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MASTER

NUCLEAR EXCITATIONS AND REACTION MECHANISMS

Report of Progress to 31 October 1972

Department of Physics
Brown University
Providence, Rhode Island

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ABSTRACT

A. (Fallieros). Sum rules for nuclear electroexcitations, transition densities, transition radii, doorway states and the doorway dominance approximation. The random phase approximation and isospin in heavy nuclei. The giant M1 resonance, neutron widths and neutron-photon width correlations. Isospin splitting of dipole states in nuclei with $N = Z$.

B. (Levin). K-matrix elements for electron-hydrogen scattering: scattering lengths, resonances below the $n=2$ threshold, calculations above the $n=2$ threshold; 2^3S excitation in He^4 by electron impact; three-body model for stripping: calculations of wave functions, scattering amplitudes, and cross sections; inclusion of tensor forces; analytic behavior of wave functions; validity of the adiabatic method; test of the zero-range approximations; validity of the separable approximation for many-body reactions.

C. (Friar). Relativistic and dispersion corrections to electron scattering, analysis of charge densities, Coulomb corrections to electron deuteron scattering and the influence of dipole states in elastic electron scattering.

1. SCOPE

The Nuclear Physics Program at Brown University currently includes five faculty members (two in experimental and three in theoretical nuclear physics), one visiting professor (from the University of Mexico) and some graduate students. During the spring semester of 1972, Professor Carl Shakin of Case Western Reserve University visited Brown University at regular intervals as a visiting professor, gave a series of lectures on advanced topics in nuclear theory and participated in several discussions. 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, B, and C describe the work of Professors Fallieros, Levin and Friar respectively (although in Professor Friar's case a good part of the work described was obviously performed before his arrival at Brown in September 1972). 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.

CURRENT RESEARCH

2A. (Faillieros)

Isovector Excitations in Nuclei

Our work in this problem was discussed in the Ph.D. thesis of Mr. R. Ö. Akyüz which was completed in June 1972. Instead of any other description, we insert here the abstract of Mr. Akyüz's thesis.

"The study of some properties of isovector excitations in nuclei is presented in this work. These, by definition, include the totality of transitions, induced in a nucleus by an external interaction of isovector character, i.e., one that transforms as a vector in isospin space. The isovector interaction has obviously three components, with each one corresponding to a different physical process. The third component leads to excited states in the same nucleus, e.g., photoabsorption, inelastic electron or nucleon scattering, etc. The other two (spherical) components, however, are charge transfer operators, and lead to excited states in neighbouring nuclei by, e.g., μ^- -capture, and (p,n), (n,p), (π^- , γ), etc. processes.

Selection rules, derivable from standard vector coupling arguments, impose restrictions on the isospin of the excited states that can be reached from the ground state through the action of an isovector operator. If T_0 and T denote respectively the isospins of the ground and an excited state, it is well known, for example, that $T_0=0 \rightarrow T=0$ transitions are forbidden, and that the only possible values for $\Delta T=T-T_0$ are, $\Delta T=\pm 1$ or 0. Although in most stable nuclei, the projection M of isospin operator ($M=\frac{1}{2}(Z-N)$, Z :number of protons, N :number of neutrons), equals to T_0 in absolute value, and therefore, excited states

with $T=T_0-1$ do not appear, their presence in neighbouring (unstable) nuclei is still of interest, since it is possible to reach them via e.g., (p,n) reactions. In this work, we investigate the average excitation energies of the excitations with isospins T_0+1 , T_0 , T_0-1 , and the systematics of their relative displacements in energy. We also consider the relative total strengths of the transitions from the ground state to the excited states with isospins T_0+1 , T_0 , T_0-1 . The presentation includes a discussion of sum rules dealing separately with different isospin components, and the derivation of a formalism on which microscopic calculations can be based. In this connection, it is noticed that the random phase approximation, a method often very useful for microscopic calculations, needs modification before becoming applicable to nuclei with a non-vanishing neutron excess. This is because, in its traditional formulation, this method tends to destroy charge independence due to an uneven truncation of the Hilbert space. This is not true for light nuclei, when $T_0=0$, i.e., there is no neutron excess and the method is perfectly consistent in this case. For heavier nuclei the problem appears, but was not properly appreciated at the time when isospin was not considered to be of any significance for such nuclei anyway.

Some numerical results are also obtained and a comparison of the theoretical predictions with experimental results is presented."

Inelastic electron scattering

Most of the results obtained so far in our investigation of sum rules for inelastic electron scattering, doorway states and the doorway dominance approximations, transition densities and transition radii are summarized in publications #1 and 5. Work still in progress will be described in the

research proposal for the coming contract year. Since also the mathematical derivations and the detailed comparisons with experiment will be summarized in the near future for a forthcoming publication, it is clear that there is no real need for a systematic description of this work in this report.

It overlaps to a large extent with the Ph.D. thesis of Mr. T. J. Deal, which will probably be completed before the end of the current academic year.

Giant M1 resonances

The main effort in this direction during the current year was the calculation of the neutron-decay widths of the isovector, as well as the isoscalar M1 resonances in the nucleus ^{208}Pb . The basic features of these resonances were discussed qualitatively in last year's proposal. Our work since then, involved the choice of an appropriate Saxon-Woods potential for Pb and the calculation of the particle-hole states $h^{-1}_{11/2} h_{9/2}$ (for protons) and $i^{-1}_{13/2} i_{11/2}$ (for neutrons). These describe the transitions that occur following the M1 absorption of protons by ^{208}Pb . These combinations were coupled via a particle-hole interaction and gave rise to two linear combinations whose (shifted) energies and radiative widths were calculated. The higher lying member of this doublet was located in the continuum, i.e., above the threshold for neutron emission. The energy available, however, was not sufficient to allow emission of neutrons leaving the residual nucleus ^{207}Pb in an excited state, i.e., only the elastic neutron channel is open at these energies.

Despite the fact that the energy allows particle emission, the configurations considered are still essentially bound (at least because of the large angular momentum barrier). The neutron-emission probability was introduced at this point through the coupling of the bound components to the unbound con-

figuration containing a $p_{1/2}$ neutron hole (the ground configuration of ^{207}Pb) and p-wave neutron in the continuum. This was calculated and gave the neutron width of the level.

The simple modes described above lead, after the coupling to more complicated multiparticle excitations is allowed to operate, to the appearance of fine structure in the compound system. If the two simple excitations are rather far apart, only one of the two is expected to be present in a fine structure state. In this case, one expects a simple correlation between the neutron-emission widths and the radiative widths of the various compound-nucleus resonances. If both particle-hole excitations appear, however, in an individual resonance, interference effects are to be expected and the simplicity of the correlation disappears. The possible appearance of such correlations was one of the problems under investigation.

Clearly the sum of the widths of the individual fine-structure states is essentially equal to the width of the simple particle hole excitations. The widths obtained in this calculation were found to compare quite reasonably with the sum of the resonance widths observed in recent experiments at Livermore, Argonne and Oak Ridge. This work will be described in detail in the Ph.D. thesis of Mr. R. M. Brill, which is close to completion.

Dipole states in a nucleus with $T \neq 0$, $T_3 = 0$

If a state has isospin $T \neq 0$, but third component $T_3 = 0$, it can be expected to lead, upon E1 absorption of photons, to dipole excitations with isospin $T - 1$, T and $T + 1$. Actually the states with isospin T will have zero radiative width because of the familiar E1 selection rule in self conjugate nuclei. In contrast, therefore, to nuclei with $T = T_3 = 0$ where the dipole state has $T = 1$, the case of a state with $T = 1$, $T_3 = 0$ will exhibit two di-

pole resonances with isospins 0 and 2 and non with $T = 1$. The situation is rather interesting and led us to calculate the dipole spectrum of the nucleus ^{42}Sc . In a detailed particle-hole calculation, the positions as well as the radiative strengths of the various states were calculated. The total strength as well as the average location of the two groups of states (i.e. $T = 0$ and 2) were obtained and found to compare reasonably with average estimates that we obtained a few years ago for these quantities for an arbitrary nucleus. Since these were estimates rather than rigorously derived results, the conclusion from this comparison is meant to justify the general results of our previous work. This work was performed in collaboration with Dr. J. Vergados (Berkeley).

2B. (Levin)

$e^- + H$ scattering

During the past year, significant progress has been made on the problem of determining $e^- + H$ collision parameters using the inhomogeneous equations method^{1,2)}. The program to compute K-matrix elements for scattering below the inelastic threshold has finally been completed and checked. K-matrix elements have been obtained at zero energy (S-wave) and at non-zero energies up to the excitation threshold (S- and P-wave) for both singlet and triplet spin states. Scattering lengths and phase shifts have been determined from these K-matrix elements.

The scattering lengths were computed in the 1s (static) approximation, the 1s - 2s (strong coupling) approximation, and the 1s - 2s - 2p (close coupling) approximation. For each of these cases, comparison was made with results obtained by ignoring exchange effects, and by using different methods. Two points are of interest here. First, exchange effects are very important, significantly altering the results when exchange is ignored (even more so than in the cases studied, e.g., by Burke and Smith³⁾ using the more usual integro-differential equations method). Second, in each of the approximations cited, our singlet results are larger and our triplet results smaller than the corresponding scattering lengths of Burke and Smith. In particular, our close coupling triplet scattering length is smaller than the variational results of Schwartz⁴⁾, which has long been accepted as a lower bound³⁾. Attempts to establish that our method is a lower bound have so far proved unsuccessful.

It was expected, after studying the results of other calculations³⁾, that resonances might have such narrow widths that they would be difficult to find numerically if only phase shifts were examined. Consequently, we studied the K-matrix as a function energy (below the $n=2$ threshold). A sign change in K,

from positive to negative, indicates the presence of a resonance. So far we have found four, occurring in the general solution only when they also occur in the homogeneous or distinguishable particle solution. A program has been written to extract resonance positions E_r and widths Γ_r , assuming that K is the sum of a slowly varying part plus Breit-Wigner form when $E \approx E_r$. So far, only E_r and Γ_r for the S-waves have reliably been determined; the P-wave values of Γ_r obtained from this program have been negative. This behavior is currently under investigation. The splitting of the S-wave resonance into triplet and singlet parts is very small in the close coupling approximation, unlike the result from the integro-differential operation method. We find $E_r = 9.79$ eV in the singlet case rather than 9.56 eV as predicted and observed⁵⁾; the inclusion of $n=3$ states in our method, planned for the future to see if E_r can thus be brought closer to the value of 9.56 eV, will be an important test of the method, especially now that we know it successfully predicts the existence of resonances.

This work has been carried out with Mr. Paul Dahlgren, now at the University of Rhode Island, as part of his Ph.D. thesis calculations. In addition to these computations, he will also calculate K-matrix elements for energies above the $n=2$ threshold. It is hoped to conclude this particular investigation by June, 1973. A short paper discussing the scattering lengths and resonance parameter calculations is in preparation and will be submitted for publication when the triplet results are understood.

Metastable He⁴ excitation by electron impact

During the 1971-72 academic year, Dr. Jean Bergeron was a research associate in the Physics Department at Brown, supported by the Canadian government. He spent part of his time here studying atomic physics, in particular the

inhomogeneous equations method. We have begun to apply this method to the problem of the excitation of the 2^3S state of He^4 by electron impact. The transition involves a spin flip ($1^1S \rightarrow 2^3S$) and since at low energies the $e^- + He^4$ system is described by a spin-independent Hamiltonian, the excitation can occur only via an exchange of electron process. The inhomogeneous equations method is ideally suited to calculating this process since it yields the exchange terms directly. Previous calculations, to our knowledge, have not been able to fit experimental data⁶⁾.

A computer program is being written and will be tested by Dr. Bergeron, now at Laval University in Quebec, Canada. The program is based on theoretical work done here prior to his departure last May. We intend to test the effects of using: a) various (approximate) wavefunctions⁷⁾ for the He^4 electronic states, as well as b) various truncations of the set of coupled equations on the theoretical calculation of the cross section for the process. Together with the calculations of $e^- + H$ scattering including both $n=3$ hydrogenic states and correlated basis states planned for the next one or two years, it is expected that this computation will conclude the testing of the inhomogeneous equations method by our group. Its application to nuclear reactions will then be examined. However, we have had several inquiries about the method and it may be applied to atom - atom scattering and to molecular rearrangement processes by workers at other institutions in the near future.

Three-Body model studies of an exact DWBA for stripping

During the academic year 1971-72, Dr. Dennis Bouldin completed his work on an exact form of DWBA for stripping⁹⁾, receiving his Ph.D. in June, 1972. (He is now a post-doctoral fellow at Manchester University in England). Several papers based on this work have been published or submitted for publication¹⁰⁾, and at least one other will be submitted for publication in the near future.

In last year's renewal proposal, we listed a number of research topics connected with this project. We briefly discuss our progress on several of them below.

1. Comparison of u_d and F . Use of the spectator function F in the stripping matrix element yields the exact amplitude T^{ND} , while use of u_d yields the DWBA amplitude T^{DW} . A previous comparison of the cross sections arising from these amplitudes gave similar results¹¹⁾, implying that F and u_d were themselves similar. Our calculations of partial wave elements of F and u_d show that this implication is false in the region where the interaction is non-zero, $R \lesssim 1.5 F$: both real parts and both imaginary parts (of F and of u_d) differ. Furthermore, the partial wave elements of T^{ND} and T^{DW} also differ significantly for $\ell \geq 2$. These unexpected behaviors, not previously noted in three-body calculations, imply that DWBA is a good approximation to the exact result only globally, and not locally. Agreement is obtained because the $\ell=2$ and $\ell=3$ partial wave amplitudes, together with their factors of $(2\ell+1)$, make the largest contribution to the amplitudes; these values are both closest and largest in magnitude. For reasons discussed below, this implies that the adiabatic method of Johnson and Soper¹²⁾ rather than DWBA should be used to calculate stripping cross sections.

2. Inclusion of tensor forces and the deuteron D-state. The three-body model offers an excellent opportunity to study effects of tensor forces in the two-body interaction, and thus the deuteron D-state. The necessary modifications of the three-body formalism used when only S-wave interactions act have been made; it is hoped to have the new integral equations programmed for calculations by next summer.

3. Properties of the one-body potential generating the spectator function F . Previous work on F and the equation it obeys is being reexamined after discussions with R. C. Johnson on a possible long range component present in $F(\vec{R})$ in addition to the elastic scattering amplitude. Current analysis suggests that such a component is not present, but rigorous arguments still need to be supplied. This work is of interest in connection with the adiabatic method¹²⁾.

4. Validity of the adiabatic method. This extension of DWBA involves two approximations¹²⁾. The first is a replacement of the three-body wave function by a product, the center-of-mass component of which we denote X^a . The second is the ignoring of excited internal deuteron states (continuum states) in deriving the equation obeyed by X^a . We have recently rediscovered¹⁴⁾ the relation $X^a = F$ (the spectator function) for the three-body model. In addition, if the neutron-proton interaction V_{np} occurring in actual nuclear reactions is given by a one-term, separable S-wave potential, then again $X^a = F$, where X^a and F are here the many-body analogues of their three-body model counterparts. Hence, use of X^a is exact in the three-body model, and in the many-body case for a particular choice of V_{np} .

The calculations discussed above (subparagraphs 1 and 3) are in fact comparisons of DWBA with the adiabatic approximation (AA); thus, comments concerning F also are relevant for X^a as well. An interesting and important feature of AA as used to analyze (p,d) data¹⁴⁾ is that a radial cutoff, often employed in DWBA analyses¹⁴⁾, is not needed. This implies that X^a is damped in the nuclear interior as compared to u_d . Harvey and Johnson¹²⁾ did not find such behavior, nor did we, in the calculations referred to above. The lack of damping plus the non-necessity of a radial cutoff can be understood as a feature arising from the complicated rearrangement nature of the stripping (or pickup process¹⁵⁾).

5. Test of the Zero-Range Approximation. A simplifying assumption that is sometimes made in computing DWBA matrix elements is that the product of V_{np} and the deuteron ground state wave function ϕ_d is of zero range (ZR) in coordinate space. The validity of this assumption can be tested for both the exact and the DWBA amplitude in the three-body model. A program to do the ZR calculation has been written and is now being checked. Results should be available by the end of the calendar year. This will be, to our knowledge, the first test of the ZR approximation against exact results.

Accuracy of the separable approximation for the many-body (Realistic) stripping process

Our results on an exact form of DWBA for stripping¹⁰⁾ are valid for the many-body case only if V_{np} is a one-term, separable potential. While such a form for V_{np} is not valid, a representation of V_{np} as a sum of separable terms does seem to be a very good approximation. A large amount of data on the two- and three-nucleon problems is accounted for by a two-body interaction containing an S-wave separable interaction in the singlet state and an S- plus D-wave separable interaction in the triplet state¹⁶⁾. Such an interaction is not adequate for three-body polarization data, although the inclusion of P-wave effects great improvements in the fits to the data¹⁷⁾.

The use of this more complex form for V_{np} does not lead to an exact DWBA unless the singlet state interaction can be ignored. Singlet terms play a negligible role: a) if there are no spin-dependent interactions in the interactions of the incident neutron and proton with the target, b) if such interactions are small compared to the spin-independent terms, or c) if the neutron and proton spin-dependent interactions are equal¹²⁾. Often, one of these

conditions is satisfied in actual cases, so that to a good approximation, our exact results will continue to hold (for angular distributions but not for polarizations). A paper on this aspect of the problem is in preparation with D. Bouldin and R. C. Johnson.

2C. (Friar)

Relativistic corrections to electron scattering by ^2H , ^3He and ^4He

(Work completed at MIT and being prepared for publication at Brown)

Relativistic corrections to the scattering of electrons by a non-relativistic nucleus are calculated, using the method of Close and Copley, and Krajcik and Foldy. Particular attention is paid to the deuteron, ^3He and ^4He . It is found that these corrections are substantially the same as those calculated by F. Gross for the deuteron. The corrections to ^3He have the effect of moving the diffraction minimum, as calculated in a non-relativistic model, outward by as much as 1fm^{-2} . Smaller corrections are found for ^4He .

Dispersion corrections to elastic electron scattering by ^{12}C and ^{16}O

II. On the use of the closure approximation.

(Work completed at MIT and being prepared for publication at Brown)

In a prior publication part of the dispersion corrections to elastic electron scattering by ^{12}C were computed using the Harmonic Oscillator Shell Model to describe the nucleus, and closure approximation to evaluate sums over intermediate nuclear states. The latter approximation is tested by computing the first order corrections to the closure result using sum rules. The results show that the average excitation energy of the nucleus is $\hbar\omega_0$, the shell spacing. The closure approximation is found to be adequate.

(This work performed in collaboration with Dr. M. Rosen (NRL))

Model independent analysis of the charge density of ^{208}Pb

(Work completed at MIT and being prepared for publication at Brown)

Electron scattering data and muonic level data are simultaneously analyzed to obtain the ^{208}Pb charge density $\rho(r)$ using a new method which does not presuppose a simple analytic form for $\rho(r)$, as is customary.

Since the density falls rapidly to zero for large r , we expand

$$\rho(r) \approx \rho_0(r) + \sum_{M=1}^{\infty} C_M \sin\left(\frac{M\pi r}{L}\right) \quad r \leq L$$

where L is some cutoff radius, and $\rho_0(r)$ is an initial guess. Using $\rho_0(r)$ to generate scattering wave functions for the electron, the cross-section for scattering can be written approximately

$$\frac{d\sigma}{d\Omega} = \left. \frac{d\sigma}{d\Omega} \right|_0 + \sum_{M=1}^{\infty} C_M f_M$$

Using data for the left-hand side and values of $\left. \frac{d\sigma}{d\Omega} \right|_0$ and f_M calculated using $\rho_0(r)$, the first N of the C_M 's can be estimated by using the least-squares method. The piece of ρ due to the C 's is then added to $\rho_0(r)$ and the procedure is iterated. The muonic level data are handled simultaneously in a similar fashion.

(This work performed in collaboration with Dr. J. Negele (MIT))

On the effect of dispersion corrections to the ^{12}C charge density

Using the method described above to obtain charge densities in a model independent fashion, the effect on the charge density of including dispersion corrections to elastic electron scattering is being investigated for the case of ^{12}C . This nucleus is important because it is the experimental standard used in many laboratories.

(This work performed in collaboration with Dr. J. Negele (MIT))

Coulomb corrections to electron-deuteron elastic scattering

The Coulomb part of the e-D second Born amplitude is calculated in closure approximation (including first-order corrections to the use of closure). It is found that the fractional correction of order a^3/a^2 to

the cross-section is independent of the deuteron wave function and can be calculated analytically. Numerical estimates of the importance of these corrections on extraction of the neutron charge form factor from elastic e-D data are being made.

Influence of dipole states on the dispersion corrections to elastic electron scattering

The results of a previous calculation of dispersion corrections to elastic electron scattering indicate that the effective excitation energy of a nucleus for virtual transitions into an intermediate state is approximately one shell spacing. This agrees with the intuitive discussion of Bethe and Molinari, who argue that low-lying dipole states, in particular the giant resonance, have an importance for dispersion corrections far exceeding their importance in the overall inelastic electron scattering spectrum. This assertion is being tested quantitatively using simple dipole collective models and by projecting out the dipole part of the two-body correlation function, which determines the dispersion correction amplitude.

3. OTHER ACTIVITIES

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

"Nuclear Electroexcitations"

(S. Fallieros, Iowa State University, November 1971)

"Doorway States and Inelastic Electron Scattering"

(S. Fallieros, University of Illinois, November 1971)

"Doorway States and Inelastic Electron Scattering"

(S. Fallieros, Invited paper, International Conference on Nuclear Structure Studies Using Electron Scattering and Photoreactions, Sendai, Japan, September 1972)

"Inelastic Electron Scattering from Nuclei"

(S. Fallieros, Syracuse University, October 1972)

"Sum Rules and Form Factors for Nuclear Electroexcitations"

(T. J. Deal, Catholic University, April 1972)

"Low Energy Scattering of Electrons by Hydrogen Atoms - A New Look at an Old Problem"

(F. Levin, Brown University Colloquium, February 1972)

"Three-Body Effects in Deuteron Stripping Reactions"

(F. Levin, University of Connecticut Seminar, February 1972)

"Investigation in a Three-Body Model of an Exact Distorted Wave Approximation for Deuteron Stripping"

(F. Levin, Laval University Seminar, May 1972)

"Two-Body Interactions and Deuteron Stripping"

(F. Levin - Series of lectures given at Laval University, August 1972)

"Three-Body Models and their Implications for Many-Body Stripping Reactions"

(F. Levin, University of Maryland Seminar, September 1972)

4. PERSONNEL

Professor S. Fallieros

Associate Professor F. S. Levin

Assistant Professor J. L. Friar

Visiting Professors C. M. Shakin (February 1972 - May 1972)

M. Bauer (September 1972 - December 1972)

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

Graduate Assistants: R. Ö. Akyüz (to July 1972)

D. P. Bouldin (to June 1972)

R. M. Brill (N.S.F. trainee to August 1973)

T. J. Deal

P. D. Dahlgren

F. J. Crowne

YEAR'S PUBLICATIONS

1. S. Fallieros, Intermediate Structure in Photon Induced Reactions, in "Statistical Properties of Nuclei" ed. by J. B. Garg, Plenum Publishing Corporation, p. 589 (1972).
2. S. Fallieros and G. E. Brown, Resonant Elastic Scattering of Protons from Analog and Compound States, in "Nuclear, Particle and Many Body Physics" Vol. II, p. 293, Academic Press (1972).
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4. Ellen Ih-liang Kao and S. Fallieros, Correlation Functions for Isovector Amplitudes, in Contr. International Conference on Nuclear Structure, p. 17, Tohoku University (1972).
5. S. Fallieros, Doorway States and Inelastic Electron Scattering, to appear in Proc. Int. Conference on Nuclear Structure Studies.
6. R. Brill and S. Fallieros, The Giant M1 Resonance in ^{208}Pb , submitted as a contribution to APS meeting, New York, January 1973.
7. J. Vergados and S. Fallieros, Dipole States and Isospin Splitting in ^{42}Sc , (preprint).
8. R. Ö. Akyüz and S. Fallieros, The Random Phase Approximation and States with Definite Isospin in Nuclei with Excess Neutrons, (in preparation).
9. T. J. Deal and S. Fallieros, Sum Rules and Form Factors for Isoscalar Nuclear Electroexcitations, Bulletin American Phys. Soc., Vol. 16, 12 p. 1395 (1972).
10. R. Ö. Akyüz, Giant Isovector Excitations in Atomic Nuclei, (Ph.D. thesis, Brown University (unpublished)).
11. D. Bouldin and F. S. Levin, On the Validity of DWBA for Stripping. I. Three-Body Model, Bulletin Am. Phys. Soc., 27-29 December, 1971, meeting of the American Physical Society.
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16. F. S. Levin, Unitarity and the Inhomogeneous Equations Method for Identical Particle Scattering, Annals of Physics (NY) 72 (1972) 497.
17. F. S. Levin and D. P. Bouldin, Validity of DWBA in a Three-Body Model of Stripping (International Conference on Few Nucleon Problems in the Nuclear Interaction, August 1972) to be published in the Proceedings.
18. D. P. Bouldin and F. S. Levin, Numerical Study of DWBA in a Three-Body Model of Stripping; to be published in Physics Letters.
19. D. P. Bouldin, Formulation and Investigation in a Three-Body Model of an Exact Distorted Wave Approximation for Deuteron Stripping, Brown University Ph.D. thesis, May 1972, unpublished.

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10. Listed in the section entitled "Years' Publications".
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