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THEORETICAL STUDIES IN
NUCLEAR REACTION AND NUCLEAR STRUCTURE

Final Report

for

Contract No. E(40-1)4856

January 1, 1975 - June 30, 1976

M. K. Banerjee and J. J. Griffin

July, 1977

UNIVERSITY OF MARYLAND
DEPARTMENT OF PHYSICS AND ASTRONOMY
COLLEGE PARK, MARYLAND

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I. INTRODUCTION

During the period January 1, 1975 to June 30, 1976, Theoretical Studies in Few Nucleon Reactions, Eikonal Approximations, and Optical Models (Part II), Pion Reactions (Part III), Nuclear Structure By Reaction Studies (Part IV), and Nuclear Dynamics (Part V) constituted the main efforts of the University of Maryland Nuclear Theory Program. Among these four areas the activity on some thirty-three different items is summarized in the following pages.

The rise in interest in Nuclear Heavy Ion Reactions is reflected in the group's growing effort in Nuclear Dynamics. In this area the studies of nuclear fission have ramified into the infinitely richer and more varied study of Nuclear Fluid Dynamics. J. Griffin's efforts in this area continued during his absence in Germany as an Alexander von Humboldt Visiting Senior Scientist.

In the area of Pion Reactions, a significant and far reaching advance has been achieved in the extension of the Chew-Low Theory to S-wave πN Scattering. This approach provides a clear basis for resolving certain ambiguities which arise in more phenomenological approaches. It is expected that those reported here are only the first of many fruits to be yielded from this approach

In other areas, also, substantial steady progress continues. The optical model analysis of reactions, in particular, the effort benefitted from the extended visit of Professor R. C. Johnson during his leave from the University of Surrey. A flux of other visitors, varying from short seminar visits to extended summer stays, and the continuation of the Nuclear Theory SWUM (Seminar Workshops at the University of Maryland) conferences also enriched and stimulated our research efforts.

II. FEW NUCLEON REACTIONS, EIKONAL APPROXIMATIONS, AND OPTICAL MODELS

A. Three-Body Approach to Nuclear Reactions

During the period in question an extensive survey of the subject of three-body effects in nuclear reactions was made. The result of this survey was the review article "Applications of 3-Body Methods to Many-Body Hadronic Systems" in Modern Three-Hadron Physics, A. W. Thomas, ed. (Springer Verlag, Berlin, 1976) pp. 181-243.

This article reviewed both the tests of reaction mechanism approximations made with 3-body models and the evidence for 3-body effects in nuclear reactions. Numerous suggestions for future directions of research were made. (E. F. Redish)

B. Convergence of Approximation Schemes in Reaction Theory

Practical reaction "theories" such as the Distorted Wave Born Approximation (DWBA), coupled channel approximations (CCA), etc., usually rely heavily on physical intuition in establishing the approximations and corrections to them. Because of the lack of a complete first-principles many-body reaction theory, no systematic expansion has ever been studied. What is worse, no "small parameter" has ever been identified to justify the validity of standard reaction approximation or to permit estimates of corrections.

The recent development of a full N-body reaction theory which is in principle capable of handling arbitrarily many continuous degrees of freedom to all orders allows us to begin an investigation of the question of convergence. In these theories, scattering amplitudes are determined by linear integral equations with compact kernels. These equations can be set up so that they yield, for example, a DWBA as first approximation with corrections given systematically by iteration of the kernel. In such a formalism the "small parameter" governing convergence of the series is the largest eigenvalue of the kernel (spectral radius). Studying these eigenvalues can lead to new insights on the problem of convergence.

We have begun these studies by investigating the simplest case possible, the Born series for potential scattering. Two cases have been studied, the

separable potential and the square well. In both cases analytic expressions can be obtained for the spectral radius. We have found that the relevant dimensionless combination of parameters appear naturally. In this example they are a strength and a range. We obtain criteria for convergence of the Born Series which include the standard condition but strengthen it considerably. (In fact the condition is strengthened optimally.) We have obtained the intuitive result that for fixed ranges of the potential, larger strengths will converge as ℓ (orbital angular momentum) increases, and have been able to quantify it.

We propose to extend these studies first to simple coupled channel models for the purpose of studying a DWBA series and eventually to realistic nuclear systems. Our ultimate goal is a physical understanding of the convergence rate of reaction approximations as a function of the nuclear parameters.

(E. F. Redish and Dan MacMillan)

C. Three-Body Models of the Deuteron-Nucleus System

There is strong evidence from the study of (p,d) and (d,p) reactions on a variety of heavy targets that three-body intermediate states play an important role in these processes. A recent example is provided by the 65 MeV (p,d) data obtained at Maryland on targets of ^{12}C , ^{14}N , ^{16}O , ^{40}Ca , and ^{90}Zr . It has been shown that the standard DWBA which, roughly speaking treats the (p,d) reaction as a pair of two-body channels coupled perturbatively, does not give an adequate description of the observed angular distribution of the outgoing deuterons. The inclusion of contributions from certain three-body channels (neutron and proton in an unbound state, plus residual nucleus) using the adiabatic prescription pro-

posed by Johnson and Soper gives an excellent fit to the data. It was shown by Johnson and Soper that a similar treatment of the contributions of these channels to elastic deuteron scattering works quite well, and subsequent work by Austern, Johnson and Tandy, Rawitscher and others has thrown considerable light on the nature of the approximation involved. However, none of these approaches had provided a basis for a systematic theoretical understanding of the role of three-body channels as a function of energy, mass number of target, and Q -value. This kind of understanding is crucial as the need for generalization to nuclear reactions of a more complex nature is being developed. With these considerations in mind research has been pursued along the lines outlined below.

1. Validity of the Adiabatic Prescription as an Approximation to the Three-Body Problem

The role of three-body effects in (p,d) reactions has been re-examined within the framework of the adiabatic approximation of Johnson and Soper and the results applied to Maryland data on light nuclei at 65 MeV. Excellent agreement with experiment has been obtained.

This work was submitted to the APS Meeting, Washington, D. C., in April 1976 and is in process of publication in Nuclear Physics (R. C. Johnson)

2. Development of a correct and Useful Three-Body Hamiltonian

In the course of the study of work by Redish and Kouri and Levin with the aims of this project in view it has become clear that many of the truncations of the many-body problem suggested by these authors do not satisfy the fundamental requirements of reciprocity. A paper outlining some consequences of this and possible way of developing formalisms which do not have this property is in the course of preparation in collaboration with Redish and Viscar. (R. C. Johnson)

3. Spin Dependent Effects in Reactions Involving Deuterons

As part of this research effort a course of lectures on polarization effects in nuclear reactions was prepared and delivered. The lecture notes are currently being prepared for circulation. An invited talk on this subject was given at the APS Meeting, Washington, D. C., April, 1976.

A novel method of partial wave analysis for spin-s particles has been developed which has some advantage when spin-dependent forces of rank higher than 1 are important. The extent to which observable effects due to second rank tensor forces can be separated out in the high angular momentum limit has been discussed. This approach may be useful in the study of high energy nucleon-nucleon scattering. This work has been written up and submitted to Nuclear Physics.

Considerable effort has been put into understanding the validity and limitations of the approach of Ioannides and Johnson to the calculation of Pauli Exclusion Principle and tensor force effects in deuteron scattering. These results will be prepared for publication in the next several months.

The study of the role of 1s states in (d,p) reactions near the Coulomb barrier is continuing. It has become clear that a more accurate treatment of the energy difference between elastic and break-up channels will be necessary and the associated modification of the formalism are underway in collaboration with G. L. Wales at Surrey.

Considerable progress has been made on the study of Coulomb polarizability and numerical results should be available in the near future. (R. C. Johnson)

D. Intermediate Energy Optical Potentials

The intermediate energy hadron-nucleus optical potential is usually constructed in practice by the use of some single scattering approximation, either following Watson or Kerman, McManus, and Thaler. We have recently developed a new three-body model of the single-scattering optical potential which permits the careful treatment of a number of effects which are usually neglected. These include proper three-particle kinematics of the single collision, the effect of the binding potential on intermediate state propagation, and the effect of intermediate state pickup. The use of the three-body model permits the extraction of a unitarity relation which specifies precisely the asymptotic states corresponding to absorption and the reaction amplitudes to these states. By restriction we are able to determine the inelastic states and the inelastic reaction amplitude which are implicit in the standard folded-T-matrix methods.

We study the case of proton-nucleus scattering and find that the best two-body approximation of the single-scattering optical potential should be provided by the impulse approximation for the Watson single scattering operator. The impulse approximation is recommended by the inelastic intermediate states it describes, and the Watson approach because of a cancellation between the effects of the projection operator off the ground state and the intermediate state distortion of the binding potential. (E. F. Redish, P. C. Tandy, D. Bolle')

E. Multiple Scattering Corrections to the Optical Potential

A study has been completed which throws an interesting light on the validity of the closure approximation and the role of quasi-free scattering in the multiple scattering theory of Watson. This work is being prepared for publication.

A new phenomenological approach to nuclear scattering by nuclei in the 50-"/50 MeV region which incorporates some of the non-local and ℓ -dependent features of multiple scattering effects is being developed in collaboration with L. W. Woo.

The relationship between the prediction of Jackson, Johnson and others for folding models for the α -nucleus optical potential and conventional phenomenological models is being studied in collaboration with N. S. Wall and A. A. Cowley. A paper is being prepared for publication. (R. C. Johnson)

F. Eikonalized DWIA Description of α - ^{12}C Scattering

An eikonalized DWIA has been used to analyze α - ^{12}C scattering at $E_{\text{LAC}} = 1.37$ GeV. With an elastic phase function parametrized to fit the elastic differential cross section, and with inelastic form factors taken from electron scattering, reasonable agreement is obtained with the data for scattering to the 2^+ and 0^+ levels. As expected the 3^- level is not well reproduced, which is also the case in most p - ^{12}C calculations. Possible causes may be the uncertainty in the inelastic form factor, or perhaps non-eikonal effects not noticeable at smaller momentum transfer. (Y. Alexander and A. S. Rinat, to be published in Nuc. Phys. A.)

G. Comparison of Multiple Scattering Approximations

Work has been completed on the comparison of multiple scattering approximations (Glauber theory, eikonal expansion of Wallace and a non-eikonal theory of Alexander, Garrits and Rinat) with exact numerical calculations for a fixed scatterer problem. This work was submitted and accepted for publication in Nuclear Physics. The principal findings were that in the small to intermediate angle range ($0 < \theta \lesssim 80^\circ$) eikonal expansion and non-eikonal theories are accurate and they definitely improve upon the Glauber approximation. At back angles, there is no accurate approximation although the non-eikonal theory does have a larger angular range than the eikonal theories. An important conclusion was that in cases where the single scattering exchange mechanisms become dominant at back angles (e.g., nucleon-deuteron scattering) the errors at back angles become unimportant. (S. J. Wallace)

III. PION REACTIONS

A. Pion-Nucleon Scattering

We have succeeded in extending the classic theory of Chew and Low to S-wave πN scattering. This has been possible by including the z-graphs and using the soft pion limit where one pion is made soft to eliminate the seagull terms instead of neglecting the latter. Nucleon recoil effects are important and have been included. In this theory the main S-wave isovector mechanism is the z-graph. The main S-wave isoscalar mechanism is the seagull terms.

(M. K. Banerjee and J. B. Cammarata)

B. Field-Theoretic Low Equation Approach to Pion-Nucleus Scattering

From the pion-nucleus Low equation in the one-meson approximation we obtain an uncoupled, nonlinear, singular integral equation to determine the crossing symmetric elastic pion-nucleus scattering amplitude. The driving term of this equation is evaluated in an impulse single-scattering approximation for ($J^\pi = 0^+ \text{ m } I = 0$) ground state nuclei. It is found that unitarity requires that we include the effects of the strong absorption of the low partial waves in the entrance and exit channels. Thus, we introduce distortion of the pion waves by a procedure used in the inelastic peripheral scattering of elementary particles. Numerical results are presented for the iterative solution of this equation for π - ^{12}C scattering in the energy region of the (3,3) resonance. (M. K. Banerjee and J. B. Cammarata)

C. Invariant Potential for Elastic Pion-Nucleus Scattering

From the Wick-Dyson expansion of the exact propagator of a pion in the presence of a nucleus, an invariant potential for crossing symmetric elastic pion-nucleus scattering is obtained in terms of a series of pion-nucleon diagrams. The Chew-Low theory is used to develop a model in which the most

important class of diagrams is effectively summed. Included in this model is the exclusion principle restriction on the pion-bound nucleon interaction, the effects of the binding of nucleons, a kinematic transformation of energy from the lab to the πN center of mass frame, and the Fermi motion and recoil of the target nucleons. From a numerical study of the effects of these processes on the $\pi^{-12}\text{C}$ total cross section, the relative importance of each is determined. Other processes contributing to the elastic scattering of pions not included in the present model are also discussed. (M. K. Banerjee and J. B. Cammarata)

D. A Laplacian Term in Pion-Nucleus Optical Potential

Adler consistency condition requires that the sigma commutator term in πN scattering be of the form $(\frac{\sqrt{2}}{f_\pi})^2 m_\pi^2 (t - m_\pi^2) \Gamma_\sigma$ where $f_\pi = 0.939 m_\pi^3$ is the pion decay constant, t is the square of the momentum transfer and Γ_σ is the sigma commutator term. This implies that the pion nucleus optical potential should contain a term

$$-(\frac{\sqrt{2}}{f_\pi})^2 m_\pi^2 \Gamma_\sigma \{m_\pi^2 \rho(r) - (\nabla^2 \rho(r))\}$$

where $\rho(r)$ is the single nucleon density. Use of this term with $\Gamma_\sigma \sim 26 \text{ MeV}$ along with the conventional Kisslinger term gives a good description of 50 MeV $\pi^+ -^{12}\text{C}$ elastic differential cross section. (M. K. Banerjee and S. J. Wallace)

IV. NUCLEAR STRUCTURE BY REACTION STUDIES

A. Fine Structure in Isobaric Analog Resonances

A study of the high resolution data taken over the region of isobaric analog resonances by the Duke University group was initiated to determine the magnitude of a charge symmetry breaking nuclear force. At present the evidence for a charge-dependent nuclear force in nuclei comes principally from the existence of the Nolen-Schiffer anomaly in the Coulomb energy shifts between members of an isobaric multiplet and from several cases of large mixing between two excited states of different isospin in light nuclei. Although the Nolen-Schiffer anomaly first forced serious consideration of symmetry violating nuclear forces the effect is a difference between large diagonal matrix elements and the evaluation of the magnitude of the force is therefore uncertain. Banerjee, for example, has recently discovered a correction arising solely from a proper treatment of the Coulomb interaction. This is a correction to the Schwinger term which can account for at least half of the Nolen-Schiffer anomaly. Similarly in recent work on the isospin impurity of the 15.1 MeV state of ^{12}C , Zamick and Sato found a large sensitivity to the proton and neutron wells. Reasonable variations in the well change the neutron-proton energy differences sufficiently to account for a large fraction of the mixing matrix element.

In contrast the fine structure observed in isobaric analog resonances results from thousands of matrix elements between states of differing numbers of particle-hole excitations. The Coulomb force is particularly weak between such configurations and the effect of a strong short-range nuclear force should be clearly discernible.

Extraction of charge-dependent matrix elements is clearly the first objective of such an analysis. Unfortunately this can only be done if the background widths of the fine structure states can be subtracted in some fashion. Information about this background can be obtained from the average

parameters for the strength function. Consequently the first step must be a reliable analysis of the strength function of the isobaric analog resonances. Although both the Duke group, in collaboration with A. M. Lane, and others (Weidenmüller and Mahaux, MacDonald and Mekjian) have published analysis of fine structure patterns their results differ significantly. In the case of ^{41}Ar the decay widths for the $3/2^-$ analog differ by a factor of two! In addition A. M. Lane, J. E. Lynn and J. D. Moses (Nucl. Phys. A232, 189 (1974)) have argued that the variance in the spreading width for most analog resonances is as much as 50% of the value. This latter result is emphasized in a recent review by Bilpuch, Lane, Mitchell, and Moses (Physics Reports 28, No. 2 (1976), 145-244)) where the point is made that the parameters of their analysis must be understood in the sense of averages over an ensemble of "similar" fine structure patterns for each isobaric analog resonance.

We therefore undertook to review the analysis of the strength function performed by Bilpuch, et al. for ^{41}Ar analog resonances. It was apparent that the sum rule used to obtain their value for the continuum width of the analog was unreliable for two reasons: (1) the energy region of spreading is poorly defined and strength can easily be omitted from the sum, (2) the result depends crucially on the background or optical potential strength function, which can only be determined from the asymptotic behavior of the strength function far from the analog. If the fine structure is that for a relatively isolated analog state, a more satisfactory analysis can be based on a fit to the strength function with Feshbach, Kerman, Lemmer doorway form. The continuum decay width of the analog appears as a factor and is determined by a fit to the strength function in the region of the maximum.

Using the strength function as defined by G. E. Brown, we have completed a re-analysis of the ^{41}Ar data and determined the parameters for both the $3/2^-$ and $1/2^+$ resonances. Contrary the experience of the Duke group we found the

parameters to be well determined. The value of the spreading width was found to be 3.95 KeV in excellent agreement both with the rough result quoted by Mekjian and MacDonald and with the much more refined result of DiToro. The result of 1.87 keV quoted by A. M. Lane and the Duke group must be rejected.

Careful consideration was given to the energy dependence of penetrability factors used by the Duke group to obtain reduced widths. Their penetrability factors were those of conventional R-matrix theory, i.e., the nuclear well was taken zero outside the matching radius. A penetrability factor can also be defined for the widths of the shell model reaction theory, which is proportional to the Jost function. This was calculated for a diffuse well of the Woods-Saxon form which fits elastic scattering. This penetrability factor was found to have a different energy dependence from that of the R-matrix. The diffuse well penetrability increases more rapidly with increasing energy, a result well known and easily understood. The reduced widths extracted using a diffuse well therefore will be smaller at higher energies than those of the R-matrix. In other words, the R-matrix leads to too large a value for the background and too small a value for the decay width of the analog. Since the background was apparently determined by using reduced widths well above the analogs, this may account for the gross underestimates of the analog decay width obtained by Bilpuch, et al. (W. M. MacDonald)

1. Definition of Strength Function

In view of the Claim that the strength function could not be filled to analogs which are weakly spread (i.e., most analogs!) I investigated the significance of different definitions of the strength function. Lane and Bilpuch use the R-matrix definition, the box energy-average of the reduced widths. Mekjian and MacDonald; Feshbach, Kerman, and Lemmer; and Weidenmüller and Mahaux use the strength function defined by G. E. Brown. According to this latter definition, the strength function is the imaginary part of the diagonal element of the R-matrix evaluated at $E + i\Gamma$.

I have been able to show that, as stated by A. M. Lane (Isospin in Nuclear Physics, ed. D. H. Wilkinson, North-Holland, 1969) the R-matrix strength function is not Lorentzian near the center of weakly spread analogs. In addition, I have been able to show that the distribution is never Lorentzian near the center of the pattern for the R-matrix strength function. Consequently, fitting the R-matrix strength function to the Lorentzian form of Feshbach, Kerman, and Lemmer will give erroneous values for the parameters. On the other hand, the strength function of Brown must assume the Lorentzian form for an averaging parameter equal to several level spacings. The corresponding spreading width is a well-defined average of the coupling matrix elements whose variance is inversely proportional to the square root of the averaging interval. (W. M. MacDonald)

2. Re-Analysis of the Duke Fine Structure Data

In view of the discrepancy between some of the Duke parameters for the ^{41}Ar analogs and results from more complete theoretical calculations, it is clearly necessary to re-analyze the Duke data. This has been begun using a tape of the complete set of the Duke results on fine structure associated with isobaric analog resonances. (W. M. MacDonald)

B. Charge Dependence of the Nuclear Force

We are completing a relativistic calculation of the contribution of intermediate state resonances to the charge dependence of the nucleon-nucleon force arising from the exchange of one pion and one photon. This will compliment our earlier, static calculations and should clarify the role of recoil. We anticipate that this will not account for the remaining charge dependence. Thus, the charge dependence of the pion nucleon coupling constant will have to be extracted. There appears to be no further process which could contribute significant charge dependence.

The calculations performed thus far have made use of the Blankenbecler-Sugar reduction. We intend to reproduce these calculations using the reduction proposed by F. Gross. Since this will be an expansion in the small parameter e^2 , both methods should converge rapidly to the same result. (Tom Wells)

C. Correlations and Dipole Excitations in Nuclei

Photonuclear cross sections have been studied in terms of moments of the distribution of the dipole strength for many years. The first moment is proportional to the total integrated absorption cross section while the zeroth moment, which is just a total transition strength, is proportional to the Bremsstrahlung-weighted cross section. Each of these moments gives different information concerning nucleon-nucleon interactions in the nucleus and the resulting two-body correlations. For example, the enhancement of the integrated cross section above the classical Thomas-Reiche-Kuhn sum rule gives the magnitude of the charge exchange part of the nucleon-nucleon interaction. The Bremsstrahlung-weighted cross section, on the other hand, is proportional to the expectation value of the square of the dipole operator. It therefore is sensitive to two-body correlations. Indeed, the observed value of this cross section is about 50% smaller than the well-established harmonic oscillator value.

It was to this discrepancy that we addressed ourselves. In addition, we studied carefully the effect of two-body correlations upon the different isospin components of the dipole sum rule. This decomposition is particularly important in view of the suggestion by Leonardi that the isotensor contribution to the sum rule is zero. Using this assumption Leonardi was able to derive the astonishing result at the RMS proton radius in ^{208}Pb exceeds that for the neutron distribution.

We began the investigation with a study of the relationship between the dipole sum rule and relative distortion of neutrons-proton orbitals. Such a relative

distortion would be produced by the isovector part of the monopole part of the nuclear Coulomb force. It is also necessary to establish this connection in order to make consistent the analysis of Leonardi, which predicts a relative distortion of corresponding neutron and proton orbitals. We were able to establish this connection and to show that as soon as a relative distortion of corresponding neutron and proton orbitals occurs the isotensor contribution to the dipole sum rule becomes important. Consequently, analysis of Leonardi is not self-consistent. In fact, the result of this study of the effect of the isovector part of the monopole force upon the nuclear wave function was to establish the stability of a certain inequality under first order perturbations of the nuclear wave function. In fact from this inequality it can be concluded that the magnitude of the isotensor components of the dipole sum rule is equal to the decrease in the magnitude of the sum rule produced by correlations.

We then investigated the effect of two-body corrections by a microscopic calculation using a two-body separable potential. We were able to show that this force introduces a component of a coherent $2p$ - $2h$ collective excitation which has a very large effect upon the sum rule. A few percent of this excitation is in fact sufficient to account for the observed reduction in the Bremsstrahlung-weighted cross section from the harmonic oscillator value. (W. M. MacDonald and A. Z. Mekjian)

V. NUCLEAR DYNAMICS

A. Classical Hydrodynamics and Adiabatic Schrödinger Fluid

Our efforts on this problem have led to results that one does not expect the Schrödinger Plumptre Fluid to resemble the hydrodynamical fluids which are described by the Navia-Stokes Equation (or higher order equations such as the Burnett Equation) at low excitation energies. Rather the mean free path in the nuclear fluid is sufficiently large at least at low excitation energy, that the entire geometry of the small droplet of nuclear fluid at every other point throughout the volume before any kind of localized equilibrium could establish itself. Thus, although one can obtain equations which resemble the hydrodynamic equations in their tensorial structure, the resemblance appears to be simply a result of matter, momentum, and energy conservation and not a sufficient basis to conclude that the hydrodynamical equations will in fact describe the matter flow. The specific way in which the difference appears to manifest itself is in the nature of the tensors which relate the internal forces with the distribution of density and momentum. These tensors in the Schrödinger Fluid seem certain to be very nonlocal objects, not expressible as locally defined derivatives of the velocity fields, as are the corresponding elements in the Navia-Stokes type hydrodynamical equations.

Further work in this area therefore focuses upon the attempts to make a constructive description of the way that nuclear matter flows, or would flow in the idealized single particle Schrödinger limit. (J. J. Griffin, M. Dworzecka, and P. C. Lichtner)

B. Overview of Dynamics of Nuclear Matter Flow

Attention continues to focus on this very rich and fascinating area of nuclear physics, which heavy ion accelerators are bringing within our reach.

An analysis of the lifetime which one must expect for a single determinantal approximate solution to a model Hamiltonian with effective nuclear two-body interactions has been completed [P. C. Lichtner and J. J. Griffin Phys. Rev. Lett. 37 (1976) 1521]]. Further effort on the critique of the Time-Dependent Hartree-Fock has been reported in preliminary form (J. J. Griffin and P. C. Lichtner, 4th Annual Workshop on Gross Properties of Nuclei, Hirschegg, Austria, January, 1975). More of this work is currently in preparation for submission partly as a letter, and partly as a more extensive critique of the Time-Dependent Hartree-Fock Methods. (J. J. Griffin, M. Dworzecka, K. K. Kan and P. C. Lichtner)

C. Nuclei as Dynamical Fluids

This research has been brought to an intermediate stage of fruition. The basic elements are described in a review paper [R.M.P. 48 (1976) 467] and in a paper to be published in Physical Review, 156 (1977) 1126. Two or three additional publications reporting this work are now in process of preparation. (J. J. Griffin)

D. Density Ripples in Nuclei

This research is at the present time no longer under active study, due to the departure of M. Mustafa, and the change of interest of T. Wells towards pion physics. The topic is still an interesting one which we expect to rise again as currently more urgent questions of dynamical behavior become refined enough to re-focus our attention on Strutinsky effects. (J. J. Griffin and M. Mustafa)

E. Canonical Hamiltonian and LaGrangian Constraints

This research has been reported [Annals of Physics 95(1975)295]. It also is a topic of potential additional interest, but one which is not at the present moment being actively pursued. (J. J. Griffin and P. Amlot)

F. Collisions of Classical Water Droplets

This work continues, and focuses at present upon the Rayleigh instability of a long droplet after collision and one-half a quadrupole-like oscillation. The possibility that droplets of mass one-half, one third, etc. of the total mass will emerge from such a collision, and whose origin can properly be described by the Rayleigh instability of the long figure, seems excellent (Univ. of Md., Tech. Rept. #76-118, ORO-4865-55). The relevance to nuclear heavy ions reactions will require further attention to other aspects of the problem. (J. J. Griffin and G. Y. Wong).

G. Fermi Liquid Theory and Nuclear Structure

Continuing effort on the quasi-particle behavior in nuclei, and its relevance to the underlying microscopic nuclear forces has occurred. This work is summarized in three items as follows: Quasi-Particle Interaction in Nuclear Matter and the Importance of Contributions from Low-Momentum States, by R. S. Poggioli and A. D. Jackson, Phys. Rev. C14 (1976) 311; Quasi-Particle Pole Posturing in Nuclear Matter, by R. S. Poggioli and A. D. Jackson, Phys. Rev. Lett. 35 (1975) 1211; and Vertex and Propagation Normalizations in Nuclear Calculations, ORO-4856-36, by R. S. Poggioli, Univ. of Maryland Tech. Rept. #76-056, Oct. 1975. (R. Poggioli)

H. Semi-Classical Approximation to Time-Dependent Hartree-Fock Theory

The use of a Thomas-Fermi approximation in a time-dependent dynamical description of nuclear matter has been considered and some of the implications of such a model are discussed. The results have been summarized in Univ. of Maryland Technical Rept. #76-115 (ORO-4856-54 entitle, "A Semi-Classical Approximation to Time-Dependent Hartree-Fock Theory." (M. Dzwirzecka and R. Poggioli)

I. Quasiparticle Pole Strength in Nuclear Matter

It is concluded that single-particle-like behavior in nuclear matter is much less probable than the Brueckner theory suggests. In particular, the quasiparticle pole strength is evaluated for nuclear matter and it is shown that, contrary to the spirit of Brueckner theory, low-momentum states play a crucial role in determining the magnitude of the residue, z_{k_F} , at the pole, indicating a weakening of the single-particle-like behavior in nuclear matter. (R. Poggioli)

J. Quasiparticle Interaction in Nuclear Matter and the Importance of Contributions from Low Momentum States

A microscopic calculation of the quasiparticle interaction in nuclear matter is detailed. In order to take special care of the contributions from the low momentum states, a model space is introduced. Excluded from the model space, the high momentum states are absorbed into the model interaction. Brueckner-Bethe theory suggests the choice of a truncated G matrix as a good approximation for this model interaction. A simple perturbative approach is attempted within the model space. The calculated quasiparticle interaction is consistent with experimental results. (R. Poggioli)

K. Vertex and Propagator Renormalization in Nuclear Calculations

It has been asserted that vertex renormalizations tend to cancel the effects of propagator renormalizations in nuclear calculations. In order to test this hypothesis, those contributions to the quasiparticle interaction in nuclear matter which represent the effect of the simplest vertex and propagator renormalizations have been evaluated. Unfortunately, almost no cancellation of effects was found to exist. (R. Poggioli)

L. Comparison of Hartree-Fock and Energy-Density Formalism Calculations for Some Spherical Nuclei

We calculate the parameters of the nuclear droplet model introduced by Myers and Swiatecki (an extension of the conventional liquid drop model) to higher powers of $A^{-1/3}$. We do Hartree-Fock (HF) calculations for a large number of spherical nuclei, using the modified δ interaction version of the Skyrme interaction and average over shell structure by making at least a square fit to the Hartree-Fock energies. We also compare the shell-averaged HF results with those obtained by using a simple version of the energy density formalism developed by Brueckner, Lombard, and others. We assume the simple form of the energy density first introduced by Skyrme of $N = Z$ nuclei, and minimize the total energy with respect to the actual density and diffuseness, subject to the constraint of fixed number of particles. Detailed comparison with the HF results was made for two $A = 100$ nuclei and $Z = 50$ and 40 . We find that the droplet model energies calculated either exactly (numerically) or analytically by expansion of the radial integrals in powers of (a/R) (a = diffuseness, R = half density radius for a Fermi density) are in good agreement with the shell averaged HF results although there is some uncertainty in the latter. However, the central density is too small by about 10% for the cases considered. Yet, for the case $Z = 40$, $A = 100$, the ratio of neutron and proton densities is close to the Hartree-Fock value. Thus, we find the energy density formalism can reproduce quite closely the results of more complicated Hartree-Fock calculations. (M. Dworzecka and S. Moszkowski)

M. Tangential and Radial Friction in Nuclear Heavy Ion Collisions

The attempt to characterize the distinctions between radial and tangential frictions in deep inelastic heavy ion reactions has been subsumed into the questions concerning the early time very rapid response of the nuclear heavy ions to their first osculation. The "instant dissipation", which we believe may occur in these earliest moments of the collision of energy, from the relative motion of the heavy ions into internal degrees of freedom in the combining two ion systems may, we feel, play a role in one's understanding of the "frictional" trajectory calculations which have had some success in describing nuclear heavy ion reaction angular distributions. Thus, at present we are concerned with the relevance, at this detailed level, of the trajectory calculations which provide the basis for the tangential and radial "friction" interpretations. When this matter clarifies, then the question of tangential versus radial friction can be taken up again on a more solid basis. (J. J. Griffin)

VI. APPENDIX

A. Research Publications - January 1, 1975 - June 30, 1976

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D. Theses Completed - 1975

Kit-Keung Kan, THE SINGLE PARTICLE SCHRÖDINGER FLUID AND ITS APPLICATION TO
NUCLEAR COLLECTIVE MOTION.