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ABSTRACT

- A. (Fallieros). Energies of giant isoscalar monopole and quadrupole excitations, energy-weighted sum rules, the random-phase approximation, Hartree-Fock calculations, spreading widths, physical consequences of the locality of current-density commutators and current-current sum rules.
- B. (Levin). Electron-hydrogen scattering using the inhomogeneous equation method; variational calculation of $e^- + H$ scattering using the symmetrized channel coupling array equation; K operators and unitary approximations for the 3-body problem; approximate calculation of model (d-p) and (dd) amplitudes and cross sections; multi-step processes in direct reactions; bound state calculations using the channel coupling array theory.
- C. (Friar). Methods for determining nuclear charge distributions, relativistic effects in nuclei, dispersion corrections and recoil corrections to elastic electron scattering; unitarity of elastic scattering amplitudes; low energy theorems for two-photon processes; pion-exchange contributions to the charge density; recoil effects and energy-dependent Hamiltonians; pion-exchange contributions to two-photon processes; hypervirial theorems for the Dirac equation; Coulomb energies of nuclei.
- D. (Hirata). Pion-nucleus scattering, diagonalization of the Δ -(nucleon-hole) configurations, doorway states and doorway dominance, calculations for ${}^4\text{He}$, discussion of experimental results.

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SCOPE

The Nuclear Physics group at Brown is currently the same as last year. It includes six physicists, two faculty members in experimental physics, three faculty members in theoretical physics and a research associate, also a theorist. The collaboration between the members of the theoretical group which is 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 and Friar and of Dr. Hirata. Professors Fallieros and Levin have returned from their sabbatical leaves at the University of Paris at Orsay, France and the University of Surrey at Guildford, England respectively. The work 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 and at MIT.

CURRENT RESEARCH

2A. (FALLIEROS)

Energies and moments of giant resonances

This is work carried out mainly at the University of Paris in collaboration with Drs. J. Martorell and O. Bohigas of the Institute of Nuclear Physics at Orsay and A. M. Lane of the Atomic Energy Establishment at Harwell. It includes both coincidence of individual investigations and studies carried out jointly. A preprint summarizing some of the main results has just been completed while a more elaborate manuscript is in preparation. The work has been confined for the time being to the two modes of excitation that are of current experimental interest namely the isoscalar monopole and quadrupole giant resonances. The basic approach starts from a consideration of various energy moments describing the distribution of the multipole strength among the excited nuclear states. These moments are defined as sums over the nuclear spectrum of squares of transition matrix elements multiplied by a power of the excitation energy. Several powers have been considered. Those of special interest turn out to be the first, the third and the inverse powers. The reason was shown to be the following: for any power, one can rewrite the energy moment as a ground-state expectation value of an operator or more generally of a product of operators. For the three powers mentioned above, however, one finds that an evaluation of this expectation value within a Hartree-Fock scheme is equivalent to evaluating the sum in the random-phase approximation (RPA). The proof involves essentially a generalization of what is known as Thouless' theorem provided one includes constrained Hartree-Fock calculations in addition to the regular ones.

The way to proceed with a detailed evaluation of the moments is then well defined: perform first a Hartree-Fock calculation (including constraints when

necessary) of the ground state of several nuclei. Identify the appropriate operators and evaluate their expectation values. The result then, according to the above arguments, gives the value of one of the energy moments in the RPA approximation. We note that no RPA calculation as such, needs to be performed explicitly and that the results so obtained are better than those of any practically possible RPA work. Taking ratios of the various moments obviously gives information about the excitation energy of the collective modes under consideration.

Detailed calculations of the type described above were performed for several nuclei both light and heavy. The nuclear interactions used in the computation were of the Skyrme type with several sets of parameters, all of which are known to give satisfactory descriptions of the ground-state properties. Since these are effective interactions, it is not obvious that the results they provide in a study of excitations should be of the same quality as those referring to the ground states: in studying excitations one probes the effectiveness of the interactions off the stability point where they have not yet been tested completely. In addition to comparing the results with experiments, it is important to present the theory in such a way as to provide a relatively easy evaluation of its content. A significant effort has been concentrated in this direction investigating the consistency of the overall scheme and comparing the results with other models and intuitive pictures. As a byproduct of this study it has become possible to interpret and obtain as limiting cases the results obtained for the quadrupole case by Bohr and Mottelson and by Suzuki. For the monopole mode, Suzuki's arguments were shown to be inoperative.

We note also that the approach outlined above does not presuppose the existence of a pure collective state concentrated in a narrow energy region but,

on the contrary, provides a test for such a picture: since more than two moments are computed, more than one ratio is obtained. If the ratios so obtained are identical then the pure collective picture is valid. If not, then their difference is interpreted as a manifestation of the spreading width of the appropriate strength function.

Transition densities and nuclear currents.

Some of the results presented in this section are related to problems considered in last year's proposal under the title "Electron Scattering and Nuclear Currents". They include the study of equal-time commutation relations between a nuclear-current density and its time derivative and an analysis of the significance of the locality that appears often (but not always) on the right-hand side of current-density commutators. The latter are of course directly related to various linearly energy-weighted sum rules investigations of which were also presented in previous work. The calculation of the current-current commutators was completed for the isoscalar case (applicable also to atomic or solid state physics). We may distinguish the case of transverse currents where the results of the present study are directly applicable to, e.g., the calculation of retardation contributions to the isoscalar photo-absorption cross section and that of longitudinal currents. The results of the latter case are equivalent (through current conservation) to those involving time derivatives of the current densities (e.g., one first and one second time derivative) and are therefore related to triple energy-weighted sum rules of isoscalar densities and transition moments. The rather formal general expressions obtained in this work found useful applications both in the computation and in the physical analysis of work on the quadrupole and monopole excitations presented in a different section of this report.

Conversely, it has been found instructive to relate the results of a relatively heavy computation to the general properties of the operators whose action is the main element of the excitation mechanism.

The question of the locality of the current-density commutators is related to a simple example discussed in last year's proposal. This was the observation of cancellations (between e.g. E2 and retarded E1 terms) in a fixed-momentum sum rule for isoscalar or atomic form factors. It was found that this behavior was a direct result of the locality of a current-density commutator and was independent of any other details of the problem. Other examples that might have useful applications were then looked for. We mention here only one case, that of isovector form factors. The density operators, in this case, do not commute with the nuclear interactions with the resulting additional terms being related, as is well known, to the exchange currents in a nucleus. The commutator is in general non local and no cancellation effects appear. If, however, we consider the particular case where the interactions are of the Skyrme type, we find that although currents of the exchange type do appear, the locality of the commutator is not destroyed and the cancellations found in the isoscalar case still occur. Although one cannot claim that the fundamental nuclear interactions are appropriately represented by Skyrme forces, this result is useful to keep in mind at least in order to test the consistency of theoretical results that are very often based on such forces. It might also be tempting to consider the possibility that this case, where locality is preserved, may at the end turn out to be more realistic even though it appears at present as a special example. The non locality may simply result from a limited phenomenology where physical effects are only partially taken into account. More work on this point is anticipated and will be discussed in the research proposal.

Excitation functions of atomic systems.

Some calculations of atomic excitations have been performed in the direction outlined in last year's proposal. The simplest picture of an atom, viz. the central-field approximation, was adopted in most cases. The main interest in these studies was in illustrating or verifying general considerations and expectations developed in connection to nuclear problems. No attempt was made toward a more realistic description of the atoms in terms of e.g. a more appropriate Hartree-Fock theory. Quantities such as sum-rule oscillator-strength distributions were studied in addition to atomic compressibilities or, more generally properties of atomic response functions. These examples were more useful than, e.g., a simple oscillator model simply because some of the quantities of interest (e.g. mean excitation energies, peak energies, etc.) tend to coincide in the oscillator model but they are clearly different for the atomic models. This is hardly surprising, since atoms are not known to exhibit sharply defined collective oscillations, but the understanding of more specific features of such quantities as the spreading widths turned out to be quite profitable.

2B. Current Research (Levin)

The work summarized below covers the period of my sabbatical in England as well as the ERDA-sponsored research done since June, 1975.

$e^- + H$ scattering via the inhomogeneous equation method. All work on this topic has been completed, a paper on it has been submitted to *Physical Review* for publication, and Paul Dahlgren's Ph.D. thesis, based entirely on the numerical calculations using the method, has been written and submitted to the Brown University Graduate School. No further work using the method is anticipated, as its inappropriateness as a basis for approximate calculations has now been established.

$e^- + H$ scattering via the channel coupling array method. The programming of the equations of this method for $e^- + H$ scattering, begun last year but delayed during my sabbatical, will be resumed after Paul Dahlgren passes his Ph.D. exam. Work on this topic has been carried out mainly by Dahlgren, who, because of his other commitments, is only able to do research part-time. A brief description of the method, etc., is given in last year's progress report and renewal proposal.

Variational calculations of $e^- + H$ scattering. The symmetrized form of the channel coupling array integral equation for the transition operator for $e^- + H$ scattering has been solved previously in the approximation in which only the ground state of hydrogen occurs in the spectral expansion of the Green's function. It is straightforward to obtain the differential equation whose solution leads to the same result as solving the integral equation.

A variational procedure has been formulated for solving $e^- + H$ scattering this way, and calculations of singlet and triplet phase shifts, begun in England, have recently been completed. At low energies, the results agree reasonably well with those of the exact (integral equation) solutions, the variational calculations of Massey and Moiseiwitsch whose trial wave function was employed, and the more standard close coupling calculations of Burke and collaborators. An article on this work is in preparation.

K operators and unitary approximations for the 3-body problem. The channel coupling array method has been used to develop K operators and unitary approximations for the three-body problem. It has been shown in detail that the transition (T) operators of the channel coupling theory obey the correct discontinuity equation, and K operators (for arbitrary channel coupling arrays) have been defined such that they have zero discontinuity. These operators are related to the T operators by a damping equation which manifestly displays the correct cut structure, and which guarantees that any approximate K operators will automatically yield T operators obeying the discontinuity relation. From this, it is trivial to introduce unitary approximations in an extremely simple way: unlike other approaches to this problem, it is unnecessary to solve a hierarchy of equations to obtain unitary approximations to the T operators. A paper on this topic, co-authored by D. J. Kouri and W. Sandhas, has been submitted to Physical Review.

Approximate calculations of (d,p) and (d,d) processes in the Mitra model. Preliminary calculations of (d,p) and (d,d) amplitudes and cross sections have been made for the 3-body, separable S-wave potential (Mitra) model of

stripping using approximations based on the K operator approach developed with Kouri and Sandhas, noted above. A Faddeev-Lovelace choice for W was made; this leads to 3-body equations which are phase equivalent to those of Alt, Grassberger, and Sandhas. The K operators were approximated by the leading terms (the "Born" terms) in the relevant integral equation. These approximate K's were then used in the damping equation to produce approximate transition operators under the further approximation that the contribution from the breakup cut could be ignored. The T's produced were thus equal to the solution of the purely "on-shell" T operator equation, i.e., the integral equation of the channel coupling theory obtained by replacing all outgoing wave Green's functions by their delta-function portions. With these assumptions, only algebraic equations occur. They were solved using the same model parameters as in the exact numerical solutions obtained by Bouldin and Levin several years ago, to which the approximate results were compared. For the low deuteron energies ($E = 1.78$ and 6.7 MeV), the approximate (d,p) cross sections were poor, while at the high energies ($E = 11.2$ and 15.1 MeV), the angular distributions were very good in shape and in magnitude. On the other hand, the magnitudes of all the (d,d) cross sections were poor, and only the shape at the lowest energy bore any resemblance to the exact results. Improved calculations, based on inclusion of both higher order corrections to K and the effects of the breakup continuum, are underway. The method will also be applied to $n + d$ scattering and breakup.

Multistep processes in direct nuclear reactions. The DWBA amplitude, plus multi-step corrections to it, have been studied within the framework of

approximations to the equations of the Kouri-Levin channel coupling array approach to many-body scattering. Two major conclusions have been reached. First, the complete cancellation arising between DWBA and the lowest order multistep correction, first found by Kunz and Rost, has been shown to occur only if certain not obvious approximations are made. When these approximations are not introduced, the cancelled DWBA amplitude is replaced by a new amplitude containing a non-orthogonality overlap. Second, the use of bound state approximations to help solve the coupled equations of the Kouri-Levin approach leads to approximate amplitudes which include effects of multistep processes but in which the DWBA terms are altered. The altered DWBA amplitudes are similar to those found in the analysis of the Kunz-Post cancellation. This work comprises an extension of previous analyses of Kouri and Levin and of Tobocman; an article on it is in preparation.

Bound-state calculations using the channel coupling array method. H. Krüger, a collaborator from Kaiserslautern, Germany, has applied the equations derived by Hahn, Kouri, and Levin from the channel coupling array method, to calculations of H_2^+ bound states. This calculation was repeated for the ground state. The basic idea is to rewrite the Schrödinger equation as a set of coupled equations corresponding to the various (two-body) channels and solve them either via a shell-model (Tamm-Dancoff) or a variational (Rayleigh-Ritz) procedure. In the H_2^+ case, a Born-Oppenheimer approach gives an equation for the electron which can be solved on a computer (for any given inter-proton separation R) to provide an energy surface $E(R)$. Minimizing $E(R)$ with respect to R gives both the equilibrium separation R_e

and the lowest energy E_e . The most accurate numerical values are $R_e = 2.00 a_0$ and $E_e = -16.398$ eV. A variational approach using a two centered trial function consisting of the 1s hydrogenic ground state gives $R_e = 2.50 a_0$ and $E_e = -15.39$ eV (this is by now a standard textbook result). The same wave function, but now used with the channel coupling array equations, gives $R_e = 2.07 a_0$ and $E_e = -16.69$ eV, a considerable improvement over the variational result for both E_e and R_e . Furthermore, just as with the earlier low energy $e^- + H$ scattering calculations, these are results based on extremely simple (and thus "crude") approximations that nevertheless are in very good agreement with the best numerical results available, based on much more complicated and sophisticated methods. A further application has been to calculating the affinity of the H^- atom. Use of the preceding method, for simple basis functions, did not lead to binding (the affinity is 0.7 eV, the small value being due to the screening of the proton by the electron normally forming the H-atom). On the other hand, simple trial functions used in a Rayleigh-Ritz variational procedure also do not lead to binding. In a further attempt to apply the channel coupling method, a variational procedure was applied to the equation used to calculate $e^- + H$ scattering lengths and phase shifts. This led to overbinding: ~ 2 eV. A more accurate evaluation, based on a numerical solution via computer, is being programmed. To estimate the expected order of magnitude of the result, a scattering length approximation was used, employing the $e^- + H$ scattering length already calculated. This estimate gave 0.34 eV, in very good agreement with 0.7 eV. The use of the channel coupling method for bound state problems thus appears very promising, and a number of applications are planned for the future.

Multichannel effective range theory. Work in this area has begun with an examination of threshold behavior of the three-body amplitudes as formulated using the channel coupling array theory. It is being done partly in connection with work on symmetry properties of the K matrix used in the three-body method of Kouri, Levin and Sandhas, and partly in connection with attempts to understand the nature of the straight line Phillips plot, relating triton binding-energy and $n + d$ doublet scattering length.

2C. (Friar)

Theoretical and experimental determination of nuclear charge distributions.

The wide-spread success of techniques⁽¹⁾ developed earlier for determining the nuclear charge distribution from experimental data obtained from elastic electron scattering and muonic x-rays has prompted us to review the entire field. An exhaustive analysis was made of techniques for determining densities from data, the constraints placed on the density by various pieces of data, techniques for calculating densities and cross-sections from nuclear wave functions, the corrections needed to supplement the usual "static" analysis, and semi-phenomenological Hartree-Fock techniques which currently provide us with the "best" nuclear wave functions. The latter is particularly important, since electron scattering is currently the best tool for investigating the fine details of nuclear structure (with J. W. Negele). (Advances in Nuclear Physics (in press)).

Relativistic effects on the wave function of a moving system.

The kinematical analysis of Krajcik and Foldy⁽²⁾ was repeated with a different point of view. Instead of determining the relativistic center-of-mass variables which allow the wave function for a moving system to be written as an intrinsic (internal) wave function multiplied by a plane wave, ordinary non-relativistic variables were used and the application of the boost operator to the wave function produces the wave function of the moving system. The latter wave function is related to the wave function in the nuclear rest frame in a simple way and the effect of relativity on the wave function of the moving system is isolated and can be used to define motional corrections to the usual non-relativistic charge form factor. (Phys. Rev. C12, 695 (1975)).

Dispersion corrections to elastic electron scattering and the closure approximation.

The validity of the closure approximation for calculations of dispersion corrections to elastic electron scattering has been tested for the special case of a fixed ^{16}O nucleus described by the Harmonic Oscillator Shell Model. Using this model deForest⁽³⁾ calculated "exact" dispersion corrections in the second-Born approximation. These results were compared to the closure approximation results and the corrected closure approximation of Friar and Rosen⁽⁴⁾. The former approximation was shown to be quite poor, while the latter approximation gives results which are substantially the same as the exact results and thus points the way to improved dispersion corrections using more realistic nuclear models. (With T. deForest) (Phys. Lett. (in press)).

Unitarity, Breitlike amplitudes, and low-energy approximations to dispersion connections.

The unitarity of the Breit approximation to dispersion corrections was investigated and found to be deficient. A correction to the Breit amplitude for dispersion corrections, which was found previously, corrects this deficiency. The problem was shown to be a manifestation of "Brown's Disease", a general defect of Breit equations⁽⁵⁾. The correction term was shown to contribute to the low energy approximation to dispersion corrections. (Nuclear Physics, to be published)

Low-energy theorems for nuclear Compton and Raman scattering and $0^+ \rightarrow 0^+$ two-photon decays in nuclei.

Low energy theorems for elastic photon scattering (nuclear Compton scattering) from a nucleus of arbitrary spin were derived in the non-relativistic approximation through terms quadratic in the photon frequency.

The same derivation was also made for the special case of $0^+ \rightarrow 0^+$ nuclear excitation by inelastic photon scattering (nuclear Raman scattering). Use was made of the general principle of gauge invariance, which bypasses the need to explicitly specify the form of the nuclear current operator. A general discussion of the contribution of mesonic exchanges was made and their effect was isolated. The center-of-mass correction to the nuclear diamagnetic susceptibility was also calculated. The $0^+ \rightarrow 0^+$ two-photon decay amplitude was obtained from the nuclear Raman amplitude and the transition rate calculated. (Annals of Physics, in press).

Pion-exchange contributions to the isoscalar charge operator.

Isoscalar contributions to the charge density which arise from pion exchange were examined using unitary transformations and time-dependent perturbation theory. By performing a Foldy-Wouthuysen (FW) transformation⁽⁶⁾ on the equations of motion of a nucleon interacting with an external pion field and an external electromagnetic field, vertices for pion absorption and emission from a nucleus can be constructed, as well as the ordinary charge and current operators (electromagnetic vertices). Using perturbation theory, the pion lines can be tied together to produce pion-exchange amplitudes and ultimately pion-exchange contributions to charge and current operators. It is found necessary to perform both mass (potential) and wave function renormalization on certain diagrams, which results in cancellation. Because of a well-known ambiguity⁽⁷⁾ in performing the FW transformation, the resulting operators do not have a definite "form". This is compensated for by a corresponding ambiguity in the form of the pion-exchange potential. Both the ambiguities were shown to be the result of a particular unitary equivalence, the same

unitary equivalence which leads to the "equivalence theorem" for pion-nucleon couplings. Thus, before specifying the form of the charge operator, one must specify the representation one chooses to work in or equivalently the form of the potential. Previous numerical calculations⁽⁸⁾ of pion-exchange contributions do not work consistently within a single representation and are therefore unconvincing. (Phys. Lett. B, in press).

Energy-dependent Hamiltonians, charge densities, and recoil effects.

The effect of an energy-dependent potential or Hamiltonian is investigated. In particular the effect on the orthonormality of the wave functions and the charge density is studied in order to understand recent results for the pion-exchange part of the nuclear charge density. A model problem, a relativistic Dirac particle interacting with a potential is reduced to semi-relativistic form by two methods: the FW transformation⁽⁶⁾ and a two-channel reduction scheme (upper and lower components of spinors). Unless care is taken, the two do not lead to the same results to order $(1/\text{mass})^3$. The two-component method leads to an energy-dependent Hamiltonian, which can be transformed into an energy independent one. The latter form is the same as the FW result, while the former is different and has unconventional orthonormality relations. The relationship between the model problem and the "recoil" and "normalization" graphs of perturbation theory is pointed out. (Phys. Review, in press).

Pion-exchange contributions to two-photon amplitudes and the nuclear magnetic susceptibility.

Pion-exchange contributions to general two-photon processes are calculated and the gauge invariance and crossing symmetry of the entire off-shell Compton amplitude is demonstrated. The low-energy theorem for such a process

involving real photons is derived and pionic contributions explicitly exhibited, in particular, the pion-exchange magnetic susceptibility. This quantity is shown to be small for n-p two-photon radiative capture. (Submitted to Physical Review Letters).

Hypervirial theorems for the Dirac equation.

Diagonal hypervirial theorems (generalization of the virial theorem) are derived for a Dirac particle interacting with a static potential. Those theorems are identities which follow from considering the commutators or anticommutators of selected operators with the Dirac Hamiltonian. Applications of these relations to the Coulomb problem are discussed. (with J. W. Negele) (submitted to Physical Review).

Relativistic corrections to electron scattering. II. Inelastic scattering.

Relativistic corrections to Coulomb inelastic electron scattering have been investigated using the results of a previous calculation⁽⁹⁾ on elastic scattering. A detailed discussion is made of the kinematics of inelastic scattering. Excitation of discrete states is treated in detail by two different methods, with particular attention paid to kinematical factors. Deuteron breakup is discussed and treated in a very similar manner to the discrete excitations. Comparison is made with analyses using plane wave final states and with previous work. (Submitted to Nuclear Physics).

Electromagnetic energies of nuclei and the nuclear Compton amplitude.

The electromagnetic energy of a nucleus is derived in perturbation theory, which relates this quantity to the amplitude for the forward scattering of virtual photons on a nucleus (Nuclear Compton amplitude). Using the gauge invariance of this amplitude, the energy is separated into Coulomb and transverse

components. Our formalism, although basically non-relativistic, admits corrections of order $(v/c)^2$ to the nuclear charge operator. This energy is further separated into one-body terms, related to the n-p mass difference, and two-body terms which lead to the Breit interaction and the nuclear Lamb shift. These results are then related to electron scattering sum rules in the manner of Cottingham⁽¹⁰⁾. Mesonic contributions to the electromagnetic energy are also discussed. (Annals of Physics, to be published).

Recoil corrections to elastic electron scattering in the Breit approximation.

Recoil corrections to the cross-sections for elastic electron scattering from spin-0 nuclei are investigated in the Breit approximation. The form of the scattering amplitude in first- and second-Born approximation is investigated in detail using time-dependent perturbation theory, and it is found that the center-of-mass (CM) frame is particularly convenient to work in. Transformation equations relating the lab and CM frames are developed. Those parts of the second-Born amplitude which correspond to the Breit amplitude are isolated, and the Breit equation⁽¹¹⁾ with the electromagnetic Breit interaction is investigated in detail. Corrections to the scattering cross-sections which are inversely proportional to the nucleus mass (recoil corrections) are calculated. Numerical results are presented for the particular case of $^{16}_0$.

(Submitted to Annals of Physics).

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2D. (Hirata)

The prominent feature of π -N scattering at intermediate energies is the strong variation of π -N amplitude at ~ 200 MeV pion kinetic energy. The description of pion-nucleus scattering by the static optical potential which is obtained by adopting the fixed scatterer approximation (FSA) and using the value of the π -N amplitude at one given energy seems to be inappropriate in this energy region. We have relaxed the FSA and have taken into account the propagation of the π -N system and its interaction with the residual nucleus. This provides a description of the scattering process in terms of multiple excitations of the Δ -h states. (h refers to nucleon-hole states). The contributions in the π -N amplitudes are divided into two parts, one smoothly and one strongly energy dependent. The former (background term) is treated by the usual optical potential method.

In solving the equation of motion of the Δ -h states, we take into account the Fermi motion of the nucleons, the binding corrections, and the Pauli-quenching effect which is shown to be equivalent to the Fock term in this equation. The non-static correction and the form factor of the π -N- Δ vertex are included.

The Δ -h doorway states are different from the usual ones which are observed in low-energy nucleon-nucleus scattering since the Δ -h doorways have large widths resulting from the Δ decays into $N+\pi$. As a result, the various resonances overlap with each other.

We may expect, however, that one of these resonances may (at least under certain circumstances) still act as a dominant doorway i.e. contain most of the excitation strength. This is related to specific features of the interaction in particular to the predominance of the annihilation matrix elements of the Δ -h potential.

In our results for ${}^4\text{He}$ the concentration of intensity in one dominant doorway state is relatively low for all partial waves in the off-resonance energy region of the $\pi\text{-N}$ scattering and the intensities are generally distributed in two or three states. The intensities, on the other hand, concentrate in one state for each partial wave for energies close to the resonance region. The resonant amplitude may therefore be approximated by a single resonance term for each partial wave. The resonance parameters however are in general energy dependent.

The corrections due to the form factor and the nucleon recoil into the $\pi\text{-N-}\Delta$ vertex are of the order of about 20% and 10% respectively. If the form factor is not included the zero point of the real part of scattering amplitude shifts toward the low energy direction too much. The effect of the correlation between Δ and N can be neglected when the form factor is included.

We have chosen a Gaussian shape for the isobar-residual nucleus interaction potential which is written as $V_{\Delta}(r) = (V+iW)e^{-\mu r^2}$, and treated V and W as the free parameters in fitting the total cross-section and the angular distribution. The energy dependence of the total cross-section and the real part of the scattering amplitude can be reproduced quite well. The agreement with the experimental data is also fairly good with regard to the angular distribution.

3. OTHER ACTIVITIES

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

"Scattering and Absorption of Photons from Bound Systems"
(S. Fallieros, Saclay, France, January 1975)

"Scattering and Absorption of Photons from Atoms and Nuclei"
(S. Fallieros, University of Grenoble, France, February 1975)

"Electromagnetic Interactions and Nuclear Excitations"
(S. Fallieros, University of Paris at Orsay, lecture series, spring 1975)

"The Forward Compton Amplitude and Dispersion Relations"
(S. Fallieros, University of Heidelberg, Germany and Max Planck Institute for Nuclear Physics in Heidelberg, April 1975)

"Scattering and Absorption of Photons from Bound Systems"
(S. Fallieros, University of Oxford, England and AERE Harwell, May 1975)

"Nuclear Excitation Mechanisms and Nuclear Structure"
(S. Fallieros, Greek Atomic Energy Center "Demokritos", lecture series, June 1975)

"Deforming and Expanding the Atomic Nucleus"
(S. Fallieros, University of Rhode Island, October 1975)

"A New Method in the Theory of Many-Body Scattering, I and II"
(F. S. Levin, University of Surrey, England, November 1974)

"A New Method in the Theory of Many-Body Scattering"
(F. S. Levin, Bonn University, Germany, November 1974)

"A New Method in the Theory of Many-Body Scattering"
(F. S. Levin, University of Kaiserslautern, Germany, November 1974)

"A New Method in the Theory of Many-Body Scattering"
(F. S. Levin, Oxford University, England, December 1974)

"A New Method in the Theory of Many-Body Scattering"
(F. S. Levin, Invited Paper, Institute of Physics Meeting on Polarization Effects and Mechanisms of Nuclear Reactions, Birmingham University, England December 1974)

"A New Method in the Theory of Many-Body Scattering"
(F. S. Levin, University of Sussex, England, January 1975)

"Non-Orthogonality Effects, Multistep Processes, and Coupled Equations for Nuclear Rearrangement Processes"
(F. S. Levin, University of Surrey, England, February 1975)

3. Other activities -- continued

"A New Method in the Theory of Many-Body Scattering"

(F. S. Levin, Daresbury Nuclear Laboratory, England, May 1975)

"Low Energy $e^- + H$ Scattering: Application of a New Theory of Many-Body Scattering"

(F. S. Levin, Royal Holloway College of the University of London, England, May 1975)

"Applications of a New Approach to the Three-Body Problem: $e^- + H$ Scattering and Model (d,p) and (d,d) Processes"

(F. S. Levin, Institut de Physique Nucleaire, France, May 1975)

"Some Aspects of the Three-Body Problem with Application to Model (d,d) and (d,p) Processes"

(F. S. Levin, University of Kaiserslautern, Germany, May 1975)

"A New Method in the Theory of Many-Body Scattering, I and II"

(F. S. Levin, Free University of Amsterdam, The Netherlands, May 1975)

"Unitary Approximations for Three-Body Scattering Using the Method of Channel Coupling Arrays"

(F. S. Levin, Free University of Amsterdam, The Netherlands, May 1975)

"The Three-Body Problem and its Application to (d,p) and (d,d) Processes"

(F. S. Levin, University of Birmingham, England, June 1974)

"Application of the Channel Coupling Array Theory to Some Simple Many-Body Systems"

(F. S. Levin, University of Maryland, September 1975)

"Probing the Nuclear Charge Distribution with Leptons"

(J. L. Friar, Pennsylvania State University, November 1974)

"Probing the Nuclear Charge Distribution with Leptons",

(J. L. Friar, University of Rhode Island, November 1974)

"Pion-Exchange Contributions to Nuclear Charge and Current Operators"

(J. L. Friar, Mass. Inst. of Tech., December 1974)

"Pion-Exchange Contributions to Nuclear Charge and Current Operators"

(J. L. Friar, SUNY at Stony Brook, February 20, 1975)

"Pion-Exchange Contributions to Nuclear Charge and Current Operators"

(J. L. Friar, Los Alamos, April 1975)

Round Table Discussion on "Model Independent Analysis" at conference "Electron Scattering at Intermediate Energy" held at Saclay, September 1975. (J. L. Friar, Chairman).

4. PERSONNEL

Professor S. Fallieros

Associate Professor F. S. Levin

Assistant Professor J. L. Friar

Research Associate M. Hirata

YEAR'S PUBLICATIONS

1. D. J. Kouri and F. S. Levin, A Resolution of Some Orthogonality and Expansion Set Problems in Many-Body Scattering Theory, Physics Letters 53B, 521 (1974)
2. D. J. Kouri and F. S. Levin, On Channel T and K Operators and the Heitler Damping Equation for Identical Particle Scattering, Phys. Rev. A10, 1616 (1974)
3. Y. Hahn, D. J. Kouri, and F. S. Levin, Channel Coupling Arrays and The Reduction Method in Many-Body Scattering, Physical Review C10, 1615 (1974)
4. Y. Hahn, D. J. Kouri, and F. S. Levin, Lack of Spurious Solutions in the Coupled Channel T Operator Formalism, Phys. Rev. C10, 1620 (1974)
5. D. J. Kouri and F. S. Levin, The K-Matrix and Unitarity Constraints on Off-Shell T-Matrix Elements, Phys. Rev. C10, 2096 (1974)
6. D. J. Kouri and F. S. Levin, General Many-Channel Variational Principles for Multiparticle Scattering, Phys. Rev. C11, 352 (1975)
7. D. J. Kouri and F. S. Levin, Coupled Channel T and K Operator Equations with Connected Kernels. I. Three-Body Problem with Pairwise Interactions, Nuclear Physics A250, 127 (1975)
8. J. L. Friar and S. Fallieros, Relativistic and Retardation Effects in the Thomas-Reiche-Kuhn Sum Rule for a Bound Particle, Phys. Rev. C11, 274 (1975)
9. J. L. Friar and S. Fallieros, Non-Relativistic Compton Amplitude, Phys. Rev. C11, 277 (1975)
10. S. Fallieros, Energies and Moments of Giant Resonances for Isoscalar Monopole and Quadrupole Excitations: A Sum-Rule Approach, (with J. Martorell, O. Bohigas and A. M. Lane) Submitted to Phys. Letters
11. S. Fallieros, Electromagnetic Interactions and Nuclear Excitations, Part I, Institut de Physique Nucleaire, Orsay. (Technical Report, 1975)
Part II, in preparation.
12. S. Fallieros, Giant Resonances (with J. Martorell, O. Bohigas and A. M. Lane), in preparation.
13. J. Friar, The Determination of the Nuclear Charge Distribution of ^{12}C from Elastic Electron Scattering (with J. W. Negele) Nuclear Physics A240, 301 (1975)
14. J. L. Friar and J. W. Negele, Theoretical and Experimental Determination of Nuclear Charge Distributions, Adv. in Nucl. Phys. (in press).

Year's Publications -- continued

15. J. L. Friar, Relativistic Effects on the Wave Function of a Moving System, Phys. Rev. C12, 695 (1975)
16. T. deForest, Jr. and J. L. Friar, Dispersion Corrections to Elastic Electron Scattering and the Closure Approximation, Phys. Lett. (in press)
17. J. L. Friar, Low-Energy Theorems for Nuclear Compton and Raman Scattering and $0^+ \rightarrow 0^+$ Two-Photon Decays in Nuclei, Annals of Physics (in press).
18. J. L. Friar, Pion-Exchange Contributions to the Isoscalar Charge Operator, Phys. Lett. (in press)
19. J. L. Friar, Energy-Dependent Hamiltonians, Charge Densities, and Recoil Effects, Phys. Rev. C (in press)
20. J. L. Friar, Unitarity, Breitlike Amplitudes, and Low-Energy Approximation to Dispersion Corrections, Nucl. Phys. (to be published)
21. J. L. Friar, Electromagnetic Energies of Nuclei and the Nuclear Compton Amplitude, Annals of Physics (to be published)
22. J. L. Friar, Relativistic Corrections to Electron Scattering II. Inelastic Scattering, submitted to Nucl. Phys.
23. J. L. Friar, Pion-Exchange Contributions to Two-Photon Amplitudes and the Nuclear Magnetic Susceptibility, submitted to Phys. Rev. Lett.
24. J. L. Friar and J. W. Negele, Hypervirial Theorems for the Dirac Equation, submitted to Phys. Rev. C.
25. J. L. Friar, Recoil Corrections to Elastic Electron Scattering in the Breit Approximation, submitted to Annals of Physics.