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NUCLEAR EXCITATIONS AND REACTION MECHANISMS

Report of Progress November 1, 1975 to 31 October 1976

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Department of Physics

Brown University

Providence, Rhode Island

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ABSTRACT

- A. (Fallieros). Sum rules, nuclear hydrodynamics, photon scattering, exchange effects, nuclear diamagnetism and gauge invariance.
- B. (Levin). Time-dependent, many-body scattering theory; channel scattering states, many-body scattering theory methods, in particular the channel coupling array theory as a bound state formalism; non-hermitian nature of approximations to many-body scattering equations in differential form; H_2^+ bound state calculations; channel coupling array calculations of covalent bonding in H_2 .
- C. (Friar). Sum rules, locality and gauge invariance of Compton amplitude; form factors and meson exchange currents in nuclei; pion exchange contributions to nuclear charge, current and Hamiltonian operators; Relativistic Compton amplitude in 1 space dimension, sum rules and analyticity.
- D. (Hirata). Photoproton reactions, excitation of the Δ resonance, collective state of the Δ -nucleon-hole type, phase-shift analysis and energy dependence of cross sections in the 33 resonance region.

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SCOPE

Since last year's progress report, the Nuclear Physics group at Brown has undergone several changes in personnel. At present, Professor Friar is on a two year leave of absence at Los Alamos Scientific Laboratory and Dr. Hirata has returned to Japan. The new Research Associate who has replaced Dr. Hirata is Dr. Jan M. Greben, a few-body nuclear theorist from Holland. The group thus consists of five physicists, two faculty members in experimental physics and the two faculty members and one Research Associate engaged in theoretical research. The collaboration between the theorists supported by this contract and the experimentalists still continues.

This progress report contains in four parts, A, B, C and D, the work of Professors Fallieros, Levin, Friar and of Dr. Hirata. Dr. Greben has joined the group too recently to report any progress in research associated with his short stay here, and hence his work is not included in this report. 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, at MIT and at Los Alamos.

CURRENT RESEARCH

2A (FALLIEROS)

Diamagnetism, gauge transformations and energy-weighted sum rules

This is a continuation of an investigation which started more than a year ago. It has now been completed and we are in the process of preparing it for publication. It involves the study of the induced magnetic moment of a quantum system, the connection of normal diamagnetism and induced paramagnetism and the dependence of this classification on the gauge adopted in the description of the external field which causes the magnetization. A very simple example which can be used to illustrate this problem is the case of an external uniform magnetic field acting on a system which in some gauge exhibits no second-order (induced) paramagnetism. A convenient gauge for this, is the one where the vector potential is located somewhere in a plane perpendicular to the magnetic field. The vanishing of the paramagnetic term can be due to some simple selection rule such as ℓ -forbiddenness. The induced magnetic moment is then completely due to the term in the interaction Hamiltonian which depends quadratically on the vector potential and the magnetic susceptibility is positive. We now change the gauge and reexamine the situation. As is well known, physical observables such as the susceptibility are unaffected by this change. Our interest is to study the detailed response of the system to such a change rather than just the overall invariance which hardly needs confirmation. It is found that the contribution due to the term quadratic in the vector potential is now different (it can e.g., be twice as large as the one obtained previously) but that, at the same time, a non-vanishing paramagnetic term appears. The two magnetic susceptibilities should add up to the value already found. This can be confirmed by a detailed calculation, but this is not particularly interesting. What is more significant is the fact that the relation expressing this equality, which incidentally appears in the form of a sum rule, is very general: it is

characteristic of the Quantum nature of the system and not on its detailed properties. In simple cases these considerations can reproduce the well-known isoscalar quadrupole and monopole sum rules but these considerations are not only applicable to simple cases. What is of interest is not so much to calculate two quantities and then notice that they are related, but rather, to establish relations between quantities that may not be easy to calculate. In the discussion of this problem we found it instructive to keep in mind the microscopic origin of the interaction term which led to the diamagnetic effect discussed above. This term is simply a phenomenological representation of processes involving virtual creation and annihilation of particle-antiparticle pairs. For many practical problems, consideration of the virtual pairs will only introduce unnecessary complications. For our investigation, however, this turned out to be profitable leading us to an understanding of the connection between the sign of the diamagnetic susceptibility and the statistics of the particles (e.g. nucleons) in the system. This work was carried out in collaboration with Prof. J. L. Friar.

Scattering and absorption of photons from a one-dimensional system

This work is in progress and is also described briefly in the research proposal. Most of it was done in collaboration with Prof. J. L. Friar. The main problem is the study of the analytic properties of the photon scattering amplitude and the validity of appropriate dispersion relations. A related question is the behavior of the scattering amplitude at very high energies, a quantity that is in general difficult to obtain and is still unknown in most cases.

Transition densities, form factors and hydrodynamic excitations in nuclei

Plans for this work were described in some detail in last year's proposal. The expectations presented therein relate quite well with results we have obtained and we shall avoid restating the problem here. We summarize only some of the conclusions. At least for the case of isovector excitations, we have shown that it is possible to define the Steinwedel-Jensen model in terms of sum rules. The probing field, as expected, has a finite rather than infinite wave length. A general sum rule for transition densities can be written down containing this probing field in one of the matrix elements. The model results from (a) an appropriate selection of the wave length in terms of a boundary condition at the nuclear surface, and (b) the assumption that a single state dominates the sum. Unlike the infinite-wave-length cases (Tassie and Goldhaber-Teller models) one is limited here to an abrupt nuclear surface (i.e. a uniform ground-state density). This is not surprising since the model we are considering contains this restriction. If the restriction is relaxed, the sum rule remains valid but the model, predictably, is lost. It is clear that more than one model can be obtained from the same general framework by imposing additional specific physical assumptions. Obviously the general principles do not "prove" a model (although they can disprove one on the basis of consistency) but they do help us understand better its fundamental assumptions. They also lead to relations between various physical quantities and these can be useful. If e.g. we know that a given sum rule is exhausted in a certain energy region then we need not (and should not) attempt to create pictures for the transition density: in this case the transition density is not an independent quantity but is uniquely predicted by the sum rule.

A simple model of excitations in the presence of exchange interactions

This is a problem of probably only pedagogical interest which was studied together with Mr. C. Ercil during the initial stage of his work in the Nuclear Theory group at Brown. Mr. Ercil was drafted for military service and spent this past summer serving in the Turkish army. He is expected to return within the month of November and the work will be continued. The model under consideration consists of two bodies or clusters interacting with each other via a force that includes a charge-transfer term. The one body is assumed to have infinite mass while the mass of the other, which can itself represent a many-particle system, is finite and its motion produces the excitation of the overall structure. The charge of the moving cluster is obviously not a constant of the motion and its time derivative is related to the divergence of an exchange current. A regular convection current is also present representing the motion of the charged particles. This system is now perturbed by an external probe coupled directly to the currents. The probe may represent photons, in which case one is studying e.g., the absorption cross section. Since the parameters of the model can be varied arbitrarily, an attempt can be made to create resonances that are specifically related to convection or to exchange currents. Calculations were performed of the various quantities e.g. scattering amplitudes, integrated cross sections, etc., that traditionally appear in problems of this type. We note also that the probing field instead of being electromagnetic may represent an interaction which removes or adds charge to the system e.g., an electron-neutrino current. Very little work was done in this particular point, but it might be of interest to consider it again after Mr. Ercil's return.

2B. (LEVIN)

Time-dependent, many-body scattering theory

An article on this topic, written jointly with D. J. Kouri and H. Krüger, was submitted some time ago. Although the main conclusions are correct, the original derivation of them was in error, and the article was not published. The successful task of providing a new and valid derivation was carried out for the most part at Brown during the current contract year, plus a short collaborative effort with H. Krüger at University of Kaiserslautern in January, 1976. The new manuscript on this topic has been accepted for publication in Physical Review D, and it would appear to be one of the most significant of those resulting from the original Kouri - Levin collaboration, even though it is purely a theoretical development.

The time-dependent formalism is based on the channel component version of the channel coupling array theory of many-body scattering. There are three main advantages to working with this form of the theory. First, it is general, in that there are choices of the channel coupling array W which lead either directly or indirectly (via phase equivalent versions) to scattering theories derived by other workers. The channel permuting array choices of W lead of course to the equations derived by Kouri and Levin and also by Tobocman. Second, the theory is a direct matrix analog of the usual one-channel Lippmann-Schwinger equation. This allows one to generalize in a particularly straightforward way many results of one-body scattering theory, as the time-dependent theory indicates. Finally, the use of the channel component states, originally introduced by Hahn, Kouri and Levin, leads to an important theorem, as follows.

Let j denote a partitioning of the n (distinguishable) particles forming the non-relativistic system of interest into bound clusters. If there are m clusters in the partitioning, j is denoted an m -body channel. Corresponding to this is a partitioning of the Hamiltonian H into $H = H_j + V_j$, where H_j contains the kinetic energies and intra-cluster binding interactions, while V_j is the sum of the inter-cluster interactions, assumed to go to zero sufficiently rapidly asymptotically. The Schrödinger equation is $H\psi = E\psi$. Channel component states ψ_j are introduced via $\psi = \sum_j \psi_j$, where for $E > 0$, the sum is over at least all 2-body channels. If ϕ is a column vector formed of the $\{\psi_j\}$, then ϕ obeys $\mathcal{H}\phi = E\phi$, where $\mathcal{H}$ is a non-hermitian matrix $(\mathcal{H}^\dagger \neq \mathcal{H})$ formed from the operators $\{H_j\}$ and $\{V_j\}$, and E is the same energy appearing in $H\psi = E\psi$. A characteristic property of ψ is that it has outgoing waves in all open channels. The theorem of interest, proved in the time-dependent paper, is that only ψ_2 among the $\{\psi_j\}$ has outgoing waves in the 2-body channel 2: all other ψ_j , $j \neq 2$, asymptotically are zero.

This result is of great significance in numerical applications, since it gives insight into the formulation of approximations. It is also useful in establishing that there is a single S operator (in matrix form) which plays the same role in many-body scattering as does the more familiar S operator in one-channel scattering.

Other features of the time-dependent work are the introduction of an interaction picture and the proof, using (assumed) rotational and time-reversal invariance, that (bound state) solutions of $\mathcal{H}\hat{\psi} = E\hat{\psi}$ having a well-defined phase under time reversal correspond to real eigenvalues E . Conversely, solutions corresponding to complex energies can be discarded on the physical ground that they do not display the symmetry properties of

the system, just as one discards symmetric solutions of the Schrödinger equation for identical Fermions. An additional, important fact about the energy is that exact solutions of $\mathcal{H}\tilde{\psi} = E\tilde{\psi}$ yield only the real eigenvalues E of the Schrödinger equation $H\psi = E\psi$.

The development of a time-dependent, many-body scattering formalism means that one has at hand a new quantal method for treating many-body systems, distinct from the Schrödinger equation. The formalism takes account from the beginning of the channel nature of a many-body scattering system, and as such, has been denoted "arrangement channel quantum mechanics". Its application to bound state problems is discussed next.

Arrangement channel quantum mechanics as a bound state formalism

The time independent form of arrangement channel quantum mechanics involves the channel component states ψ_j , which obey $\mathcal{H}\tilde{\psi} = E\tilde{\psi}$ as noted above. The use of this formalism for bound state calculations was initiated with the 1s-approximation calculations on the H_2^+ molecular ion, described in last year's progress report. A considerable amount of effort was devoted during the current contract year to the general development of this formalism into a general tool for bound state calculations for many-body systems, and an article on this topic, including a detailed discussion of the H_2^+ (1s) calculation, has been submitted for publication with H. Krüger. The thrust of this article is that because the arrangement channel nature of a many-body system as exhibited in the positive energy ($E > 0$) portion of its spectrum should also be an aspect of the negative energy, bound state ($E < 0$) portion of its spectrum, then the connected kernel equation methods required to solve scattering problems ($E > 0$) should have application to bound state problems ($E < 0$). Of particular interest are approximation

methods to be used in applications. Various schemes have been developed, including a projection-diagonalization method, perturbation theory, and a variational method. The derivation of these approximation schemes was greatly facilitated by the analogy of the matrix theory (arrangement channel quantum mechanics) to ordinary Schrödinger mechanics. A discussion of the possibility of complex eigenvalues, similar to that noted above was also included. (Since this is an aspect common to most, if not all, many-body scattering theories when applied in approximate form to bound state problems, especially the Faddeev 3-body formalism, we have written a short note on it which will appear in Physics Letters.) In addition, symmetry effects were shown to reduce the pair of coupled equations in the 2-channel case to one uncoupled equation. The conclusion, based in part on the H_2^+ and H_2 calculations discussed below, is that arrangement channel quantum mechanics could have wide applicability in atomic, nuclear and molecular physics.

H_2^+ bound state calculations

The first calculations on this system using the preceding methods were described in last year's progress report. This work is part of a collaboration with Professor H. Krüger of the University of Kaiserslautern, applying arrangement channel quantum mechanics to atomic and molecular systems. The H_2^+ numerical calculations are being done at Kaiserslautern, and during the current contract year, the initial 1s calculation has been extended to a five-state-basis calculation: the 1s, 2s, $2p_x$, $2p_y$, $2p_z$ hydrogenic states were included. Using only the 1s state gives two energies and their concomitant H_2^+ wave functions: the bonding orbital and a non-bonding, rather than an anti-bonding orbital, the non-bonding case

corresponding to infinite attraction at zero separation of the two protons in H_2^+ . This latter solution must obviously be discarded. Extension, even to one additional expansion state, e.g., $2s$ or $2p_z$, immediately leads to an almost unchanged bonding result and an approximation to the anti-bonding state as good as the original $1s$ approximate bonding orbital result. Inclusion of three or five expansion states, on the other hand, leads to both real and complex energy eigenvalues, the latter occurring, as expected from the reality of the matrix elements of H , in complex conjugate pairs. These are also to be discarded since the corresponding wave functions do not display the correct behavior under time reversal. So far convergence to the exact bonding result, as the number of expansion states is increased, has not been found. The next step is inclusion of $3d$ states; this is currently being undertaken in Kaiserslautern.

H_2 bound state calculations

Calculations for the H_2 molecule of the equilibrium separation of the protons and the dissociation energy into two H-atoms were begun during the current contract year. This is part of the Levin-Krüger collaboration referred to above; the H_2 work has been carried out at Brown. The formalism employed was arrangement channel quantum mechanics. Unlike H_2^+ , which has two 2-body channels, H_2 has six 2-body channels corresponding to $H+H$, H^++H^- and $H_2^++e^-$. (The electrons are treated as distinguishable although the proper symmetry is taken into account). This increase in channels reflects the additional complexity of H_2 compared to H_2^+ , and because of it, results less accurate than those for H_2^+ were anticipated.

Initial calculations were made using two assumptions. First, only the two $H+H$ channels were retained and second, only the ground state of hydrogen

was included in the expansion of the channel components. These approximations lead to a 2×2 secular equation for the electronic energy $E(R)$, which depends on the proton-proton separation R . All integrals can be done analytically, and the equilibrium value of R , viz. R_{eq} , is easily evaluated. From it, the electronic binding energy $E(R_{eq})$ and dissociation energy $D_e = E(R_{eq}) + 27.10$ eV can be determined. The values obtained are $R_{eq} = 1.42a_0$, $E(R_{eq}) = -31.467$ eV and $D_e = -4.437$ eV, compared to experimental values of $1.40a_0$, -31.956 eV, and -4.746 eV, respectively, with corresponding accuracies of 1%, 1% and 6.5%.

This is, on comparison with the analogously simple calculation for H_2^+ , nearly a factor of two increase in accuracy, even though H_2 is a more complicated system! Furthermore, the resulting approximate wave function is identical to that used in the classic Heitler-London-Sugiura degenerate-perturbation/variation calculation, which produced, for example, R_{eq} and D_e accurate to only 18% and 34%, respectively. While the model suggested by the H-L-S calculation leads to bonding, it is not accurate enough to justify the classic valence-bond picture of covalent bonding. In fact, no picture of covalent bonding has ever before been justified, in the sense that simple models lead to inaccurate results while accurate results are obtained only from calculations for which one cannot build a simple physical picture. However, unlike any preceding calculation, the present one does justify the valence-bond model. That is, the valence-bond wave function coupled with arrangement channel quantum mechanics as a calculational technique lead to sufficiently accurate results so as to validate the statement that H_2 substantially consists of two hydrogen atoms in their ground states bound together by an accumulation of negative charge between the two protons. We regard this as a major new result in the field of molecular physics, and a triumph of the new calculational procedure. It suggests that arrangement channel quantum mechanics may have wide applicability in atomic, molecular and

nuclear physics where the channel nature of the relevant many-body systems is evident. An initial program involving simple calculations of this kind is enumerated in the accompanying renewal proposal.

Apart from the conclusions just noted, the specific results for H_2 are suggestive of further consequences that are particular to molecular physics and quantum chemistry, and relate to the basic structure of molecules. It is generally accepted by experimentalists that molecules are composed of identifiable atoms, and empirical evidence, e.g., molecular electronic density studies, support this. On the theoretical side, a calculational method was developed by Moffitt 25 years ago that incorporated this as the basic idea. It was denoted the "atoms in molecules" method and relied on the assumed smallness of the interatomic interactions in a molecule to justify, within a standard quantal perturbation scheme, the existence of atoms in molecules. The atoms in molecules method has not been successful, and has led some theoretical chemists and/or molecular physicists to suggest that there are no atoms in molecules, only unstructured nuclei and electrons. Indeed, standard molecular orbital calculations confirm this, since the wave functions in such calculations simply do not lead to any models of the molecules at all. The H_2 molecule is indicative of this, and even molecular orbital calculation on H_2 that produce results less accurate than those from the arrangement channel procedure, but more accurate than the valence-bond model, still fail to produce a recognizable atomic model of the molecule.

The results of the arrangement channel calculations, however, suggest that the "atoms in molecules" concept may indeed be valid, and that what has been lacking in the past has been the proper calculational procedure for incorporating it. One of the most difficult quantities to calculate accurately has been the dissociation energy D_0 , since D_0 is typically of the order of eV

while (for a diatomic molecule) $E(R_{eq})$ may be of the order of 10^3 eV, implying an 0.1% accurate calculation in order to determine D_e accurately. Most of $E(R_{eq})$ is composed of the separated atom binding energies, themselves of the same order as $E(R_{eq})$. In the arrangement channel approach, these numbers are input data, and are not determined by the calculation: in effect, only D_e is so determined. It is this aspect, plus the relatively high accuracy of the H_2 results that make validation of the atoms in molecules concept a not unlikely possibility. Should this eventually be true, then the arrangement channel procedure may, with "crude" approximations, be able to produce values of D_e accurate to perhaps 10%. This is to be contrasted with some very complicated molecular orbital calculations that give D_e off by 100% or more. The future possibilities of the arrangement channel procedures are indeed exciting and will be the subject of investigations for some time to come.

While we feel justifiably enthusiastic about these results and possibilities, it is also necessary to point out that there are also some unsolved problems. For example, we do not fully understand why the simplest (crudest) calculations for H_2^+ and H_2 give better results for the more complicated system. Nor is the rate of convergence in either case known, much less understood. Finally, preliminary results for H_2 including four channels are worse, not better, than those for the two channel, $H+H$ calculation, and this phenomenon is not understood, except to note that the projection/diagonalization technique used does not provide variational bounds. Hence, addition of more states in the original set of channels or more channels need not lead to a lowering of the energy as in the case when employing the Rayleigh-Ritz variational procedure for the Schrödinger equation. These various problems will be the subject of future investigations.

2C. (FRIAR)

The following collection of abstracts summarize Prof. Friar's work during the period February 1 to July 31, 1976.

Current conservation, exchange currents, and hadronic electromagnetic form factors.

The introduction of phenomenological form factors for the electromagnetic interactions of pions and nucleons is shown to lead to a violation of current conservation in standard treatments of exchange effects in nuclei unless these form factors are assumed to be equal. If they are not equal, other processes, which traditionally are not calculated, must contribute to the electromagnetic interaction of a nucleus.

Gauge invariance, locality, and the σ_2 photoabsorption sum rule

The requirements of gauge invariance for the photoabsorption and Compton amplitudes are used to evaluate σ_2 sum rule through terms of order $(1/mass)$. This expression is shown to equal the derivative of the dispersive part of the forward Compton amplitude with respect to the squared photon energy. In the absence of "frozen" meson degrees of freedom this is equivalent to the derivative of the entire Compton amplitude. If static exchange currents or finite nucleon charge distributions are present, the seagull terms of our model are non local and modify the sum rule.

Pion-exchange contributions to the nuclear charge, current, and Hamiltonian operators

Using a Foldy-Wouthuysen reduction procedure and time-dependent perturbation theory, we have calculated the one-pion-exchange contribution to the nuclear charge and current densities to order $(v/c)^2$. At the same time a renormalization scheme defines the pion-exchange potential including non-static and three-

body correction terms of order $(v/c)^2$. The requirements of relativity are investigated, and it is found that the retardation effect in the potential and charge density plays a critical role. The covariance conditions for the potential, charge, and current densities are shown to be satisfied to the order we have calculated. Finally, the deuteron case is discussed in detail. Throughout the calculation the role of the equivalence theorem is stressed.

2.D (HIRATA)

The reaction $^{16}\text{O}(\gamma, p)^{15}\text{N}_{\text{gnd}}$ and the Δ -nuclear states.

In previous work (on the π - ^4He system) it was shown that each partial-wave amplitude in π -nucleus scattering around the 33 resonance energy is dominated by one collective Δ -hole state. This state exhausts the transition strength to the π -nuclear ground state. The S-matrix elements for each partial wave have a pole in the second sheet at this energy.

We have subsequently investigated the importance of a collective state of this type in the reaction $^{16}\text{O}(\gamma, p)^{15}\text{N}_{\text{gnd}}$ in the energy region $\epsilon_\gamma \geq 200$ MeV. The contribution from direct processes was found very small for the high-momentum protons. We expect that the most important mechanism will involve the absorption of photons producing the collective Δ -hole state and followed by the transition $\Delta N \rightarrow NN$. The energy dependence of the cross section has been studied. A phenomenological interaction for the transition $\Delta N \rightarrow NN$ was determined from total nucleon-nucleon, pion production data. This work which is still in progress was carried out in collaboration with Drs. Koch, Lentz, and Moniz of MIT.

OTHER ACTIVITIES

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

"Application of the Channel Coupling Array Theory to Some Atomic Three-Body Systems"

(F. S. Levin, invited paper presented at the Few-Body Conference, Delhi, India, December 1975).

"Three-Body K Operators and Unitary Approximations: Application to Model (d,p) and (d,d) Processes"

(F. S. Levin, invited paper presented at the Few-Body Conference, Delhi, India, December 1975).

"Nuclear Reactions and Scattering -- Few-Body Aspects"

(F. S. Levin, Rapporteur's talk presented at the Few-Body Conference, Delhi, India, January 1976).

"Application of the Channel Coupling Array Theory to Some Atomic Few-Body Systems"

(F. S. Levin, University of Kaiserslautern, January 1976).

"Calculations of $e^- + H$ Scattering, Model (d,p) and (d,d) Processes, and H_2^+ and H_2^- Bound State Properties Using the Channel Coupling Array Theory"

(F. S. Levin, University of Surrey, Oxford University, A.E.R.E., Harwell, all in January 1976).

"A New Method for the Not-Very-Many-Body Problem"

(F. S. Levin, University of Rhode Island, February 1976).

"Topics in the Theory of Reactions and Bound States of Complex Systems"

(F. S. Levin, National University of Mexico (two lectures), June and July, 1976).

"New Ideas in Many-Body Scattering and Bound States: Application to the $e^- - p - e^-$ System"

(F. S. Levin, National Institute of Nuclear Energy, Mexico, July 1976).

"New Methods for Calculating Bound and Continuum States in Atomic, Molecular and Nuclear Physics"

(F. S. Levin, National University of Mexico, July 1976).

"Channel Coupling Theory of Covalent Bonding in H_2 "

(F. S. Levin, Chemistry Dept. Brown University, October 1976).

"Nuclear Charge and Current Operators and Relativity" (J. L. Friar, University of Virginia, October 1975).

Other Activities - continued

"Pion-Exchange Contributions to the Nuclear Charge Operator"
(J. L. Friar, Case-Western Reserve Univ. November 1975).

"Pion-Exchange Contributions to the Nuclear Charge Operator"
(J. L. Friar, SUNY, Stony Brook, January 1976).

"Recent Progress in Understanding Photonuclear Sum Rules" (J. L. Friar,
Invited talk at Washington APS Meeting, April 1976).

PERSONNEL

Professor S. Pallieros

Associate Professor P. S. Levin

Assistant Professor J. L. Frier (to July 31, 1976, on 2-year leave of
absence at Los Alamos Scientific Laboratory)

Research Associate M. Hirata (until July 31, 1976)

Research Associate J. M. Greben (from September 1, 1976)

Research Assistant C. Ercil

YEARS'S PUBLICATIONS

1. D. J. Kouri and F. S. Levin, Coupled Channel T and K Operator Equations with Connected Kernels. II. N Coupled, Two-Body Channels, Nuclear Physics A253 (1975) 395.
2. D. J. Kouri and F. S. Levin, Some Effects of Particle Identity in Many-Body Scattering Using the Method of Channel Coupling Arrays, Phys. Rev. C13 (1976) 14.
3. D. J. Kouri, F. S. Levin and W. Sandhas, On K Operators and Unitary Approximations for the Three-Body Problem, Phys. Rev. C13 (1976) 1825.
4. P. Dahlgren and F. S. Levin, Low Energy e^-+H Scattering as a Test of the Inhomogeneous Equation Method, to appear in J. Phys. B.
5. D. J. Kouri, H. Krüger and F. S. Levin, Arrangement Channel Quantum Mechanics. I. A General Time-Dependent Formalism for Multiparticle Systems, Phys. Rev. D (in press).
6. F. S. Levin, Application of the Channel Coupling Array Method to Atomic Few-Body Systems, invited paper presented at the VIIth International Conference on Few-Body Problems, Delhi, India, 29 December, 1975, to 4 January, 1976 (published in Few Body Dynamics, p. 371, ed. by A. N. Mitra et al, North Holland, 1976).
7. F. S. Levin, Three-Body K Operators and Unitary Approximations: Application to Model (d,p) and (d,d) Processes, invited paper presented at the VIIth International Conference on Few-Body Problems, Delhi, India, 29 December, 1975 to 4 January, 1976 (published in Few Body Dynamics, p. 408, ed. by A. N. Mitra et al, North Holland, 1976).
8. F. S. Levin, Nuclear Reactions and Scattering -- Few-Body Aspects, Rapporteur's Talk presented at the VIIth International Conference on Few-Body Problems, Delhi, India, 29 December, 1975 to 4 January, 1976 (published in Few Body Dynamics, p. 726, ed. by A. N. Mitra et al, North Holland, 1976).
9. H. Krüger and F. S. Levin, Possibility of Complex Eigenvalues in Approximate Solutions of the Homogeneous Faddeev Equations and Their Implication for the General n-Body, Physics Letters (in press).
10. D. J. Kouri and F. S. Levin, Effects of Bound State Approximations on DWBA and Multistep Processes in the Channel Coupling Array Theory, to appear in Phys. Rev. C.
11. H. Krüger and F. S. Levin, On the Validity of the Simplest Molecular Orbital Approximation for H_2^+ Bonding, to appear in Chem. Phys. Letters.
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