the results of some of our H_2 calculations. At present, it seems as if the only remaining work to be done on this is connected with the question of spurious bound state solutions, which are a feature common to almost all many-body scattering theories. The role of spurious solutions in this regard is currently under investigation; it is hoped to complete this research in another few months.

A self-consistent field procedure for ACQM.

Hartree-Fock theory is the simplest self-consistent field (SCF) procedure for treating the identical particle problem in quantum mechanics. In this current contract year an SCF procedure has been developed for arrangement channel quantum mechanics (ACQM), and is being applied to two-electron atoms, in particular He. Because the CCA equations used in ACQM do not automatically incorporate effects of particle identity, the development of a general SCF procedure is not as straightforward as in the case of the Schrodinger equation.

The SCF equations derived to date are based on a reduction of the

CCA equations for n identical particles to a single equation which, however, is not connected. Hence the results can apply only to bound state problems for which there are no disconnected diagram effects. Since diagonalization in ACQM is effected by means of a bi-orthogonal basis, there are two sets of SCF equations: one each for the right- and left-hand eigenfunctions. The operators appearing in these latter two sets of equations are hermitian conjugates of each other. In contrast to the Hartree-Fock equation, the SCF equations for ACQM are asymmetric and state-dependent. It is anticipated that these new SCF equations will play a role in ACQM analogous to that of Hartree-Fock for the Schrodinger equation. A simple test of this hypothesis is through the calculation of the He-atom binding energy, a calculation being carried out in collaboration with Professor E. McCullough of the Chemistry Department of Utah State University. This collaboration resulted from our meeting at the recent Gordon Conference on Atomic and Molecular Interactions. Professor McCullough is an expert on atomic and molecular Hartree-Fock calculations and is programming the new SCF equation to be solved self-consistently (i.e., as an integro-differential eigenvalue equation). Since basis expansion results do not in all cases go monotonically towards the exact ones as the basis size is increased in ACQM (see the accompanying renewal proposal for work related to this), the SCF procedure is of great interest and the results of Professor McCullough's calculations are eagerly awaited.

ACQM bound state calculations.

A number of new ACQM molecular bound state calculations have been car-

ried out in collaboration with Mr. Wayne Ford during the current contract year. These include determination of the HeH^+ ground state parameters, various four-channel H_2 calculations, and variational-type CCA calculations for the H_2^+ molecular ion.

The first and last calculations were exploratory in nature. Unlike H_2^+ , two-electron atoms, or H_2 , the HeH^+ system is asymmetric. It is also one for which a two-channel approximation cannot suffice, since most of the binding energy comes from the asymptotic $\text{He} + \text{H}^+$ channel rather than from either of the two $\text{He}^+ + \text{H}$ channels. Two HeH^+ computations were carried out. In the first, no attempt was made to impose identical particle symmetry on the two electrons other than in the approximate He ground state wave function, i.e., the sum Ψ of the approximate channel components ($\Psi = \psi_1 + \psi_2 + \psi_3$) was not required ab-initio to be antisymmetric. The resulting equilibrium separation R_{eq} and dissociation energy D_e were found to be $1.49 a_0$ and 1.32 eV respectively, accurate to 1% and 35%. This is a very reasonable set of results given that the approximate He ground state wave function yields only 99% of the total energy. The second HeH^+ computation was based on the equations derived by Bencze and Levin discussed above. Using the same He approximate wave function as in the first calculation, but new dynamical equations, the values of R_{eq} and D_e changed to $1.65 a_0$ and 1.59 eV , an improvement in D_e but a worsening of R_{eq} . Only the second computation can be trusted however, since only that calculation yields a result which lies in the subspace of anti-symmetric functions. For reasons stated below, we do not anticipate extending these computations in the immediate future. Despite this latter remark, these two computations are

important ones, since they demonstrate that the CCA method can be used in conjunction with approximate (variationally determined) wave functions and still yield physically interesting, relatively accurate results. Hence, if the SCF He-atom calculations are successful, and Professor McCullough is able to undertake additional ones, the HeH^+ system will probably be computed in this manner also.

The other exploratory calculation, that for H_2^+ , was performed simply to determine if a variational calculation based on the CCA equations would yield a finite result. Two computations were done. In the first, a trial wave function of the form $\exp(-\alpha r)$ for each center was used. Both α and the internuclear separation R were varied. The minimum energy was found to be $-\infty$ at $R = 0$, implying that one can not proceed variationally. However, the second calculation used a trial function of the form $\exp(-r/a_0) + \beta \exp(-r)$, with α and β both variational parameters, and gave a minimum at a finite value of R . Although the minimum lies below the exact energy, this is an interesting result, and suggests, contrary to the above, that it may be possible to use variational methods with the CCA procedure. Work in this area is planned for the future.

The third set of calculations, on H_2 , is now the main area of the bound state work, and research on this is outlined in the accompanying renewal proposal. In the past year, we have developed a procedure for carrying out calculations involving inequivalent channels such as $\text{H} + \text{H}$ and $\text{H}^+ + \text{H}^-$. This is based on the ansatz used for the channel component wave functions and a specific choice from among the $(N - 1)!$ channel permuting arrays. To date, two sets of four-channel calculations have been made, each using very simple wave function approximations.

Triplet states have been computed using the (four) $H + H$ and $H^+ + H^-$ channels and singlet states have been determined using the $H + H$ and $H_2^+ + e^-$ channels.

Each case included unexpected results. One spurious and one non-spurious triplet state was found, thus disproving our earlier hypothesis that incorporation of other channels would eliminate the triplet solutions for which $E^-(R) \rightarrow -\infty$ as $R \rightarrow 0$. Although this latter type of spuriousity was not found in the singlet calculations, another was: the state which dissociates into two ground state atoms was found in the singlet case to have a potential energy surface that is almost flat, i.e., shows no binding portion. However, the non-spurious singlet energy surface does display the proper behavior. There are only three possible explanations for the continued presence of these spurious states: the ansatz used for the channel component states; the channel truncation from six to four channels; and/or their existence as actual spurious solutions to the approximate, non-hermitian equations. Research on this problem is detailed in the accompanying renewal proposal. Such research, along with investigations of the spectra of non-hermitian operators, are sufficiently important that other molecular bound state studies are being postponed for the time being.

2 C. (J. M. Greben)

A Dispersion Relation Approach to Three-Body Systems.

Two of the most basic concepts in quantum mechanics are unitarity and analyticity, the former describing the conservation of probability, the latter thought to be due to causality. Despite their fundamental importance many approximate theories do not obey these principles; in particular any Born approximation, be it for a strong, electromagnetic or weak process, violates unitarity. It then becomes quite hard to understand the success or failure of such an approximation as both the purely dynamical features and the basic constraints on the process have been dealt with in an approximate fashion. A dispersion relation approach will not allow such a mixture: it strictly obeys the quantum-mechanical constraints, and allows for a thorough study of the dynamics of the reaction.

In the present study we are concerned with the implementation of three-particle unitarity. An exact unitary three-body theory is possible if one introduces both $2 \leftrightarrow 2$, $2 \leftrightarrow 3$, and $3 \leftrightarrow 3$ amplitudes. Such a theory is, however, prohibitively difficult to use. Previously, one of the authors (JMG) has used an on-shell reduction of the unitarity equations, which basically connects the $2 \leftrightarrow 3$ and $3 \leftrightarrow 3$ amplitudes to the on-shell $2 \leftrightarrow 2$ amplitude, and therefore leads to a set of effective two-body unitarity equations. This set of equations was applied to nucleon-deuteron scattering, assuming that the singlet-deuteron was slightly bound.

In this investigation we insist on the simple form of the unitarity equations, but also construct an off-shell model for the $2 \leftrightarrow 3$ and $3 \leftrightarrow 3$ amplitudes in order to improve the calculation of the three-body unitarity cut, and to allow for virtual singlet-deuterons.

Using this off-shell model -- which is practically model-independent -- we calculate off-shell functions, which occur quadratically in the three-body discontinuity. In earlier work we found good agreement between exact calculations and our dispersion calculations if these functions were close to unity. The present study, however, indicates that the off-shell functions are quite large for moderate energies (we checked $E = 14.4$ MeV), and approach unity for larger energies (except at one of the integration points where the off-shell function is singular). Off-shell functions derived directly from the Faddeev equations lead to the same qualitative features, although the quantitative results are sensitive to the form of the interaction.

The present study, therefore, indicates that a model-independent effective set of two-body unitarity equations is hard to obtain, as the three-body contributions are very sensitive to the off-shell functions, which in turn are sensitive to the dynamical model used.

A final conclusion concerning this model dependence can only be obtained by solving the full dispersion relations, as the integration over all energies may still lead to cancellations which explain the success of the simple on-shell model. On the other hand, a less model-dependent theory can be obtained if one introduces additional $2 \leftrightarrow 3$ and $3 \leftrightarrow 3$ amplitudes in the equations restricting oneself to one or two momentum (or

subenergy) values. In a paper on this subject with Yu. A. Simonev, we show that by using the analytic properties of the amplitudes one can maximize the choice for these subenergies, and at the same time handle the problem of the singularities in the off-shell functions.

OTHER ACTIVITIES

The following invited lectures were given by members of the group:

"Time-Dependent Many-Body Scattering Theory and Nuclear Reaction Applications" (F. S. Levin, National University of Mexico, November 1977).

"Many-Body Scattering Theory Methods as a Means for Solving Bound State Problems" (F. S. Levin, National University of Mexico, November 1977).

"Channel Coupling Array Calculations of H_2^+ , H_2 , H^- , He and Li^+ " (F. S. Levin, National University of Mexico, November 1977).

"Many-Body Scattering Theory Methods as a Basis for Molecular Structure Calculations" (F. S. Levin, invited paper presented at the 18th Sanibel Symposia, March 1978).

"Many-Body Scattering Theory Methods as a Basis for Molecular Structure Calculations" (F. S. Levin, University of North Carolina, March 1978).

"The Channel Coupling Array Approach to Molecular Structure" (F. S. Levin, invited lecture presented at the Gordon Conference on Atomic and Molecular Interactions, July 1978).

"Application of Few-Body Methods to Atomic and Molecular Structure" (F. S. Levin, invited paper presented at the VIIIth International Conference on Few-Body Problems, Graz, Austria, August 1978).

"Quantum Theory for Non-Hermitian Matrix Hamiltonian Operators" (F. S. Levin, Central Research Institute for Physics, Budapest, September 1978).

"Many-Body Scattering Theory, Non-Hermiticity and the Structure of H_2 , HeH^+ , and Two-Electron Atoms" (F. S. Levin, Central Research Institute for Physics, Budapest, September 1978).

"A Dispersion Relation Approach to Three-Body Systems" (J. M. Greben, Free University, Amsterdam, January 1978).

"A New Coupled Channel Description of Transfer Reactions" (J. M. Greben, Free University, Amsterdam, January 1978).

"A Dispersion Relation Approach to Three-Body Systems" (J. M. Greben, Stanford Linear Accelerator Center, January 1978).

"Application of Dispersion Relations to Few-Body Systems" (J. M. Greben, Brooklyn College, June 1978).

PERSONNEL

Professor S. Fallieros

Professor F. S. Levin

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Research Assistant W. Ford

YEAR'S PUBLICATIONS

1. J. M. Greben and F. S. Levin, Comparison of the Channel Coupling Array and CRC Methods for a Realistic Nuclear Transfer Reaction Model, Phys. Letts. 71B, 252 (1977).
2. F. S. Levin, Time-Dependent, Many-Body Scattering Theory and Nuclear Reaction Applications, invited paper published in the Proceedings of the International Symposium on Nuclear Reaction Models, Balatonfured, Hungary 27 June - 1 July 1977, p. 25.
3. F. S. Levin, Many-Body Scattering Theory Methods as a Basis for Molecular Structure Calculations, invited paper presented at the 18th Sanibel Symposia, to appear in Int. Journ. of Quant. Chem.
4. F. S. Levin, Application of Few-Body Methods to Atomic and Molecular Structure, invited contribution, 8th International Conference on Few-Body Problems, held at Graz, Austria, 24 - 30 August 1978 (published in Few-Body Systems and Nuclear Forces, Vol. I, p. 352, ed. by H. Zingl, M. Haftel and H. Zankel, Springer, 1978).
5. F. S. Levin and H. Kruger, Unexpected Behavior of the CCA Transition Operators under Particle Interchange, *ibid*, p. 185.
6. F. S. Levin and J. M. Greben, On Off-Shell Transformations and Wave Function Formalisms in Many-Body Scattering Theories, *ibid*, p. 377.
7. F. S. Levin, Quantal Rules for Non-Hermitian Bound State Formalisms Based on N-Body Scattering Theory, *ibid*, p. 381.
8. J. M. Greben and F. S. Levin, On the Description of Direct Nuclear Rearrangement Reactions Using Various Coupled Channel Equations (with J. M. Greben), accepted for publication in Nuclear Physics A.

9. F. S. Levin and J. M. Greben, On the Validity of Neglecting Continuum Contributions in Two-Body Rearrangement Collisions, accepted for publication in Physical Review Letters.
10. J. M. Greben and Yu. A. Simonov, A Dispersion Relation Approach to Three-Body Systems, Phys. Rev. C18, 642 (1978).