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NUCLEAR EXCITATIONS AND REACTION MECHANISMS

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ABSTRACT

A. (Levin). S-matrix elements for electron-hydrogen scattering using the inhomogeneous equations method: phase shifts below the $n=2$ threshold, position and widths of resonances, scattering lengths, search for resonances above the $n=2$ threshold; three-body methods: formulation of an exact DWBA in the separable-potential model of stripping and its extension to the many-body case, extension of the Lovelace method and the Mitra model to include rank-N separable potentials, calculations of cross sections, comparison and properties of wave functions, convergence of the DWBA series, inclusion of tensor forces.

B. (Faillieros). Properties of isovector excitations in nuclei; form factors, transition densities and sum rules for nuclear electroexcitations; radiative transitions in ^{89}Y ; s-wave neutron strength function in the $A=90$ region; damping of simple nuclear excitations.

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1. SCOPE

The Nuclear Physics Program at Brown University includes presently four senior faculty members (two in experimental and two in theoretical nuclear physics), one research associate (with a one-year fellowship from the Canadian Government) and several graduate students. Although the experimental program is no longer funded by the AEC, the collaboration between experimentalists and theorists (in the jointly organized nuclear seminar, training of graduate students, discussions, etc.) continues.

The research work (completed or in progress) of the two principal investigators is presented separately in the following section. Parts A and B describe the work of Prof. Levin and Prof. Fallieros respectively, and their graduate students. Work is carried on in the Barus-Holley Physics-Engineering Building. Numerical analysis entailed in the theoretical program is executed on the University's IBM System 360/50.

2A. (Levin)

RESEARCH COMPLETED

$e^- + H$ scattering

During the past year, the program for computing $e^- + H$ S-matrix elements, using the inhomogeneous equations method¹ has been completed and its accuracy checked. Calculations of the S-matrix elements for electron energies below the $n=2$ threshold in hydrogen are currently in progress. A survey of the energy dependence of the S-wave and P-wave phase shifts calculated so far in the $1s-2s-2p$ approximation has shown that this new method predicts resonances. Resonances have been seen experimentally below the $n=2$ threshold and also have been predicted by the older methods of calculation.^{2,3} The success of the inhomogeneous equations method in producing resonances means that it may become a useful method for doing atomic physics calculations, and is not merely a theoretically correct but numerically impractical scheme for taking account of Pauli principle exchange effects. Two points are of interest here. First, the method is linear in the number of states one wishes to consider in the truncation approximation unlike the older method²; this is especially important since computing costs will be correspondingly lower with the new method compared to the old. Second, no problems connected with iteration due to the presence of integral terms in the coupled equations arise in this method.

In order to ensure that the S-matrix elements calculated with our method are unitary, a new means for solving the inhomogeneous equations was developed using the K-matrix. A paper on this topic⁴ has been submitted for publication; copies have been forwarded to the New York Office recently.

This work has been carried out in collaboration with Mr. P. W. Dahlgren

and will be the basis for his Ph.D. dissertation, expected to be completed by June, 1972.

Three-body methods

In last year's progress report, a very promising start on the three-body treatment of deuteron stripping was noted. Since then, an extremely interesting breakthrough in this problem has occurred, and a great deal of work has been and is being done on it. The breakthrough concerns the discovery that in the separable-potential, three-body model of stripping (Mitra's model⁵), a DWBA can be formulated such that the DWBA matrix element is exact, i.e., is identical to the exact stripping matrix element. This is equivalent to the statement that for this model, the exact, three-body scattering wave function can be replaced by a product of two-body wave functions, one the deuteron (internal) ground state, and the other a center-of-mass (CM) deuteron wave function, with no change in the matrix element. The new CM wave function is not the elastic wave function, u_d but the so-called "spectator wave function" F ⁵. The work of Reiner and Jaffe⁶ shows that use of u_d leads to a matrix element which is very close to that obtained by use of F , i.e., close to the exact matrix element. This discovery justifies the validity of DWBA in the model, a justification heretofore never given for DWBA in any model whatsoever.

The results of the model have been extended to the many-body case of actual direct nuclear stripping reactions under the assumption that Pauli principle exchange amplitudes can be ignored and that the neutron-proton interaction V_{np} in the deuteron can be represented by a separable, S-wave potential. The first assumption is standard in direct reaction theory but the second is an approximation we know is only adequate, not exact. However, when this assumption

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direct and knock-out amplitudes for the j-forbidden stripping reaction $O^{18}(d,p) O^{19*}$ has been done using the wave functions of Federman based on the nuclear co-existence model¹². In addition, a computer program for carrying out these calculations has been obtained from G. Strobel¹³ and most of it has been interpreted. This work has been done with Mr. D. Fein as part of his Ph.D. dissertation. As of September, 1971, Mr. Fein decided to discontinue his studies of physics. No further calculations on this problem have been undertaken, nor will they be until the large amount of work remaining to be done on the e^-+H and three-body problems is more or less completed.

Wave packet description of scattering

Further attacks on this problem were carried out in the summer of 1971, with no progress to be reported. As with the knock-out amplitude work noted above, work in the wave packet analysis will not be resumed until the e^-+H and three-body problems are much closer to completion.

RESEARCH IN PROGRESS

e^-+H scattering

Work in the following three areas will be pursued in the next few months.

1. Widths and positions of the resonances below 10.2 ev. Our calculations show that the inhomogeneous equations method¹ properly predicts the existence of resonances. We intend to do calculations over a fine-meshed energy grid to determine the positions and widths of the resonance and compare with both observed and calculated values.

2. Scattering length. The value of the singlet and triplet scattering lengths are numbers calculated using both the older methods^{2,3} and an accurate

trial wave function in a variational calculation¹⁴. It is of interest to calculate these quantities using the inhomogeneous equations method and compare them with the results of the above named methods.

3. S-matrix elements above threshold. Resonances have been observed¹⁵ in e^-H scattering just above the $n=2$ threshold at 10.4 eV and 10.6 eV. We shall extend our calculation to this region and determine if the inhomogeneous equations method is as successful above threshold as it is below.

It is anticipated that the results of the calculations noted in 1 and 2 above, plus our existing results will be published, both in the form of letters and as longer articles. A short note for Physics Letters on this is in preparation¹⁶.

Three-body methods

Following the discovery that an exact DWBA can be formulated for the three-body model, we are at present studying various implications of this result. This includes work in the following areas.

1. Comparison of $u_d(\vec{R})$ and $F(\vec{R})$. Computations are being made to compare the elastic scattering wave function u_d with the new (exact) DWBA wave function⁴ F . The work of Reiner and Jaffe⁶ indicates that matrix elements differing only by substitution of u_d for F are very similar, the agreement improving with increasing energy. Our comparison will be between the two functions themselves, since it is of interest to know where, as a function of the deuteron CM coordinate $\vec{R}$, they differ. This is important since it is u_d that is traditionally involved in DWBA.

2. Convergence of DWBA series. The fact that use of the function F is exact in the three-body model⁴ means that in this case the DWBA series converges, in contrast to the general arguments of Dodd and Greider.¹⁷ We

are examining in detail this series to try to understand the meaning of this result and to see if it can be generalized.

3. Rank-N separable potentials. We are examining the extension of the Mitra model to the case where the two-body interaction is a rank-N, separable, S-wave potential. This is of interest both intrinsically and for its application to the many-body case of actual (d,p) or (d,n) reactions, since in the latter case, the neutron-proton interaction V_{np} is better approximated by a rank-N than a rank-1 potential. We have solved the problem when the number of bound states is equal to the degeneracy N, and are now concentrating our efforts on the case where the number of bound states, k, is less than N. This situation arises if V_{np} is represented by a rank-2 potential. The difficulty in trying to solve this problem is that the potential spans a rank-N space, while the bound states span a rank-k space, so that the transformation from N to k is singular.

4. Inclusion of tensor forces. Results similar to those of the rank-1, separable, S-wave potential obtain if V_{np} is extended to include a tensor force in the form of a rank-1, separable, S-wave potential. We will be working out the details of this extension during the next few months.

5. Properties of the one-body potential generating F. As noted above, we have derived the one-body equation obeyed by F. Appearing in this equation is the one-body potential $\mathcal{V}$, which we have shown in the sum of $\mathcal{V}_{el}$, giving rise to elastic scattering, and a correction $\mathcal{V}_R$ which vanishes on the energy shell. $\mathcal{V}_R$ can be put in a form which seems simple enough to allow an analytic investigation of its properties. We shall attempt to deduce these properties in the next few months. These are of particular interest since F differs from the elastic wave function u_0 by just the effect of this correction term.

Furthermore, this may provide some insight into the relationship between our work and that of Johnson and co-workers¹⁸ who have attempted to improve DWBA by approximate inclusion of continuum deuteron states into the DWBA wave function and have also found as a new wave function one which is not u_d .

2B. (Fallieros)

Isovector Excitations in Nuclei

Some of the results obtained in this investigation have already been published¹⁹. They include a general estimate of the separation energy between the two isospin components of the giant dipole resonance as a function of the mass number and the isospin of the nucleus. Refinements of this work are possible and are presently under study. They include the systematic introduction of ground-state correlations and the related problem of the dipole sum rule. Since the isovector excitations have three components in isospin space, the results of this work are related not only to photonuclear reactions (γ, n) , (p, γ) , (e, e') etc., but also to μ^- capture, (π^-, γ) or also nucleon charge-exchange reactions. The introduction into the problem of the effect of ground-state correlations is not straightforward since the isospin structure of the various components in the ground or the excited-state wave functions has to be kept in mind in every stage of the problem. This work is related to the Ph.D. thesis of Mr. R. O. Akyuz which is expected to be completed within the present academic year.

Inelastic electron scattering

In this work sum rules are derived containing the form factors for inelastic electron scattering from nuclei. These sum rules are used to evaluate the contribution of a given measured form factor in the sum. In addition they are used as the starting point for approximations which can lead to a theoretical understanding of the observed form factors. The approximation that has been used so far²⁰ is the single-doorway-dominance assumption which considers the form factor as dominated by the same door-

way state as the photons in a photon-resonance-absorption experiment. Combined with the sum rule this assumption leads to a unique determination of the form factor if the lifetime of the state is known and if the form factor for elastic scattering is available. A considerable number of specific cases were studied during the past year. In some cases the agreement with experiment is excellent whereas in others the approximate form factors are seen to reproduce the experimental results quite well for low momentum transfers, but show discrepancies for higher values of the momentum transfer. This is consistent with the expectation that relatively near the photon limit the single doorway approximation is valid while at higher momentum transfers additional doorways will become important. This work which is still in progress will be the Ph.D. thesis of Mr. T. J. Deal.

Radiative transitions in ^{89}Y

Calculations on E1 radiative transitions in the nucleus ^{89}Y have been completed and the results have been published²¹. Recent experiments²² indicate a very satisfactory agreement with the theoretical predictions. This particular nucleus was chosen not only as a good example of isospin dependence of the various electric dipole transitions, but also for the study of the systematics of the total-angular-momentum-dependence of these transitions. Some of the nuclear-structure work already available for ^{89}Y contains useful information about magnetic-dipole transitions in this nucleus. Although the calculations of the latter have not yet been completed, some work has been done in an attempt to anticipate the simplest features of the complete spectrum. Both the isospin and the total angular momentum play again an important role. An oversimplified model of the nucleus was used and the dominant M1 transitions were calculated. When the results of the more detailed work become available, the estimates based on the simple model

will be used in order to identify the distribution of the simple excitations among the complex states of the nucleus. This work is performed in collaboration with Dr. J. Vergados (Berkeley).

Damping of simple nuclear excitations

Work on the "Damping of Deep Single-Hole Excitations in Nuclei" was completed during the past year. Since this work has already appeared in print, it will not be discussed here. Some of the results obtained in this study (e.g., the nuclear-mass dependence of the average spacing of two-hole-one-particle excitations or of the nuclear coupling matrix elements) were subsequently applied to the investigation of other damping widths. Spreading widths of giant resonances were estimated and in particular, an expression was obtained for the ratio of the damping widths of the $T + 1$ and T dipole modes. The physical problem to understand was the experimental observation²³ that the total width of the dipole resonance with isospin $T + 1$ is comparable to that for the resonance with isospin T for relatively light nuclei, but became much smaller for heavier nuclei. The theoretical expression was found to reproduce this trend quite successfully. The approximations made in deriving it were, however, very crude and more work will be required before the result is considered reliable.

S-wave neutron strength function in the $A \approx 90$ region

This research was performed by Dr. J. Bergeron²⁴ who has been in the Physics Department of Brown University since September 1971 as a research associate with a fellowship from the Canadian Government. Although his work is not sponsored by the AEC contract, we will describe it briefly since it is directly related to studies that we proposed in the last year's AEC contract proposal.

In our previous calculations on isovector excitations we found some states with $J^\pi = 1^-$ that were expressed as coherent linear combinations of neutron-proton-hole configurations. The energy of these predicted levels was in the region of the threshold for neutron emission. Their analogs were subsequently observed in (p,γ) reaction experiments, but the present states themselves are not easy to observe directly. Since attempts to observe them in neutron-scattering experiments are presently considered, an estimate of the effect of these states on the neutron cross section is clearly desirable. Dr. Bergeron has done that. In a continuum calculation taking into account the coupling of the scattering states with the particle-hole excitations he obtained estimates of the neutron-emission widths. The coupling to more complicated, compound-nucleus levels was also considered and estimates of the spreading widths were also obtained.

3. OTHER ACTIVITIES

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

"Doorway Dominance in Nuclear Electroexcitations"

(S. Fallieros, Univ. of Maryland, Nov. 1970)

"Damping of Deep Single-Hole States in Nuclei"

(S. Fallieros, SUNY - Stony Brook, Nov. 1970)

"Sum Rules for Inelastic Electron Scattering"

(S. Fallieros, SUNY - Stony Brook, Nov. 1970)

"Doorway Dominance in Nuclear Electroexcitations"

(S. Fallieros, MIT, December 1970)

"Inelastic Electron Scattering from Nuclei"

(S. Fallieros, Brooklyn College, March 1971)

"Form Factors and Sum Rules in Inelastic Electron Scattering"

(S. Fallieros, Rutgers Univ., April 1971)

"Doorway-State Dominance in Nuclear Electroexcitations"

(S. Fallieros, Brookhaven National Laboratory, July 1971)

"Sum Rules for Inelastic Electron Scattering"

(S. Fallieros, Invited paper, Gordon Conferences on Photo-nuclear Reactions, August 1971)

"Intermediate Structure in Photon-Induced Reactions"

(S. Fallieros, Invited paper, International Conference on Statistical Properties in Nuclei, Albany, N. Y., August 1971)

"Isoscalar and Isovector Electromagnetic Transitions in Nuclei"

(S. Fallieros, Bartol Research Foundation, October 1971)

"Isoscalar and Isovector Electromagnetic Transitions in Nuclei"

(S. Fallieros, Univ. of Rochester, October 1971)

"Mitra's Three-Body Model and the Validity of DWBA for Stripping"

(F. Levin, University of Surrey, August, 1971)

"Mitra's Three-Body Model and the Validity of DWBA for Stripping"

(F. Levin, Institut de Physique Nucléaire, Orsay, September 1971)

4. PERSONNEL

Professor S. Fallieros

Associate Professor F. S. Levin

Research Associate: Dr. J. Bergeron (Postdoctoral fellowship from the
National Research Council of Canada
to August 31, 1972)

Graduate Assistants: R. O. Akyuz

D. P. Bouldin (N.D.E.A. Title-IV Fellow to
31 August 1971)

R. M. Brill (N.S.F. Trainee to 31 August 1972)

P. D. Dahlgren

T. J. Deal (N.D.E.A. Title IV Fellow to
31 August 1971)

D. B. Fein

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1. F. S. Levin, Unitarity and the Inhomogeneous Equations Method for Identical Particle Scattering, to be published in Annals of Physics.
2. D. Bouldin and F. S. Levin, The DWBA and Mitra's Three-Body Model of stripping, Physics Letters 37B, 145 (1971).
3. D. Bouldin and F. S. Levin, On the Validity of DWBA for Stripping. I. Three-Body Model, Bull. Am. Phys. Soc., 27-29 December, 1971, meeting of the American Physical Society.
4. F. S. Levin and D. Bouldin, On the Validity of DWBA for Stripping. II. The Many-Body case, Bull. Am. Phys. Soc., 27-29 December, 1971, meeting of the American Physical Society.
5. D. Bouldin and F. S. Levin, On the Validity of DWBA for Deuteron Stripping. I. The Mitra Three-Body Model, to be submitted to Nuclear Physics when 6 is complete.
6. D. Bouldin and F. S. Levin, On the Validity of DWBA for Deuteron Stripping. II. The Many-Body Case, in preparation.
7. P. W. Dahlgren and F. S. Levin, Prediction of Resonances in Low Energy $e + H$ Scattering Using the Inhomogeneous Equations Method, in preparation.
8. T. A. Hughes and S. Fallieros, Radiative $E1$ Decay of Analog States in ^{89}Y , Phys. Rev. 3, 1950 (1971).
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13. T. Deal and S. Fallieros, Transition Densities for Isoscalar Monopole Electroexcitations; to be published.
14. J. Bergeron, Étude de la Réaction $^{89}Y(n,n')^{89}Y$, Ph.D. Thesis (Université Laval)

15. T. J. Deal and S. Fallieros, Sum Rules and Form Factors for Isoscalar Nuclear Electroexcitations; submitted as contribution to the Cambridge meeting of the APS (December 1971)

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24. J. Bergeron, Ph.D. Thesis, Université Laval, to be published.