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RESEARCH IN THEORETICAL NUCLEAR PHYSICS

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The work done during the past year or so may be divided into three separate areas, low energy nuclear reactions, intermediate energy physics and nuclear structure studies. In what follows, we shall separately summarize our achievements made in these three areas.

Low Energy Nuclear Reactions

The primary goal of nuclear reaction studies is to establish an approach for describing a wide variety of nuclear reactions in a systematic way based on a unified approach. In the past we have developed for this purpose a few techniques which allow us to calculate cross sections of complete fusion, and also various types of incomplete fusion reactions within the framework of direct reaction theory.¹⁻⁶ The DR theory itself can be formulated on the basis of the unified theory of nuclear reactions.⁷ Within this theory, the fusion part of the reaction process is incorporated into the imaginary part of the optical potential (though such a description can account for the energy averaged behavior only). This is the key ingredient in our approach.

The technique developed for the incomplete fusion reaction calculation is the breakup-fusion (BF) approach.¹ In this approach, we assume that the incomplete fusion reaction proceeds as the breakup of the incident particle a into, say, $b + x$, followed by absorption of x by the target A , b being the emitted particle. In other words, the incomplete fusion reaction is viewed as a partial fusion taking place in three (or more) body channels that are reached by breakup (or by some other direct reaction, knockout reaction, for instance). We then treat this partial fusion using the imaginary part of the optical potential W_x for the $x + A$ system. Since the first breakup reaction itself is a typical direct reaction, it can be treated by the usual direct reaction theory. It is thus possible to calculate the whole BF process within the framework of direct reaction theory.

The earlier BF studies¹⁻⁵ were all restricted to cases where the particle x , which is produced in the first breakup $a \rightarrow b + x$ and absorbed in the target A , is left in a positive continuum state. It has been shown^{8,9} recently, however, that the same description can be applied to the case where x is left (captured) in a negative energy bound state. Even so, we still use the complex optical potential for the $x + A$ system. The imaginary part of the potential describes the spreading of the single particle state.¹⁰ In fact, we have shown that the BF cross section is nothing but the energy averaged DWBA stripping cross section.

The technique developed for calculating the fusion cross section,⁶ which is called the direct reaction approach to fusion (DRAF), also utilizes the imaginary part of the optical potential. More specifically, fusion is treated as absorption by the inner part of the imaginary potential W . We call this inner portion of W the fusion potential W_F . The remainder (outer part) of W may then be ascribed to the incomplete fusion plus direct reaction part, which we simply call the direct reaction part. We then calculate the total fusion and direct reaction cross sections, σ_F and σ_D respectively, as $\sigma_i = (2/\hbar v) \langle \chi^{(+)} | W_i | \chi^{(+)} \rangle$ ($i=F$ or D), where $\chi^{(+)}$ is the optical model wave function.

With the BF technique well developed, together with the use of the multistep direct reaction (MSDR) method, also developed by our group,¹¹ it is now possible to calculate the cross sections of all possible incomplete fusion and direct reactions that contribute importantly to the total reaction cross section σ_R . During the past year or so, such calculations were performed for the first time for the $d + {}^{93}\text{Nb}$ system with $E_d = 10\text{-}25$ MeV¹² and the $\alpha + {}^{59}\text{Co}$ system with $E_\alpha = 80$ MeV¹³. The sum of the calculated total incomplete fusion and direct reaction cross sections, σ_{IF} and σ_{DR} , respectively, amounts to about 50% and 58% of the total reaction cross section, respectively, for the above two systems.

The sum of σ_{IF} and σ_{DR} thus calculated approximates the non-compound nuclear (total direct reaction) cross section σ_D very well. This means that we may estimate the complete fusion cross section σ_F by subtracting from the total reaction cross σ_R , σ_{IF} and σ_{DR} , i.e., $\sigma_F = \sigma_R - \sigma_{IF} - \sigma_{DR}$, where σ_R may be calculated from the optical model. We may then compare this calculated σ_F to the experimental data. Unfortunately, such data are not available. However, for the $\alpha + {}^{59}\text{Co}$ system, data are available for the linear momentum transfer (LMT),¹⁴ which is very sensitive to σ_F . Therefore, a test of the calculated σ_F may be made by comparing the calculated LMT/nucleon (p/a) to the data. An estimate of p/a was thus made by using the σ_F , and also the various calculated incomplete fusion and direct reaction cross sections. The result obtained was $p/a = 163 \text{ MeV/c}$, which agrees very well with the experimental value of 160 MeV/c . This good agreement strongly supports the validity of our calculated fusion cross section ($\sigma_F = 967 \text{ mb}$). Good agreement was also obtained for the calculated total and differential emission cross sections for the particle $b = p, d, t$, and h .

Using DRAF and the calculated $\sigma_{CF} = 967 \text{ mb}$, we further estimated the fusion potential radius R_F ,⁶ which is a sharp cut-off radius parameter dividing the imaginary part W of the optical potential into fusion and direct reaction pieces. The value of R_F thus determined was found to be $R_F = 6.57 \text{ fm}$, which corresponds to a reduced radius parameter of $r_F = 1.69 \text{ fm}$. A similar estimate was also made for the $d + {}^{93}\text{Nb}$ system, resulting in $r_F = 1.58 \text{ fm}$. These two values are both larger than the typical nuclear radius parameter, say, $r_0 = 1.2 \text{ fm}$, indicating that fusion begins at a fairly large radial distance. This conclusion is in very good agreement with what was concluded for heavy-ion fusion.⁶

Another aspect of the low energy nuclear reaction studies was our focus on heavy ion scattering and fusion in the near-Coulomb-barrier region. We have demonstrated¹⁵ that DRAF allows us to perform simultaneous χ^2 -analyses of elastic scattering and fusion data. We were able to construct in this way a fully dispersive optical model potential for the ${}^{16}\text{O} + {}^{208}\text{Pb}$ system, similar to that constructed for nucleon-nucleus systems.¹⁶ In our case, the volume and surface parts of the polarization potential are ascribed to fusion and direct reactions. The dispersive optical potential thus determined was further applied to successfully explain the linear systematics of fusion in the near-Coulomb-barrier region, discovered recently by Stelson, *et al.*¹⁷

Intermediate Energy Physics

The work done in the area of the intermediate energy physics concerned the peak position of the Δ -excitation spectra in (p,n)- and (${}^3\text{He},t$)-charge-exchange reactions at intermediate energies.^{18,19} The data have revealed a systematic downward energy shift of the $\Delta(1232)$ -resonance peak position for targets with $A \geq 12$ with respect to that observed for a proton target. In contrast to this, in the case of γ -absorption and inelastic electron scattering experiments, the Δ -peak does not show such a pronounced displacement. The electromagnetic probes excite the Δ transversely, while the hadronic probes measure both the transverse and the longitudinal spin-isospin response.

It has been speculated that the shift of the Δ -peak could be due to a nuclear medium effect in the isovector spin longitudinal channel. That is, if the delta-particle-nucleon-hole (ΔN^{-1}) residual interaction becomes strongly attractive at large momentum transfers $|\vec{q}| \approx 1 - 2 \text{ fm}^{-1}$ in this channel, then this attraction might lead to a lowering of the Δ mass produced in the target. Along this line of reasoning, no shift of the Δ -peak position is to be observed with the electromagnetic probes. Recently, we have made²⁰ some realistic calculations of the Δ -excitation spectra of the ${}^{12}\text{C}(p,n)$ and (${}^3\text{He},t$) reactions, based on the isobar model²¹ and DWIA. We took into account in the calculations all important nuclear medium effects including the ΔN^{-1} interaction and the nuclear distortion effects. The result showed that an energy shift of about 30 MeV could be obtained from the energy-dependent π -exchange interaction and that the energy-dependence included in the interaction played a crucial

role in obtaining this shift. The calculation was also found to explain the observed spectra very well. We have studied also the angular distribution, confirming that the angular dependence of the observed spectra are also well accounted for by the calculations.²²

Nuclear Structure

The goals of our nuclear structure studies are similar to those of our nuclear reaction studies. We intend 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 an example of such a description, we have recently developed²³ a very powerful method for continuum Tamm-Dancoff and/or random-phase-approximation (RPA) calculations. The work described above in the intermediate energy physics was done by using the same method. The method has also been successfully applied to monopole and quadrupole giant resonances.²³ In particular, we have succeeded to calculate the total, as well as various partial widths of the resonances.

The calculations made thus far all 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, we have made an extensive effort so as to include a realistic finite range residual interactions (a nuclear matter G-matrix for instance), and also to properly include the exchange effect. The formulation of the calculations and the construction of the computer program have been completed, and a few preliminary calculations have been made.²⁴ We are currently applying the program developed to realistic problems.

Finally we have found²⁵ that the method developed for solving the continuum RPA equations, which are inhomogeneous coupled-channel integral equations, can also be used very efficiently for solving the usual coupled-channel equations for nuclear reactions and/or nonlocal optical model Schrödinger equations for nuclear scattering.

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