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RESEARCH IN THEORETICAL NUCLEAR PHYSICS

Progress Report

November 1, 1992 - October 31, 1993

Takeshi Udagawa

Theoretical Nuclear Physics Group

Department of Physics

The University of Texas at Austin

P. O. Box 7726, Austin, Texas, 78713-7726

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Introduction

This report describes the accomplishments in basic research in nuclear physics carried out by the theoretical nuclear physics group in the Department of Physics at the University of Texas at Austin, during the period of November 1, 1992 to October 31, 1993. The work done covers three separate areas, low energy nuclear reactions, intermediate energy physics, and nuclear structure studies. Although the subjects are thus spread among different areas, they are based on two techniques that we have developed in previous years. These techniques are: a) a powerful method for continuum-random-phase-approximation (CRPA) calculations of nuclear response;¹ and, b) the breakup-fusion (BF) approach² to incomplete fusion reactions, which enables us to calculate on a single footing various incomplete fusion reaction cross sections within the framework of direct reaction theories. The approach was developed as a part of our more general program for establishing an approach to describing all different types of nuclear reactions, i.e., complete fusion, incomplete fusion and direct reactions, in a systematic way based on a single theoretical framework. In what follows, we first summarize our achievement made in these three areas, and then give final remarks.

Low Energy Nuclear Reactions

The research in low energy nuclear reactions has covered the following two subjects: development of a fast computer code for coupled-channel (CC) calculations of heavy ion scattering, and spectroscopic analyses of the $^{40}\text{Ca}(^3\text{He},d)^{41}\text{Sc}$ reaction with incident energy of $E=240\text{ MeV}^3$ as well as the $^{40}\text{Ca}(^6\text{Li},d)^{44}\text{Ti}$ reaction with $E=60\text{ MeV}^4$.

The development of a computer code for CC calculations of heavy ion scattering was accomplished by using a technique developed for the CRPA nuclear response calculations.¹ The method can take into account Coulomb excitation effects very effectively. The essence of the method is to modify first the basic CC equation for the scattering wave function Ψ to that for an auxiliary function λ defined as $\lambda = v\Psi$, where v is the coupling potential. λ thus defined is localized. Because of this, one can solve λ by means of the Lanczos method.

This procedure has turned out to be very efficient, speeding up the computation time by a large factor. This factor becomes larger as the dimension of the coupled equation increases and thus can easily become an order of magnitude, if the dimension of the coupled-channel equations reaches about 100. Using the code, analyses of a variety of experimental data are now in progress.⁵ Following the same idea, we have also developed a very efficient computer code for nonlocal optical potential model calculations, which has been published recently.⁶

The spectroscopic analyses of the two reactions mentioned above were carried out by using the BF method.² As already remarked above, the method was originally developed for calculating cross sections of incomplete-fusion reactions to the highly excited continuum.² It has been shown⁷ that the method can also be used for spectroscopic purposes, i.e., for analyzing data of nuclear transfer reactions. The merit of the method, as compared with the usual DWBA method, is that it provides a unified description of the reactions to both bound and unbound final states. The unification is achieved by utilizing the complex optical potential for the transferred particle even in the bound state, instead of utilizing the real potential used in the usual DWBA method. The BF method also enables us to calculate the so-called background cross section on the same footing as the transfer cross sections are evaluated; in the conventional analysis with the DWBA method, the background component is subtracted from the observed cross section in a rather arbitrary manner, which inevitably introduces an ambiguity in the analysis. With the BF method, one can thus carry out the analyses without such an ambiguity.

The main aim of the analyses was to extract information on single particle and cluster structure of the residual nuclei in the bound and unbound regions. For the $^{40}\text{Ca}(^3\text{He},d)^{41}\text{Sc}$ reaction, we were able to deduce fairly conclusive information on the distribution of the $f_{5/2}$ and $g_{9/2}$ single particle strength in the unbound region and also the $f_{7/2}$ and $p_{3/2}$ strength in both bound and unbound regions. In the case of the $^{40}\text{Ca}(^6\text{Li},d)^{44}\text{Ti}$ reaction, we were able to identify for the first time all $0^+ - 12^+$ members of the α -cluster states of the principal quantum number $N=12$ band. The spectroscopic factors of these states were extracted to

be about 30% of the sum rule limit, thus indicating that the cluster strength is largely spread into other states. We could then identify most of the states into which the strength was spread. Another important result obtained is that we could identify a strong candidate for the 0^+ band head of the $N=14$ cluster band at an excitation energy of 9.32 MeV. The successful results have given us a great deal of confidence in the validity of the BF method as a spectroscopic tool. The work described above will be published soon.^{8,9}

Intermediate Energy Physics

The work done in the area of intermediate energy physics is concerned with a theoretical method for dealing with the nuclear medium effects on the delta (Δ) excited in nuclei by means of hadronic charge-exchange reactions as well as γ - and π -absorption at intermediate energies. Using the technique for solving the CRPA equation,² we have developed a method for calculating singles cross sections of these reactions, in which all important nuclear medium effects, i.e., those of one body mean fields for the target nucleons as well as the excited Δ , two-body Δ -hole interactions, and Δ spreading, are taken into account. It has been shown that the calculations done by using the method reproduce the observed spectra very well.¹⁰

During the past year, we have made an effort to extend the theoretical method to calculate exclusive cross sections, such as those of the coherent pion production $^{12}\text{C}(p,n\pi^+)^{12}\text{C}$ and $^{12}\text{C}(^3\text{He},t\pi^+)^{12}\text{C}$ reactions, since the analyses of these reactions can provide a more sensitive test of the theoretical method. The achievements made during the past year along this line include development of a computer program for performing numerical calculations. Using the computer program, we have performed¹¹ numerical calculations for the $^{12}\text{C}(p,n\pi^+)^{12}\text{C}$ and $^{12}\text{C}(^3\text{He},t\pi)^{12}\text{C}$ reactions. The result showed the interesting features that the peak of the calculated neutron spectra appears at much lower excitation energies than that of the singles cross section, and also that the calculated angular distribution of the emitted pion is strongly forward peaked. Such characteristic features of the calculated

cross section were later verified experimentally by the data taken at SATURN in France for the $^{12}\text{C}(^3\text{He},t\pi)^{12}\text{C}$ reaction.¹² The data were found to agree very well with our theoretical prediction even at a quantitative level. This has proved the validity of our method and has encouraged us to generally apply it for treating similar nuclear medium effects on other isobars and hyperons created in nuclei.

Nuclear Structure

The CRPA method of ref. 1 was primarily developed for the nuclear structure studies, particularly for calculations of the particle emission strength (widths) of the giant resonance states. One of the studies made along this line was calculations of emission widths of the isobaric analogue (IA) and Gamow-Teller (GT) resonance states in ^{208}Pb . We were very successful¹⁴ in reproducing the observed partial escape widths for both IA and GT resonance deduced from very recent coincidence measurements¹⁵ of the $(^3\text{He},tp)$ reaction with the incident energy of $E = 450$ MeV. The CRPA method can treat the continuum effects in an exact manner, which was found to be necessary to make reliable predictions of the emission widths.

Final Remarks

We have explored during the past year the possibilities made accessible by the techniques we had developed in previous years. This is in line with what we proposed in our original proposal, and we plan to continue to work along this direction in the next year.

We remark that in carrying out the work described above we have been benefited by many fruitful collaborations with Dr. F. Osterfeld at KFA, Juelich, Drs. S.-W. Hong and B. T. Kim at Sung Kyun Kwan University in Seoul, Dr. H. Langevin at Orsay, Drs. L. Zetta and P. Guazzoni in Milano, Dr. Izumoto at Rikkyo University, Tokyo, and Drs. D. Knobles and S. Stotts at the Applied Research Laboratory at the University of Texas. We are continuing these collaborations. It is remarkable that such collaborations not only

benefit us, but can also impact developments in other fields; Dr. D. Knobles, one of our ex-postdocs and now at the Applied Research Laboratory, has successfully applied the technique developed for the CRPA nuclear response calculations¹ to analyze a sound wave response from underwater acoustics, i.e., to solve coupled-mode equations with a large dimension for sound wave propagation in ocean acoustics. Dr. Knobles plans to extend his effort to electromagnetic waves.

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List of Publications (November 1992 - October 1993)

"NLOM - A Program for Nonlocal Optical Model Calculations", B. T. Kim, M. C. Kyum, S.-W. Hong, M. H. Park, and T. Udagawa, *Comput. Phys. Commun.* **71**, 150 (1992).

"Pauli Violation in Breakup-Fusion Formalism", C.-Y. Kim and T. Udagawa, *Journal of the Korean Physical Society* **25**, 498 (1992).

" Δ Excitation in Nuclei and the Coherent Pion Decay", F. Osterfeld, B. Koerfgen, P. Oltmanns, and T. Udagawa, *Physica Scripta* **48**, 95 (1993).

"Nuclear Response in the Continuum: From Giant Resonance to Δ Excitation Region", T. Udagawa, *Proceedings of the International Symposium on Spectroscopy and Structure of Molecule and Nuclei*, ed. by N. R. Johnson, W. N. Sheldon, and M. El-Sayed (World Scientific, 1992), p. 211.

"Coherent Pion Production in Intermediate Energy Charge-Exchange Reactions", P. Oltmanns, F. Osterfeld, and T. Udagawa, *Phys. Lett. B* **299**, 194 (1993).

"Comments on (p,n) Reactions in the Δ -Resonance Region", T. Udagawa, F. Osterfeld, and P. Oltmanns, *Proceedings of Workshop on N-N and N-Nucleus Scattering*, ed. by T. Taddeucci, M. McNaughton, and J. Ullmann (Los Alamos National Laboratory, 1993) p. 175.

"Coherent Pion Production at Small Scattering Angles", F. Osterfeld, B. Koerfgen, P. Oltmanns, and T. Udagawa, *Proceedings of 105th Intern. WE-Heraceus-Seminar on Hadronic Processes at Small Angles in Storage Rings*, ed. by E. Roessle and O. W. B. Schult (Konferenzen des Forschungszentrums, Juelich, 1993) p.83.

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