Triune nuclear physics

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Abstract

Genuine collaboration between nuclear reaction, nuclear structure, and nucleon-nucleon effective interaction studies, i.e., Triune Nuclear Physics (TNP), is proposed. First, a new multiple scattering theory for nucleus-nucleus scattering is introduced, as a basic framework of TNP. Then some recent achievements of TNP are reported.

1 Introduction

For some decades, importance of close collaboration between nuclear structure and nuclear reaction studies has been suggested. It is rather obvious that direct comparison of theoretical results with scattering observables is indispensable to draw some definite conclusions on properties of nuclear many-body systems. This has not been established, however, at least as a standard manner of theoretical nuclear physics. For most structural studies, calculation of scattering observables have not been done. On the other hand, direct nuclear reaction studies usually adopt a very simplified structural model for the projectile and the target nucleus. Recently, reaction calculations with "shell-model wave functions" have been accomplished [1]. Though this is a good starting point of strong collaboration between structure and reaction studies, structural information is included in the reaction calculation through only spectroscopic factors, not wave functions.

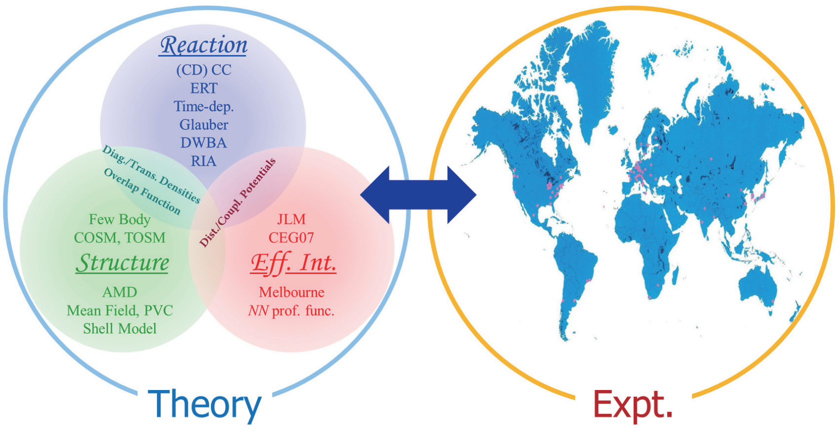

Figure 1: Trinity of theoretical nuclear physics, to be validated by experimental data.

In this situation, we, nuclear theory group, aim at constructing a framework to directly incorporate many-body wave functions of reaction particles in the calculation of scattering observables. Furthermore, we describe nucleus-nucleus scattering on the basis of a nucleon-nucleon effective interaction in nuclear medium, which is an essential ingredient of a fully microscopic description of nuclear reactions. In this sense, it can be said that nuclear reaction, nuclear structure, and effective interaction studies form *trinity* of theoretical nuclear physics. Thus, our goal is to establish genuine collaboration between them, i.e., *Triune Nuclear Physics (TNP)*.

In this article, we report some recent achievements of TNP. In Sec. 2 we show how to describe nucleus-nucleus scattering microscopically, by introducing a newly-developed multiple scattering theory. Studies of neutron-rich Ne isotopes located near or in the so-called "Island of Inversion" are reported in Sec. 3. We then discuss in Sec. 4 how resonance states of ^{22}C, the dripline nucleus of the C isotopes, will be observed in a breakup cross section. We give a summary in Sec. 5.

2 Multiple scattering theory for nucleus-nucleus scattering

Our basic equation for nucleus-nucleus scattering is [2]

$$(K + h_{\rm P} + h_{\rm A} + \sum_{i\in{\rm P},j\in{\rm A}} \tau_{ij} - E)\hat{\Psi}^{(+)} = 0\ , \qquad (1)$$

where E is the energy of the total reaction system, K is the kinetic-energy operator for the relative motion between a projectile (P) and a target (A), and $h_{\rm P}$ ($h_{\rm A}$) is the internal Hamiltonian of P (A). τ_{ij} is the effective interaction of ith nucleon in P and jth in A, which is constructed by taking a summation of ladder diagrams between the two nucleons. Equation (1) is an extension of the Kerman-McManus-Thaler formalism [3] for nucleon-nucleus scattering to nucleus-nucleus scattering. It should be noted that we have assumed that the number of pairs (i, j) is much larger than unity, which is valid for usual nucleus-nucleus scattering. Also assumed is that the antisymmetrization between incident nucleons in P and target nucleons in A can be approximated by using τ_{ij} that is properly antisymmetrical with respect to the exchange of the colliding nucleons; this is known to be accurate at intermediate and high incident energies [4].

As mentioned above, τ_{ij} describes nucleon-nucleon scattering in nuclear medium. A possible simplification of τ_{ij} is to replace it with the Brückner g-matrix interaction, which has been done in many applications; see, e.g., Refs. [5, 6, 7, 8, 9, 10, 11]. The g-matrix interaction, however, does not include effects induced by finite nucleus, e.g., effects of projectile breakup and target collective excitations, because the interaction is evaluated in infinite nuclear matter. Therefore, in general, it is not easy to solve the many-body Schrödinger equation (1). However, it becomes feasible at least in the following cases [12].

First, if we consider a) nucleus-nucleus scattering at high incident energies, or, b) scattering of lighter projectiles from lighter targets at intermediate incident energies, effects induced by finite nucleus mentioned above are small. Then, the double-folding model becomes reliable, with which we can analyze the elastic-scattering cross section and the total reaction cross section $\sigma_{\rm R}$.

Second, let us consider a projectile that is a weakly bound system of two nucleus b and c. Then the many-body Schrödinger equation (1) is approximated well into a three-body Schrödinger equation, in which the potential U_γ (γ =b or c) is constructed to reproduce the scattering of γ on A. When γ is not a weakly bound system, the potential can be constructed microscopically with the double-folding model, i.e., by folding the effective NN interaction with the densities of A and γ. Thus, in this case, we can solve with high accuracy Eq. (1) by introducing a three-body reaction model with all the input optical potentials obtained microscopically.

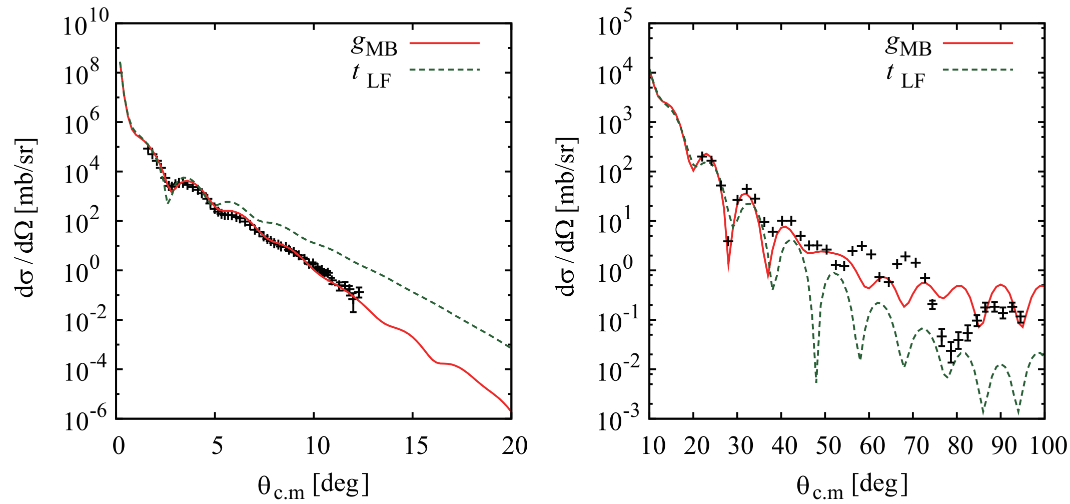

Figure 2: Angular distribution of the ^{12}C+^{12}C elastic cross sections at 135 MeV/nucleon (left panel) and 74.25 MeV (right panel). In each panel, the solid (dashed) line shows the result of the double-folding model calculation with $g_{\rm MB}$ ($t_{\rm LF}$). Experimental data are taken from Refs. [13] (135 MeV/nucleon) and [15] (74.25 MeV).

To see the accuracy of the double-folding model, we show in Fig. 2 the angular distribution of the ^{12}C+^{12}C elastic scattering at 135 MeV/nucleon (left panel) and 74.25 MeV (right panel). For the nuclear density of ^{12}C, we take the phenomenological proton-density [16] deduced from the electron scattering by unfolding the finite-size effect of the proton charge in the standard manner [17], and the neutron density is assumed to have the same geometry as the corresponding proton one.

The folding model calculation with the Melbourne g matrix ($g_{\rm MB}$) [10] reproduces very well the data [13], whereas that with the Love-Franey t-matrix interaction ($t_{\rm LF}$) [14] does not. The medium effect is thus important, and the double-folding model with $g_{\rm MB}$ is found to be quite reliable at these incident energies. It should be noted that the present calculation has no free adjustable parameters, which guarantees the *predictability* of TNP approach to frontiers of nuclear many-body systems.

3 Exploration of the "Island of Inversion"

Exotic properties of nuclei in the "Island of Inversion", i.e., the region of unstable nuclei from ^{30}Ne to ^{34}Mg, fascinate many experimentalists and theoreticians. The low excitation energies and the large $B(E2)$ values of the first excited states of nuclei in the island are considered to indicate strong deformations, which eventually cause the *melt* of the neutron shell corresponding to the $N = 20$ magic number (N: neutron number). In particular, the ^{31}Ne nucleus is very interesting in view of its intruder configurations of the single-particle orbit and a halo structure due to strong deformations.

Recently, a systematic investigation employing Antisymmetrized Molecular Dynamics (AMD) with the Gogny D1S interaction has been performed for both even and odd N nuclei in the "Island of Inversion" [18]. As shown in the left panel of Fig. 3, AMD describes very well the odd-even staggering of the one-neutron separation energy S_n measured. As for ^{31}Ne, AMD suggests rather large deformations and small S_n, as indicated by preceding studies. Then it is very interesting and important to see whether microscopic reaction calculation with AMD wave functions can describe scattering observables.

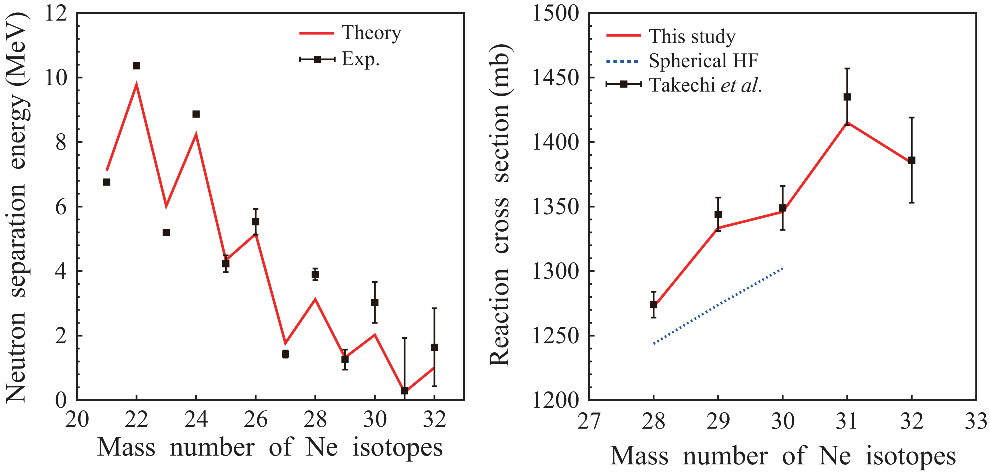

Figure 3: (left panel) One neutron separation energy S_n of the Ne isotopes. Experimental data are taken from Refs. [19, 20]. (right panel) Reaction cross sections of Ne isotopes by ^{12}C at 240 MeV/nucleon. The solid line represents the theoretical result with AMD wave functions. For ^{31}Ne, RGM calculation of the valence neutron is adopted. The dotted line corresponds to the result of a spherical HF calculation. Experimental data are taken from Refs. [21, 22].

In the right panel of Fig. 3 we show the reaction cross section $\sigma_{\rm R}$ of $^{28-32}$Ne by ^{12}C at 240 MeV/nucleon. We adopt the double-folding model with $g_{\rm MB}$; the values of $\sigma_{\rm R}$ calculated have been reduced by 1.8%. This fine-tuning factor is introduced to make the theoretical result (796 mb) agree with the mean value of the experimental data of $\sigma_{\rm R}$ for the ^{12}C+^{12}C scattering at 250.8 MeV/nucleon, i.e., 782.0 ± 10 mb [23]. Note that the 1.8% factor is fixed in the evaluation of $\sigma_{\rm R}$ shown in the right panel of Fig. 3.

One clearly sees microscopic calculation (solid line) yields excellent agreement with the data for the Ne isotopes. For ^{31}Ne, a neutron-halo structure is suggested. We thus perform Resonating Group Method (RGM) calculation to obtain proper asymptotics of the valence neutron. For comparison, results of spherical Hartree-Fock (HF) calculations are shown by the dotted line, which significantly undershoot the data. More seriously, no bound-state solution is found for ^{31,32}Ne. Thus, we have validated the following findings of AMD through direct comparison with scattering observables: i) $^{28-32}$Ne are strongly deformed and ii) ^{31}Ne has a halo structure due to the last neutron in the $1p_{3/2}$ orbit. This will be an important achievement of TNP. More detailed discussion can be found in Ref. [24].

4 Resonance structure of a dripline nucleus ^{22}C

The Cluster-Orbital Shell-Model (COSM) [25, 26] is a powerful method to describe a system consisting of a core nucleus and several valence nucleons. COSM has successfully been applied to the systematic studies of ^{6}He, ^{7}He, and ^{8}He [27], which correspond to three ($\alpha + 2n$), four ($\alpha + 3n$), and five ($\alpha + 4n$) body systems, respectively. A great advantage of COSM is that it generates not only the bound state(s) but also the pseudostates above the particle threshold energy. The pseudostates can be used as discretized continuum states in the Continuum-Discretized Coupled-Channels method (CDCC), as in Ref. [28]. We call this framework of CDCC using COSM wave functions *COSM-CDCC*.

We here study ^{22}C, the dripline nucleus of the C isotopes, with COSM-CDCC. By measuring reaction cross sections [29] and neutron removal cross sections [30], ground state properties of ^{22}C have been intensively studied; the results strongly support the picture that ^{22}C is a s-wave $2n$ halo nucleus. On the other hand, possible resonance states of ^{22}C have never been observed. We investigate the nuclear breakup process of ^{22}C by ^{12}C at 250 MeV/nucleon and see how resonance states of ^{22}C predicted by COSM are found in the breakup spectrum.

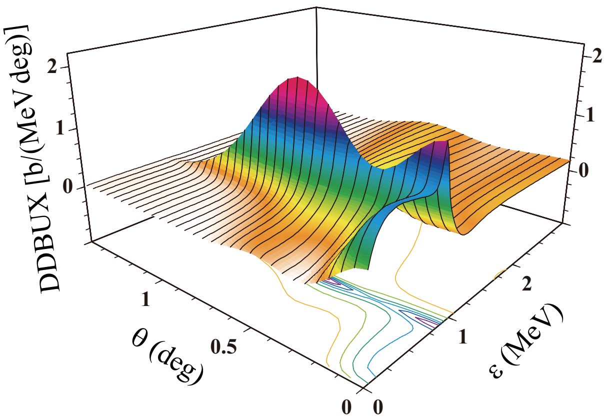

Figure 4: Double differential breakup cross section of ^{22}C-^{12}C at 250 MeV/nucleon.

The double differential breakup cross section is shown in Fig. 4; ϵ is the breakup energy of ^{20}C+n+n measured from the three-body threshold and θ is the scattering angle of ^{22}C after breakup. The optical potentials of n-^{12}C and ^{20}C-^{12}C are obtained by microscopic single- and double-folding models, respectively, with the CEG07 nucleon-nucleon effective interaction in nuclear medium [31]. As for the nuclear densities of ^{12}C and ^{20}C, we adopt the results given in Ref. [32]. We have made the so-called no-recoil approximation to the ^{20}C core. To obtain the smooth cross section, we use the Complex Scaling Method (CSM) proposed in Ref. [33].

One sees some structures in the breakup cross section, reflecting the resonance properties of ^{22}C. In fact, the present COSM calculation predicts the low-lying resonance states of ^{22}C and ^{21}C shown in Table 1. Using CSM,

Table 1: Energy eigenvalues of resonance states of ^{22}C and ^{21}C in complex-energy notation.

J^π (nuclide)	0_2^+ (^{22}C)	2_1^+ (^{22}C)	2_2^+ (^{22}C)	$3/2^+$ (^{21}C)
eigenenergy	$1.02 - 0.26i$	$0.86 - 0.05i$	$1.80 - 0.13i$	$1.10 - 0.05i$

one may decompose the breakup cross section into contributions of each resonance and nonresonant continuum states. With detailed analysis, it is found that i) the two peaks located at (ϵ, θ) = (0.8, 0) and (0.8, 0.5) are both due to the 2_1^+ resonance, whereas the 2_2^+ resonance and the $3/2^+$ binary resonance (^{21}C) are not observed as a peak. Another interesting finding is that the 0_2^+ state has almost zero contribution at its resonance energy (1.02 MeV). This can be understood as a Fano resonance [34]. Complete discussion on these findings will be shown elsewhere [35].

5 Summary

In this article, we introduced a new key subject of nuclear theory group at RCNP, i.e., Triune Nuclear Physics (TNP), with showing some recent achievements. Once TNP has been established, one can *quantitatively* discuss static and dynamical properties of nuclear many-body systems, and theoretical conjectures and findings will be validated by direct comparison with experimental data of scattering observables. There will be many interesting subjects for TNP, e.g., proving clustering structures, nucleon correlations, exotic deformations, and so forth. Another important aspect of TNP is that accurate predictions for reaction probabilities will be achieved, with reasonably small uncertainties. This is of crucial importance for nuclearastrophysics and nuclear engineering.

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