DOE/ER/40145--6

DE92 002408

RESEARCH IN THEORETICAL NUCLEAR PHYSICS

Progress Report

November 1, 1990 - September 30, 1991

Takeshi Udagawa
Theoretical Nuclear Physics Group
Department of Physics
University of Texas
Austin, Texas, 78712

October 1991

PREPARED FOR THE U.S. DEPARTMENT OF ENERGY
UNDER GRANT NUMBER DE-FG05-84ER40145

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The work done during the past year covers three separate areas, low energy nuclear reactions, intermediate energy physics, and nuclear structure studies. This manuscript summarizes our achievements made in these three areas.

Low Energy Nuclear Reactions

The research in this area has been focused on heavy-ion scattering and fusion in the sub- and near-Coulomb barrier energies, and has been undertaken as a part of our program for establishing an approach for the description of a wide variety of nuclear reactions in a systematic way based on a unified theory. One of the techniques developed for this purpose, specifically for a unified treatment of elastic scattering, fusion and total direct reaction cross section calculations, is the extended optical model.¹ The basic idea is simple; we separate the imaginary absorption potential into fusion and direct reaction parts, calculating the fusion and total direct reaction cross sections as absorption cross sections coming from these two separate parts.

The extended model was used in the past to make simultaneous χ^2 -analyses of the elastic scattering, fusion and total direct reaction cross sections. The results of such analyses² showed that the fusion potential, assumed to have a Woods-Saxon shape, should have a large radius parameter $r_F \approx 1.4$ fm, placing the fusion potential radius beyond the peak in the Coulomb barrier. Similar conclusion have also been drawn in an earlier and much simpler analyses.¹

Satchler *et al.*³ proposed then that the large r_F values have their origin in the known importance of the coupling to direct reaction channels; in a coupled-channel approach, the “bare” imaginary fusion potential, i.e., the potential to be used as an input for the calculation, may still be confined inside the Coulomb barrier and have a small radius, say 1.0 fm. If one projects, however, this coupled-channel problem onto the elastic channel, there appears an additional fusion potential term as a part of the dynamical polarization potential coming from the coupling. The proposal made in Ref. 3 is that r_F becomes large due to this additional term.

In order to test the above idea, we made⁴ during the past year fairly extensive calculations of fusion and direct reaction parts of the dynamical polarization potential. The results indicate that the fusion potential resulting from the coupling is somewhat shifted outward as compared with the bare fusion potential, but still stays inside the barrier, and is much inside the fusion radius determined from the phenomenological analyses.² The region where the direct reaction occurs is found to be confined in the so-called grazing region where the direct reactions are supposed to take place.

Another study made was on the linear systematics recently discovered by Stelson *et al.*⁵ in the sub-barrier fusion cross section σ_F . What was discovered is that the quantity S defined as $S = \sqrt{E\sigma_F}$, where E is the incident energy in the center of mass system, becomes linear as a function of E . This enables us to define rather unambiguously the threshold energy for the sub-barrier fusion reactions from its zero intercept. We then found⁶ evidence that this threshold energy for the sub-barrier fusion is very much related to another threshold energy of the imaginary part of the optical potential at the strong absorption radius. At this moment, the number of evidences found are still limited to a few cases, but the finding leads us to conclude that the threshold behaviour (strong energy dependence) observed in the optical model potential⁷ is primarily due to couplings to fusion channels, not direct reaction channels as previously believed, although the direct reaction channels play the role of door ways. It also indicates that fusion plays an important role even at such a large radial distance as is the strong absorption radius. In Ref. 6, we have also shown that the main features of the systematics

observed in the fusion cross sections in the sub-barrier region can be understood within the framework of our extended optical model.

Intermediate Energy Physics

The work done in the area of the intermediate energy physics is concerned with the nuclear medium effects on the delta (Δ) excited in nuclei by means of hadronic charge-exchange reactions at intermediate energies^{8,9} and also γ - and π -absorption.^{10,11} In the previous progress report we described our calculations¹² of the spectra of the $^{12}\text{C}(p, n)$ and $(^3\text{He}, t)$ reactions at the intermediate energies. The calculations were based on the isobar model¹³ and DWIA, assuming a $\pi + \rho + g'$ model¹⁴ for the delta-hole interaction and essentially a δ -function type $t_{NN\Delta}$ -amplitude for the external force field applied to the target in the reaction processes. A one body complex mean field for the excited Δ was also taken into account. The calculations thus properly included all important nuclear medium effects and also the distortion effects on the projectile wave functions. The result of the calculation showed that the π -exchange interaction reduces the mass of the Δ created in ^{12}C by about 30 MeV. Because of this, the peak of the charge-exchange reaction cross section for the ^{12}C target case is shifted downward by about the same amount as compared with that of the cross section for the proton target. The result agreed well with the shift observed experimentally.^{8,9}

We continued the work on the Δ during the past year. First of all, we made a critical test of the $t_{NN\Delta}$ -amplitude used in our earlier calculations against newly taken data¹⁵ of the analyzing power for the $p(\vec{d}, 2p)\Delta^0$ and $^{12}\text{C}(\vec{d}, 2p)$ reactions with $E_{lab} = 2 \text{ GeV}$. The result showed that the $t_{NN\Delta}$ -amplitude assumed before explains well the analyzing power data,¹⁶ particularly for the proton target case. This indicates that the $t_{NN\Delta}$ we used is basically valid. We have found, however, that the fit of the calculated forward angle analyzing power for the ^{12}C target case is not good at lower excitation energies. Similar failures at the lower excitation energies were also observed in the results of the cross section calculations of the $^{12}\text{C}(d, 2p)$ reaction. It has been speculated that these failures may be due to "background" components from nucleon knockout processes that are not taken into account in the calculations. We presented in Ref. 16 some justification of this speculation.

We extended our calculations, restricted so far to the hadronic charge-exchange reactions, to γ - and π -absorption. We have found¹⁷ that the excitation cross section of the γ -absorption is peaked at an excitation energy which is too high, indicating that our interaction consisting of $\pi + \rho + g'$ is too repulsive in the spin-transverse channel. We have not observed this in the previous analyses of the charge-exchange reaction data, since the cross sections at higher excitation energies are reduced by the t -amplitude involved. On the other hand, the interaction could explain well the data for the π -absorption. These results show that we need to improve our Δ -hole interaction for explaining all observed data consistently, including those of the γ -absorption.

We also initiated during the past year a study of the decay of Δ excited in nuclei by means of the (p, n) ¹⁸ and $(^3\text{He}, t)$ ¹⁹ reactions in coincidence with the outgoing n and t , respectively. Some preliminary calculations were made²⁰ of the $\pi + p$ and $2p$ production cross sections within the same framework as used in our earlier calculations^{12,16} of the singles cross sections. We were able to show²⁰ that a large difference in the peak positions observed in the $\pi + p$ and $2p$ spectra could be accounted for well by such calculations.

Nuclear Structure

The goal of our nuclear structure studies is to establish a description for the nuclear excitation spectrum in various excitation energy regions, such as giant resonances, quasi-elastic, dip and Δ -excitation regions, within a single theoretical framework. As such a description, we have recently

developed²¹ a method for continuum Tamm-Dancoff and/or random-phase-approximation calculations. The work described above in the intermediate energy physics was done by using the same method.

The calculations made in Ref. 21 assumed a δ -force, for instance the Skyrme force, for the basic residual particle-hole(ph) interaction, since zero-range interactions greatly simplify the calculations. During the past year or so, we have made an extensive effort so as to include a realistic finite range residual interactions (a nuclear matter G-matrix for instance), properly including the exchange part of the residual interaction. In order to achieve this goal it was necessary to introduce a more general formalism²² than the one presented in Ref. 21. The numerical implementation of this formalism is now complete and has been used to investigate the lowest collective 3^- state and the giant quadrupole resonances (GQR) in ^{16}O and ^{40}Ca . We were successful in reproducing the observed properties of both the lowest 3^- state and the GQR using the same G-matrix interaction. The importance of this is that previous attempts to fit the properties of both bound collective states and collective states in the continuum using a Skyrme interaction have not been successful²³.

We are currently applying the program developed to the isobaric analogue (IAR) and Gamow-Teller (GTR) resonance in ^{208}Pb . Using the so called Bertsch-Esbensen zero-range interaction²⁴ one can obtain both the IAR and GTR at the experimental resonance energies. We have been successful in reproducing the partial escape widths for the IAR and the total width of the GTR. The quenching effect of the GTR is reproduced by the imaginary part of the optical potential which introduces spreading as previously discussed. One interesting finding made is that the diagonal part of the two-body ph interaction matrix elements plays a significant role on the escape width,²⁵ particularly for explaining relative magnitude of the escape widths for particles in the $p_{1/2}$ and $p_{3/2}$ states.

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12/10/91